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PROCEEDINGS OF THE INTERNATIONAL STUDENT SCIENTIFIC CONFERENCE POSTER – 29/2025







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PROCEEDINGS OF THE INTERNATIONAL STUDENT SCIENTIFIC CONFERENCE POSTER – 29/2025

The objective of the international scientific student conference POSTER 2025 is to provide an international forum for presentation of undergraduate and postgraduate student research work in fields related to electrical engineering.

All contributions were presented as posters in seven parallel sections at the Faculty of Electrical Engineering, Czech Technical University in Prague on May 22, 2025. The international student conference POSTER 2025, organized by the Faculty of Electrical Engineering, Czech Technical University in Prague, started as an internal meeting of doctoral students in 1995. In 1997, the first International Student Conference POSTER was held. On May 22, 2025 we organized the Conference for the 29th time. As in previous years the conference was held in cooperation with the Faculty of Biomedical Engineering and Faculty of Information Technology.

One of the main goals of the POSTER conference is to promote discussions and interactions among postgraduate and undergraduate students from various countries, universities and fields of study related to electrical engineering. Another important goal is to support independent creative work of students and stimulate practical application of acquired theoretical knowledge since we consider the students' research activity an inevitable part of the whole educational process at all universities.

This year we introduced the following change to the conference. Students can submit either a two-page abstract or a four-page full paper for publication. They can also opt out of publication of their contributions.

The program committee of Poster 2025 conference selected a total of 60 papers for presentation at the conference. Twenty four authors opted out of the publication of their papers in proceedings. The contributions are divided into seven sections:

- Biomedical Engineering
- Communications
- Electronics and Instrumentation
- History of Science
- Informatics and Cybernetics
- Natural Sciences
- Power Engineering

A total of 34 contributions come from Czech Technical University in Prague, 1 from another Czech university and 25 contributions are from abroad. Criteria of acceptance were based on the originality of scientific contribution and good English. Each paper was reviewed by at least two members of the respective section of the Programme Committee.

We would like to thank all students who produced outstanding research results and contributed to this proceeding.

Last but not least, we would like to express our gratitude to all colleagues from the Office for Science, Research and International Relations and from the Computing and Information Centre who helped us a lot in preparation of the proceedings and organization of the conference.

Prague May 2, 2025

Libor Husník on behalf of the Organizing Committee of POSTER 2025

LIST OF PAPERS

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BI	3	An ANOVA-based Sequential Forward Channel Selection Framework for BCI Application based on EEG Signals	Forouzan Salehi Fergeni		Full Paper
BI	4	An active model of the respiratory system as a phantom for the forced oscillation technique	Adéla Rojíčková		Ext abstract
ВІ	5 Analysis of Facial Temperatures and Galvanic Skin Response for Correlations and Possible Estimation		Tobias Reinhardt		No publication
BI	6	Comparison of blood gas analyzers	Martin Šantrůček		No publication
BI	7	Comparison of perfusion index obtained by smartwatch and pulse oximeter	Matěj Losos		No publication
BI	8	Developing a digital twin of a human knee Andreas Wurzinger prosthesis for acoustic analysis Andreas Wurzinger			No publication
BI	9	Effect of the light conditions on the accuracy of SpO2 measurements	Radek Nejman		No publication
BI	10	Generalization Ability of a GREIT-Like Matrix Based on Real-World EIT Data	Theresa Nolte		Full Paper
BI	11	Hyperspectral Photoplethysmography Imaging	Maurice Rohr		Full Paper
BI	12	Measuring an ECG via an ECG-Stick	Immo Baarling	Onno Linschmann	No publication
BI	13	Model of Applicator for Regional Hyperthermia based on eight "Bow-tie" Antennas	Filip Zajan	Michaela Nečasová, Kateřina Pavelková	Full Paper
BI	14	Classification of healthy and impaired plantar foot microcirculation using photoplethysmography imaging and deep learning model	Ján Šeleng		No publication
BI	15	State of the Art in Pulsed-Dose Oxygen Delivery for Mechanical Ventilation	Nika Khosravi		Full Paper
BI	16	Design and experimental verification of novel types of microwave applicators for use in cardiology	Kateřina Pavelková	Michaela Nečasová, Filip Zajan	Full Paper
BI	17	Variability of perfusion index in selected pulse oximeter models	Jonas Horak		No publication
С	1	Influence of Environmental Conditions on Metrological Optical Signals in Standard and Hollow-Core Optical Fibers	Michal Špaček		No publication
С	2	Subjective test methodology design for spatial audio transmission	Jakub Turinský		Ext abstract
С	3	Pulse to Tone Dialling Converter	Urban Jacobs	Nathan Kuehr, Lukas Mardak	Full Paper

Secti Pape	on/ er ID	Paper Title	First Author	Other Authors	Publication
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EI	7	Soa Protection Circuit for eFuses	Lukáš Buryanec		Full Paper
EI	8	Real-Time Data Capture with TI mmWave Radars Jakub Velich			Full Paper
EI	9	Characterisation of a Low-Cost Acoustic Chamber	Patricia Zofia Jesionkowska	Florian Kraxberger	Full Paper
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HST	7	A Historical Overview of Electrocardiography: From Early Discoveries to Modern Advances	Jannik Pruessmann	Immo Baaarlink	No publication
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HST	9	Acquisition of key precision machining technology as a prerequisite for adopting mass production of mechanical wristwatches in Czechoslovakia in the 1950s.	David Hamr		Full Paper

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IC	2	Adaptive RANSAC for Robust Camera Pose Estimation	Vojtech Pánek		No publication
IC	3	Simulation of position improvement in multi- agent system with relative measurements	Michal Koldinský		Ext abstract
IC	4	Leveraging Invertible Neural Networks for Enhanced Uncertainty Quantification in Bayesian Neural NetworksJonathan Wohlmuth			No publication
IC	5	Densoising Time Series Transformer	Lars Reckmann		No publication
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IC	7	Neural Network-Based Estimation of Acoustic Impulse Response	Jakub Urbánek		Ext abstract
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PE	4	Automated Battery Management System Simulation for State-of-X Estimation Algorithm Development	Elias Hempen		Full Paper

1

An ANOVA-based Sequential Forward Channel Selection Framework for BCI Application based on EEG Signals

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Abstract. Converting the movement intents of a person into commands for action employing brain signals like electroencephalogram signals is a brain-computer interface (BCI) system. When left or right-hand motions are imagined, different patterns of brain activity appear, which can be employed as BCI signals for control. In the present study a method of analysis of variance is used to select more appropriate and informative channels from a category of a large number of different channels. After ordering channels based on their efficiencies, a sequential forward channel selection is employed to choose just a few reliable ones. Finally, the selected features are classified with different machine learning and neural networks classifiers with the purpose of comparing their performance in this application. Utilizing a ten-fold crossvalidation approach, tests are performed on a motor imagery dataset found in the BCI competition III. Outcomes demonstrated that the SVM classifier got the greatest classification precision of 97% when compared to the other available approaches. The entire investigative findings confirm that the suggested framework is reliable and computationally effective for the construction of BCI systems.

Keywords

Brain-computer interface, channel selection, motor imagery, support-vector-machine.

1. Introduction

Transmitting information from the individual brain to a computer via the user's unique mental signals is known as a BCI or brain-computer interface framework. BCI has made significant achievements in previous years in multimedia technologies and rehabilitations [1, 2]. In the field of healthcare, BCI has caused an advance by creating numerous brain-controlled devices [3], such as a mind-controlled wheelchair, incontinence control machines, and robotic limbs. Motor imagery is the engagement of the neurological system when imagining the performance of a task or body movement [4]. In fact, as a cognitive

mechanism when a participant imagines that they execute a motion of their body organs without really evolving that region of their body, they are conducting motor imagery (MI). To illustrate, 'right-hand movement' or 'left-hand movement' imagination can be differentiated. Generally, a computerized EEG classifying system includes three aspects of preprocessing, feature extraction, and classification of data. Capturing EEG signals manufactured by the person generally is the first step of a real-time BCI structure. After preprocessing, features of the aforementioned signals are extracted, and the following, suitable characters are chosen and then categorized for the aim of being interpreted into orders for usage, ultimately, feedback is delivered to the participants that include knowledge of whether their cognitive orders were identified or not [5]. An essential step in signal processing is decreasing the number of channels since establishing a system with a lot of channels is time-consuming and annoying for the user. The remaining manuscript is constructed in the following fashion. In the next part, the dataset that was used in the proposed research is explained. Section III outlines the proposed approach, while the outcomes are reported in Section IV, and lastly, section VI deduced the presented work.

2. Materials

To construct a computerized structure for MI EEG task classifications, the data set IV-b from BCI competition III has been employed in the present research [6]. This data set consists of two classes, one for imagining the right hand and another for the imagination of the right foot. A number of 118 channels are monitored that were sites as the famous standard of 10/20-system [7].

3. Methods

3.1 Signal Preprocessing

To eliminate the noise with higher frequency caused by movement and eye blinking and retrieve information within the relevant frequency bands, we employed a band-pass butter-worth filter of order 3 which improved the accuracy significantly. A common average reference (CAR) spatial filter is also employed to eliminate the common noise. Additionally, it lessens the impact of channels with unique noise. For a dataset with M channels and for the channel number j, we reached the CAR-filtered signal ch'_j using the following equation.

$$ch'_{j} = ch_{j} - \frac{1}{M} \sum_{i=1}^{M} ch_{i}$$
 (1)

Where ch_j is the original signal samples of *j*th channel.

3.2 Channel Selection

EEG equipment can obtain brain activity data via many channels on the skin surface of the brain. To avoid some disadvantages of using too many channels, Researchers must establish methods to determine the greatest channels amongst numerous ones. These techniques are designed with the purpose of decreasing the computation time, boosting the categorization efficiency, and choosing the most significant channels for a particular function or operation [8]. In this research, we aim to diminish the number of channels by a combined method. In this method, firstly we employed a filter method to extract the most effective channels. In the filter method, channels are selected based on their score in some statistical tests. These techniques choose the best channels via others without considering the relationship between different channels. On the other hand, wrapper methods put high importance on the performance of channels in relation to each other. These approaches are costly in terms of computational aspects. In contrast, scaler or filter methods are much more time-saving.

This study executes channel selection in a way that with the least possible number of channels, a high precision will be achieved. Fig. 1 demonstrates a schematic drawing of the introduced approach for channel selection.

The process commences when we represent every single channel with some features considering the features extracted from the feature selection stage. These categories, which are representative of different characteristics of channels, then, undergo an analysis of variance (ANOVA) method, a filter method, to be evaluated. An ANOVA test is a technique to realize if the outcomes of a survey or experiment are important and convincing. Every channel in each group will gain a particular order, representing its effectiveness. In this stage, every channel is assessed separately without taking into account its relationship to other channels or even considering the particular classification that will be used. After sorting the channels based on their orders, half of the channels (the best ones) are separated from the rest of them. We use a sequential forward channel selection (SFCS) method to rank the best channels. From the beginning of our selected channel group, we evaluate each channel with the help of the particular classifier we aim to use. This will reveal the channel which results in higher accuracy. This is followed by combining other channels to it to reach the best performance in the case of using two channels. This process will continue to obtain the combination ending in the most significant performance.



selection method

This method resulted in a high accuracy of 97 percent with just 3 channels using the SVM classifier, which is a remarkable outcome from the proposed algorithm. Fig. 2 shows the position of all 118 channels of the dataset and the 3 most noticeable ones respectively.



Fig. 2. 3 channels selected with the SFCS method among all the channels on the head

Combination of the 4th channel would not increase the accuracy significantly. To keep a balance we choose a trade-off between the number of channels and achievement, we use the three first selected channels.

3.3 Classification

After extracting features in time and frequency domains, selecting the most informatic ones using t-test method, and then normalization stage, we employ classifiers. In order to have a comparison between the efficiency of various classifiers on the presented issue we have used seven methods. The classifiers employed in this research are some machine learning techniques including support vector machine (SVM), K-nearest neighbor (K-NN), linear discriminative analysis (LDA), decision tree, and some neural networks namely multilayer perceptron (MLP), extreme learning machine (ELM), and probabilistic neural network (PNN).

4. **Results**

In the proposed investigation, 10-fold cross-validation is utilized in all classes to objectively assess the convincingness of our suggested strategy. The feature set was partitioned into 10 sections at random for each trial. Every instance in the feature vector was therefore assessed in both training and test sets. We utilized dataset IV-b from BCI competition III for investigating the efficiency of our introduced technique. The accuracy obtained from the SVM classifier with a linear kernel function is 97% by using only 3 EEG channels.

Tab. 1. compares the gained result from all the classifiers used in this study. In addition to accuracy, to further confirm the effectiveness of the suggested approach, some other performance metrics including sensitivity, specificity, precision, kappa, and F1_score are also calculated. The tenfold average of Sen, Spe, Pre, Kappa, and F1-Score employing time-domain and wavelet features and SVM classifier are 96%, 98%, 98.1818%, 96.7566%, and 0.94% respectively. Moreover, another performance evaluation concerning the number of channels which was used is CRR, which is equal to 0.974 in our case.

The difference between the features elicited in the time domain and wavelet domain can be shown in Fig. 3 which represents the different classifier outcomes obtained for the two domain features. For the time domain feature, the accuracy is 96% in SVM, and in the case of using wavelet domain features the average classification result is 86%. As it can be inferred from the figure the combination of both kind of feature result in a better classification outcome, emphasizing the effectiveness of our feature vector.

The efficiency of our method is further assessed with the help of the receiver operating curve (ROC) as represented in Fig. 4. As seen, the ROC curve is plotted for different employed classifiers. It is evident that ROC is near 1 and is above the reference line for all the classifiers and among them, the best performance belongs to SVM. Such findings similarly indicate and confirm the results we gain from other evaluation criteria. These acquired outcomes are identical to and entirely consistent with those of CA, proving the viability of the suggested technique.

	precision	F1_score	sensitivity	specificity
K-NN	98.1818	92.8049	89	98
Decision Tree	96.6667	93.7271	92	96
LDA	98.0909	93.7328	91	98
SVM (Kernel	88.1768	85.7548	85	88
Function= 'Polynomial'.	94.0256	91.3318	90	93
'Gaussian', 'PBE'	94.0256	91.3318	90	93
'Linear')	98.1818	96.7566	96	98
MLP	91.7922	92.9578	95	90
#Neuron=10,	91.7922	91.8467	93	90
20, 30	91.7922	92.4315	94	90
ELM	82.4016	88.5563	97	77
#Neuron=10,	85.7093	91.5187	99	82
20,	84.0816	89.1897	96	80
30				
PNN	94.9957	92.042	90	95
	kappa	Selected Channels	CRR	Accuracy
K-NN	0.87	C3, CFC3, C4	0.9746	93.5
Decision Tree	0.88	C3, CFC3	0.9831	94
LDA	0.89	C3, CFC3, C2	0.9746	94.5
SVM (Kernel	0.73	C3, C4, O2	0.9746	86.5
Function= 'Polynomial',	0.83	C3, C4, O2	0.9746	91.5
'Gaussian', 'RBF'	0.83	C3, C4, O2	0.9746	78.5
'Linear')	0.94	C3, C4, O2	0.9746	97
MLP	0.85	C3, PO7,	0.9746	92.5
#Neuron=10,	0.83	PO4		91.5
20, 30	0.84			92
ELM	0.74	C3, P6	0.9831	87
#Neuron=10,	0.81			89
20, 30	0.76			88
PNN	0.85	Cz, PO8, C4	0.9746	92.5

Tab. 1. Comparison between different classifications and the number of channels used for each of them

Reducing the number of channels not only is beneficial in time-saving, but it also helps the classifier to reach better accuracy as it eliminates redundant information and computational complexity. Tab. 2. brings a comparison between two cases of using only ANOVA and diminishing the number of channels by half and employing the SFCS after that. As can be concluded from this table in most classifiers with the reduction in the number of channels, we achieved a higher performance.



Fig. 3. The accuracy of different classifiers employing features of the time domain, features of the wavelet domain, and features of the of both time and wavelet domains



Fig. 4. Receiver operating curve (ROC) of different classifiers used in the proposed method

Classifier	SVM	K-NN	LDA	D-Tree	MLP	PNN	ELM
56 Channel (Selected by ANOVA)	96	92.5	90	92.5	93.5	92	88.5
2 or 3 Channels (Selected by SFCS)	97	93.5	94.5	94	92.5	92.5	89

Tab. 2. Comparison of accuracy of classifiers using 56 channels selected by ANOVA and a couple of channels selected after employing SFCS

5. Conclusion

In this research, the scalar and wrapper methods are coupled to produce a powerful channel selection technique applied to multichannel EEG data. We employed the ANOVA method for reducing the number of channels and the sequential forward feature selection for eliminating the redundant channels. This approach has been used to distinguish between two classes of the BCI EEG dataset. By taking advantage of this channel selection approach, from a dataset with 118 channels only a few channels were used without deteriorating the classification accuracy The number of features extracted from time and wavelet domains could be further and also the frequency band that is selected could be divided into more sub-bands. These are considered as limitations and must be taken into account in future research.

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State of the Art in Pulsed-Dose Oxygen Delivery for Mechanical Ventilation

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Abstract. While oxygen is readily available in developed regions, many hospitals and clinics in low-resource settings struggle with life-threatening shortages, as reported by the World Health Organization (WHO). Pulsed dose oxygen delivery, which conserves oxygen by administering it only at the start of inspiration, presents a potential solution. Therefore, this study examines key advancements in oxygen conservation within advanced ventilation systems through pulsed dose oxygen delivery, particularly in resource-limited settings. It also explores how to balance reduced oxygen consumption with adequate patient oxygenation through an in-depth analysis of in vivo and in vitro studies on pulsed dose oxygen delivery, emphasizing its role in improving oxygen efficiency while enhancing oxygenation.

Keywords

Pulsed dose oxygen delivery, Oxygen conservation, Resource-limited settings, Mechanical ventilation.

1. Introduction

Although oxygen supplies are typically stable in developed nations, the WHO indicates that many healthcare facilities in developing countries lack consistent access to medical oxygen [1]. This challenge also impacts military operations and remote medical facilities in these areas [7]. Given these challenges, the need for efficient oxygen delivery underscores the importance of investigating innovative oxygen delivery systems and strategies in mechanical ventilation that ensure optimal patient care while conserving oxygen resources. An optimal ventilation system should adjust the parameters, such as Tidal Volume (V_T), Positive End-Expiratory Pressure (PEEP), Fraction of Inspired Oxygen (FiO₂), Inspiratory Time (T_I), Expiratory Time (T_E), Peak Inspiratory Pressure (P_{peak}), and others, while minimizing unnecessary oxygen delivery to prevent both hypoxemia and hyperoxemia. This can be achieved by designing a system that administers oxygen in controlled pulses at specific intervals during the inhalation phase instead of providing continuous flow. This method, known as pulsed-dose oxygen delivery, is the primary focus of this paper. The following sections examine pulsed-dose oxygen delivery, reviewing experimental in vivo studies conducted in animals and humans, as well as in vitro studies. Finally, the discussion analyzes the findings of these studies and identifies potential directions for future research.

2. Pulsed Dose Oxygen Delivery

As discussed in the previous section, one effective approach to optimizing oxygen supply is the use of pulsed-dose oxygen delivery rather than continuous flow. This method aligns with the anatomical structure of the lungs, where gas exchange occurs in the alveoli, which make up approximately 90% of the lung's volume. The remaining 10% consists of conducting airways and larger blood vessels, forming the anatomical dead space [10], where no gas exchange takes place. The principle behind pulsed-dose oxygen delivery is to administer sufficient oxygen to the alveolar region at the start of each breath, followed by air or non-oxygen-rich gas to ventilate the dead space effectively. Figure 1 illustrates the difference between pulsed dosing and continuous flow oxygen delivery. Administering a bolus at the start of the ventilator breath ensures that higher oxygen concentrations reach the alveoli, rather than mixing with air at the intake.



Fig. 1: Comparison of Oxygen (O_2) concentrations at the onset of the ventilator breath for pulsed dose versus continuous flow delivery. From [2].

To assess the effectiveness of the reviewed pulsed-dose oxygen delivery methods, physiological parameters such as the Partial Pressure of Oxygen in Arterial Blood (PaO_2), oxygen saturation (SpO_2), and the oxygenation ratio in the

blood relative to the inhaled oxygen concentration (P/F ratio), defined as $\frac{PaO_2}{FiO_2}$, are monitored. For example, the target ranges for PaO₂ and SpO₂ during mechanical ventilation could be approximately 95 [mmHg] and \geq 95%, respectively [13], [11]. The normal value for the P/F ratio is 400-500 mmHg at sea level [9]. According to the American-European Consensus Conference Committee, the P/F ratio can also be used to classify Acute Lung Injury (ALI) and Acute Respiratory Distress Syndrome (ARDS), with a P/F ratio of \leq 300 for ALI and \leq 200 for ARDS and severe hypoxia [12].

The following sections provide a review of exploratory in vivo and in vitro studies conducted over the years to test and validate the effectiveness of pulsed-dose oxygen delivery.

2.1. Exploratory In-Vivo Studies in Animals

This section reviews studies on animals, starting with [6], which examines the effectiveness of pulsed-dose oxygen delivery using the EverGoTM Portable Oxygen Concentrator (POC) to treat hypoxemia during anesthesia in 16 free-ranging brown bears, 18 bighorn sheep, and 5 captive reindeer. Oxygen was administered intranasally via pulsed delivery, with pulse volumes ranging from 12 to 70 [mL], and a maximum capacity of 1.05 [L/min]. The goal was to achieve target PaO₂ levels of 83 [mmHg] for brown bears, 73 [mmHg] for bighorn sheep, and 82 [mmHg] for reindeer. Results showed significant improvements in arterial oxygenation for brown bears and reindeer, but only minor changes in bighorn sheep. The authors suggest adjusting the pulse volume according to the respiratory rate and note that shallow breathing increases dead space ventilation, reducing pulsed oxygen delivery efficiency. Additionally, they found that if pulse delivery exceeds 70% of the inspiratory duration at high respiratory rates, oxygen is lost in the anatomical dead space.

Another study by the authors in [8] investigates the effectiveness of continuous versus pulsed-dose oxygenation using a POC in volume-controlled and pressure-controlled ventilation settings on pigs with ALI. ALI was induced in 15 pigs by administering oleic acid. Standard settings were used, including a respiratory rate of 14 breaths per minute, a V_T of 450 [mL], FiO₂ of 40%, and no PEEP. The POC provided continuous oxygen flow at 3 [L/min] and pulsed doses of 180 [mL], about 40% of V_T. Figures 2a and 2b show the differences in oxygen delivery between continuous flow and pulsed doses in both ventilation modes. In volume-controlled mode, pulsed-dose delivery resulted in a staircase-like flow pattern, with a notch at the end indicating oxygen delivery at the start of each breath, improving oxygenation efficiency without significantly increasing airway pressures. The authors found that pulsed-dose delivery achieved a higher P/F ratio compared to continuous flow, es-



(a) Comparison of pulsed dose oxygenation (on the left) versus continuous flow oxygenation (on the right) in volume-controlled ventilation.



(b) Comparison of pulsed dose oxygenation (on the left) versus continuous flow oxygenation (on the right) in pressure-controlled ventilation.

Fig. 2: Comparison of pulsed dose and continuous flow oxygenation in different ventilation modes. From [8].

pecially in volume-controlled mode. This method was more effective, delivering a larger volume of oxygen to the airways and enhancing alveolar uptake during the initial part of each breath, while the latter part ventilated the anatomical dead space. However, the study had limitations: the maximum attainable FiO_2 of the POC was about 60%, which may not be sufficient for all clinical scenarios, and conventional oxygen systems may be needed for cases requiring higher flow rates.

The authors of [2] conducted an animal study with 18 female Yorkshire pigs, sedated with propofol to eliminate spontaneous breathing. Baseline ventilator settings included a V_T of 8–10 [mL/kg], a PEEP of 5 [cmH₂O], and an FiO₂ of 100%, with the respiratory rate adjusted to maintain a pH between 7.35 and 7.45. They used the Zoll 731 series portable ventilator (Zoll Medical Corp., Chelmsford, MA) along with a Sequal Saros POC (Chart Industries, Ball Ground, GA). The system employed a closed-loop proportional-integralderivative (PID) control mechanism, adjusting the oxygen bolus size based on SpO₂ readings, aiming for a target of 94%. The ventilator automatically adjusted the tidal volume to match the oxygen bolus delivered by the POC. The timing of bolus delivery was carefully controlled within a range of -4.500 to +150 milliseconds, as shown in Figure 3. Arterial blood gases were sampled 20 minutes after any changes in pulsed dose timing. The ventilator and POC communicated effectively, allowing adjustments to both tidal volume and oxygen output.

Furthermore, the authors of [2] aimed to identify the optimal timing for oxygen bolus delivery to achieve the highest PaO_2 levels. Boluses delivered at -150 [ms] and -300 [ms] before inhalation significantly increased oxygen levels compared to other intervals. They also compared the effects of 1 [mL] and 16 [mL] oxygen bolus increments. No sig-



Fig. 3: Timing of bolus doses in relation to V_T delivery and its effects on PaO₂ and PaCO₂ levels. From [2].

nificant differences were observed between the 1 [mL] and 16 [mL] bolus schemes in terms of SpO_2 , O_2 doses, and PEEP. However, discrepancies in SpO_2 were lower with the 16 [mL] bolus scheme at 60 and 90 minutes.

2.2. Human Subject In-Vivo Studies

Research studies such as those in [14], [4], and [3] have conducted human trials to compare pulsed dose oxygenation with continuous flow oxygenation in patients with various conditions.

The study detailed in [14] evaluates both the effectiveness of oxygenation and patient satisfaction when using a single portable pulse-dose oxygen-conserving device (PDOCD) versus a combined system that includes a fixed device for continuous-flow oxygen and a portable device for pulse delivery during ambulation. This investigation involved 25 participants diagnosed with Chronic Obstructive Pulmonary Disease (COPD). The researchers maintained oxygen flow at rest for each participant to ensure that SpO₂ remained at or above 92%, based on arterial blood gas analysis. Their findings indicated that using portable concentrators alone resulted in more frequent periods of low oxygen levels compared to the combined system. Additionally, the study reported that portable concentrators were associated with longer durations of adequate oxygen levels during the night, achieving 44.3% versus 13.4% for the combined system. Survey results also revealed that 43% of participants preferred portable concentrators, while 36% favored the combined systems, and 21% expressed no preference.

The study in [4] also use PDOCD for nocturnal oxygenation compared to continuous flow. The study involved 10 home-oxygen patients with emphysema or pulmonary fibrosis. They underwent sleep-apnea to provide baseline SpO_2 and heart rate data. Patients were switched from continuousflow systems to a PDOCD for one night, and oximetry data were analyzed. Their results showed a statistically significant but clinically unimportant difference in SpO₂ between continuous-flow and PDOCD, with the PDOCD maintaining adequate SpO₂ levels in most patients. Specifically, the mean SpO₂ for continuous-flow was 95.7% and for PDOCD was 93.2%. The study concluded that the PDOCD was able to maintain adequate SpO₂ during sleep in selected patients.

In study performed by [3], the authors conducted a study to compare the effectiveness of continuous flow oxygen from cylinders with pulsed dose oxygen from portable concentrators in treating altitude-induced hypoxemia. A total of 30 participants were randomly divided into three groups and subjected to simulated altitude conditions. The results demonstrated that both continuous flow and pulsed dose oxygen successfully reversed hypoxemia in all subjects. However, the quantity of pulsed dose necessary to achieve oxygen saturation levels comparable to those attained with continuous flow varied significantly among the groups. Furthermore, the increase in subjects' V_T at altitude required the pulse dose setting to be increased by 6-37% compared to the manufacturer's suggested setting for continuous flow, in order to achieve oxygen saturation levels equivalent to continuous flow oxygen delivery. As a result, pulse-dose oxygen delivery did not result in significant oxygen savings at high altitudes, where increased tidal volume and deeper breathing raised oxygen demand.

2.3. In-Vitro Studies

The research by [7] presents a closed-loop system for regulating oxygenation using a POC (SeQual Eclipse 3) and a mechanical ventilator (Impact 731). These devices are interconnected through a computer program for seamless communication. SpO₂ measurements from pulse oximetry provide feedback to adjust the oxygen delivery parameters, including FiO₂, ensuring adequate oxygenation.



Fig. 4: Closed-Loop Control Diagram Featuring Concentrator Integration. From [7].

Tidal volumes of 350 [mL], 550 [mL], and 750 [mL] were paired with inverse respiratory rates of 22 [bpm], 16 [bpm], and 10 [bpm], respectively. In pulse dose mode, oxygen bursts were delivered 1,000 [ms], 750 [ms], and 500

[ms] before each breath, with volumes of 192 [mL], 128 [mL], and 64 [mL]. Results showed that pulse dose oxygenation achieved higher peak FiO₂ values compared to continuous flow, reaching 76.83% without PEEP and 70.95% with PEEP. Continuous flow reached a maximum of 47.81% without PEEP and 47.18% with PEEP. The concentrator in pulse dose mode consumed only 68% of the power while providing up to 161% higher FiO₂, reflecting a 237% improvement in oxygen delivery efficiency. However, the study's dependence on a test lung model with constant compliance is a limitation.

The study by [5] developed an in vitro model using acrylic replicas of adult nasal airways to compare pulsed and continuous oxygen delivery from a POC. The model included a lung simulator for precise breathing control and real-time oxygen concentration measurements at the trachea outlet. The results showed lower FiO_2 values for pulse flow, especially with decreased minute ventilation, such as during sleep. However, these findings are specific to one POC and may not apply to all devices. A limitation is the lack of oxygen uptake in the simulated lung, which impacts real-world accuracy.



Fig. 5: Schematic representation of the experimental setup, highlighting the direction of oxygen flow indicated by arrows. From [5].

3. Discussion

This paper reviews current studies on pulsed dose oxygen delivery, highlighting improvements in some cases and limited benefits in others, with challenges that still require further investigation. Notably, the studies lack patientspecific tailoring for oxygen dosage timing and quantity. Future research should focus on refining this tailoring, integrating spontaneous breathing, and conducting more in vivo evaluations to ensure these methods meet patient needs effectively.

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A Single Helical Interstitial Applicator for Microwave Hyperthermia

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Abstract. This article presents the design and experimental evaluation of a single helical interstitial applicator for localized microwave hyperthermia treatment. The applicator operates at a frequency of 2.45 GHz and is intended to treat small tumors with a 2-3 cm diameter located under the skin. The study includes numerical simulations in Sim4Life focusing on the distribution of the specific absorption rate (SAR) and the reflection coefficient |s11|.

The designed applicator was manufactured and tested using an agar phantom with dielectric and thermal properties similar to human muscle tissue. Experimental results confirm efficient energy delivery with a measured reflection coefficient of -46.5 dB and a controlled thermal response. This research supports the potential of single-antenna hyperthermia for interstitial cancer treatment. At the same time, the optimized applicator can be used in the design of a more complex hyperthermia system.

Keywords

Microwave thermotherapy, local hyperthermia, helical antenna, interstitial applicator.

1. Introduction

Electromagnetic (EM) fields have various applications in medicine, particularly in oncology, where they are utilized for both diagnosis and treatment. Traditional cancer therapies such as surgery, chemotherapy, and radiotherapy remain the standard; however, innovative approaches using EM fields at microwave frequencies (300 MHz–300 GHz) are being actively researched. One of the most promising techniques is microwave hyperthermia, a thermotherapy method that selectively destroys tumor cells by exploiting their lower heat resistance compared to healthy tissue. Tumor cells undergo apoptosis (cell death) when exposed to temperatures above 42 °C, while healthy tissue can tolerate temperatures close to 45 °C [1, 2].

Since biological tissue behaves as a lossy dielectric, which absorbs EM energy and converts it into heat, microwave hyperthermia enables controlled heating for oncological treatment. A hyperthermic system typically consists of a microwave generator, a coaxial cable, and a microwave applicator. The designed applicator is the key component that determines the 3D Specific Absorption Rate (SAR) distribution and the temperature profile in the treated tissue. Hyperthermia can be applied in a non-invasive manner using an array of antennas surrounding the patient (regional hyperthermia; e.g., at 70 MHz), or through an invasive method, in which an interstitial applicator is directly inserted into the tumor, enabling localized heating with significantly lower power levels (e.g., 20 W instead of >1000 W in regional hyperthermia). Various types of applicators are used depending on the clinical application, with waveguide or planar applicators being common for regional hyperthermia, while coaxial and helical interstitial applicators are more suitable for precise, localized heating of deep-seated tumors (e.g., 2-3 cm beneath the skin). In clinical practice, interstitial hyperthermia is often combined with interstitial brachytherapy, where the same catheter is used first for microwave heating and then for inserting a radioactive source such as Iridium-192, making it an effective treatment for radiation-resistant tumors [1–8].



Fig. 1. Scheme of the combined interstitial hyperthermia and interstitial brachytherapy.

Microwave hyperthermia has been successfully used for the treatment of pancreatic, gastrointestinal, esophageal, breast, cervical, bladder, and head/neck tumors, particularly when combined with radiotherapy, as it improves perfusion, oxygenation, and immune response activation. Larger tumors (>2 cm) are more resistant to radiotherapy, and hyperthermia is particularly effective in the tumor center, where it enhances therapeutic outcomes [9]. This paper focuses on the design, numerical modeling, and experimental validation of a single interstitial helical applicator operating at 2.45 GHz for localized microwave hyperthermia. The primary objective is to optimize the applicator's performance by evaluating its reflection coefficient (|sII|), SAR distribution, and temperature rise in an agar phantom, which mimics human muscle tissue [4–10].

2. Materials and Methods

The microwave applicator is based on a helical dipole structure utilizing the properties of a coaxial cable. The key design requirement for interstitial hyperthermic applicators is minimizing their diameter to ensure minimally invasive insertion into biological tissue. To meet this requirement, a commercially available RG178 coaxial cable was selected, featuring a wave impedance of 50 Ω and an operating frequency range of up to 3 GHz [13].

2.1 Design of the Helical Applicator

The microwave applicator is based on a helical dipole structure. The antenna consists of two helices wound from the inner conductor of the coaxial cable. One helix is connected to the inner conductor, while the other is connected to the outer conductor. The material properties and helix dimensions are determined by the chosen coaxial cable, as specified in the mentioned datasheet [13].

To ensure effective microwave energy penetration into biological tissue, the effective penetration depth (d) was calculated based on cylindrical wave propagation, using the following formula:

$$d = \frac{1}{2\alpha},\tag{1}$$

where α represents the attenuation constant that depends on the medium's electrical conductivity and permeability. This formulation provides a more accurate estimation for cylindrical wave propagation, which better represents the field behavior around the helical applicator. Using this approach, the effective penetration depth was determined to be 1.52 cm for biological tissue [9–12].

The applicator was designed to operate in the normal (radial) mode, meaning the circumference of the helix is smaller than the wavelength of the radiation. In this mode, the radiation maximum is perpendicular to the axis of the helix, while the minimum is along the axis, ensuring effective energy delivery to the surrounding tissue. The helix length, number of turns, pitch, and circumference were optimized based on electromagnetic simulations in Sim4Life software. Figures 2 and 3 in the next subsection illustrate the designed applicator [12, 15].

2.2 Model in Sim4Life

The numerical model of the helical applicator was implemented in Sim4Life to evaluate its electromagnetic performance at an operating frequency of 2.45 GHz. Sim4Life is a specialized electromagnetic simulation software based on the Finite-Difference Time-Domain (FDTD) method [16].

The primary goal was to optimize the impedance matching of the applicator, ensuring efficient power transfer into the treated tissue. The applicator was placed in a homogeneous agar phantom, mimicking human muscle tissue, with dielectric parameters obtained from the IT'IS Foundation database [14]. The key dielectric properties at 2.45 GHz are summarized in Tab. 1.

Component	Relative permittivity (-)	Electric conductivity (S/m)	Density (kg/m³)
Helices and conductors	PEC	PEC	PEC
Dielectrics and jacket	2.1	0	2200
Tissue phantom	52.7	1.76	1090

Tab. 1. Dielectric properties of a model for frequency 2.45 GHz.



Fig. 2. Detail of the connection of helices in the Sim4Life.



Fig. 3. Model demonstration of applicator inserted into an agar phantom in Sim4Life (initial applicator design).

2.3 Simulation of Reflection Coefficient and SAR Distribution

For the simulation setup, an edge source was used as the input excitation, which is a common simplification in computational models. The primary goal of the simulations was to optimize the reflection coefficient (|s11|), ensuring that microwave power is efficiently transferred into the tissue. A lower reflection coefficient means that less power is reflected to the generator, maximizing energy deposition within the target region. The target value for |s11| was below -10 dB to minimize reflection losses [9, 11]. During the simulations, the parameters of the helical structure were adjusted to achieve the best possible results (minimization of the reflection coefficient). The final parameters of the designed applicator are:

- coaxial cable length: 47 mm,
- helices pitch: 1 mm,
- length of the first helix: 8 mm (~8 turns),
- length of the second helix: 1.5 mm (~1.5 turns),
- distance between helices: 5 mm.

PEC



Fig. 4. Illustration of the applicator for implementation in the Sim4Life program.

The final simulation results showed an impedance matching of -39.4 dB, which is far below the -10 dB threshold, ensuring efficient energy transfer at 2.45 GHz. Figures 5 and 6 show the SAR (Specific Absorption Rate) distribution in both the XY and ZX planes, demonstrating the energy absorption pattern in the tissue model. The maximum SAR absorption occurs between the helices, creating a well-localized heating region. Minor variations in SAR distribution may be due to current distribution along the helices and internal wave reflections.



Fig. 5. Simulated SAR distribution in XY plane.



Fig. 6. Simulated SAR distribution in ZX plane.

In the simulation, the applicator was placed in a 30 mm cubic agar phantom. The SAR distribution shows how energy is absorbed in the tissue phantom. Uniform heating improves therapeutic effectiveness and minimizes side effects.

2.4 Implementation of the applicator

The applicator was manufactured using an RG174 coaxial low-loss cable, which shares similar electromagnetic properties with the RG178 cable used in simulations. The RG174 cable was selected due to its availability and compatibility with the designed helical structure. During the fabrication process, the inner dielectric was carefully removed from the coaxial cable and subsequently used as internal insulation for the helical structure. Extreme precision was required to prevent small deformations in the helices. Figure 7 shows the final fabricated applicator equipped with an SMA connector (50 Ω).



fig. 7. Manufactured applicator with a helix wound on the inner dielectric.

2.5 Measurements and Results

The applicator was experimentally tested to validate its simulated performance using two measured quantities: reflection coefficient (|s11|) measurement to assess impedance matching and 3D SAR temperature distribution analysis to evaluate power absorption and heating characteristics. The reflection coefficient was measured at 2.45 GHz using an Agilent Technologies E5062A network analyzer in the laboratory of the Department of Electromagnetic Field, Czech Technical University in Prague. The applicator was inserted into an agar phantom at a depth of 22.5 mm, and the measured reflection coefficient was -46.5 dB, closely correlating with the simulated value

of -39.4 dB. Figure 8 compares the simulation and measurement results.



Fig. 8. Comparison of the reflection factor |*s11*| from the simulation in Sim4Life and the factor measured in the laboratory environment.

The temperature distribution was analyzed in the Faculty of Biomedical Engineering, using a Sairem microwave generator (output power up to 200 W, frequency range 2400-2500 MHz) and an infrared (IR) thermal camera (FLIR E60) for temperature monitoring. The experimental setup included an agar phantom designed to replicate muscle tissue properties, ensuring realistic thermal and electromagnetic behavior. After 60 seconds of microwave exposure at 2.45 GHz, thermal imaging analysis was conducted. The IR thermograms confirmed that the temperature distribution in the agar phantom closely aligned with numerical simulations, verifying the applicator's effectiveness in controlled energy deposition and localized heating.

The initial temperature of the agar phantom's interior was 15.5 °C. Throughout the thermal imaging measurement, a sliding caliper was placed next to the phantom to provide a clear reference for the total heated area visible on the thermogram, Figure 9.



Fig. 9. Thermogram of temperature distribution in the ZX axis after a long exposure of 60 seconds.

The measurement results showed that after 60 seconds of microwave exposure, the temperature in the immediate vicinity of the applicator increased from 15.5 °C to 29.2 °C at the center of the heating zone, while at approximately 1 cm from the center, the temperature reached 21.4 °C. The temperature distribution formed an elliptical shape, demonstrating that the applicator design successfully meets the requirements for heating tumors of 2–3 cm in diameter. The highest temperatures were concentrated in an ellipse with a major axis of 3 cm, ensuring effective localized hyperthermia treatment.

3. Conclusion

This study demonstrated the design, numerical modeling, and experimental validation of a single helical interstitial applicator for localized microwave hyperthermia at 2.45 GHz. The proposed applicator was optimized to ensure effective impedance matching, with a simulated reflection coefficient of -39.4 dB and an experimentally measured value of -46.5 dB, confirming excellent energy transfer efficiency. The SAR and temperature distribution analyses indicated that the applicator effectively heats a localized tumor region of 2-3 cm, with peak temperatures concentrated in an elliptical heating zone. The measured temperature increased from 15.5 °C to 29.2 °C at the heating centre while maintaining controlled peripheral heating, confirming the applicator's suitability for targeted hyperthermia treatment. The simulated SAR distribution corresponds to the observed temperature distribution, confirming the consistency between electromagnetic energy absorption and thermal response.

The experimental results closely aligned with simulation data, verifying the applicator's efficiency in controlled energy deposition. These findings suggest that the helical applicator design is a viable solution for minimally invasive hyperthermia treatment, with potential applications in future multiport applicator hyperthermia arrays for deepseated tumor treatment.

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Genaralization Ability of a GREIT-Like Matrix Based on Real World EIT Data

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Abstract. In the innovative imaging modality of Electrical Impedance Tomography (EIT), many experiments are conducted with simulated data, and out-of-the-box algorithms are often used for image reconstruction. It was suggested before that the reconstruction results of data-based reconstruction algorithms can be improved using real-world measurement data for algorithm development or training. Therefore this paper compares the reconstructions of two different GREIT matrices. One GREIT matrix provided by pyEIT is based on simulated data and the other is calculated on data from real tank measurements. The results on several test datasets show that the matrix based on real measurements outperforms the pyEIT matrix in visual quality and in the applied Figures of Merit. Especially the position and the edges of the targets are reconstructed more precisely. This suggests that using real-world data for data-based reconstruction algorithms is beneficial.

Keywords

Electrical Impedance Tomography, GREIT, Phantom Tank, Real-World Data, Simulated Data

1. Introduction

Electrical impedance tomography (EIT) is an imaging technique that visualizes the conductivity distribution within a region of interest by injecting low-amplitude alternating currents, measuring the resulting voltages at the surface, and reconstructing these measurements into an image. The measurements can be generated by real-world measurements or by simulations [1]. Using simulations facilitates generating large datasets. Therefore, most data-based reconstruction algorithms use simulated data for algorithm development and testing [2, 3]. One well-known data-based algorithm is the GREIT algorithm. This algorithm originally calculates a matrix for image reconstruction with simulated data [4]. Gaggero et al. [5] have shown that there can be significant differences between using real-world data and simulated data in algorithm development. This paper examines the generalization abilities of two different GREIT-like matrices to conclude possible improvements in the reconstruction quality. One matrix is provided by pyEIT, a Python library for EIT, and is calculated with simulated data [6]. The pyEIT matrix is not specifically adapted to the real measurement conditions in a phantom tank. The other matrix, the "tank matrix", is calculated based on a dataset collected in a phantom tank setup. Both matrices are tested on several setups, which include different target sizes, two targets in the same tank, and data collected in a different tank setup. The reconstruction results are compared qualitatively and quantitatively.

2. Methods

This paper utilizes the GREIT algorithm for reconstruction, as described by Adler et al. [4]. The GREIT-Algorithm reconstructs an image vector $\hat{x} \in \mathbb{R}^{n_N}$ with the equation $\hat{x} = \mathbf{R} \cdot y$, where $y \in \mathbb{R}^{n_i}$ are the voltage measurements and $\mathbf{R} \in \mathbb{R}^{n_N \times n_M}$ is the reconstruction matrix. The original paper proposes calculating the matrix \mathbf{R} with simulated voltage measurements. For the voltage measurements, a point-like conductivity abnormality is moved to different positions in a tank. The matrix provided by pyEIT is calculated this way [6]. For the tank matrix, this approach is adapted for tank measurements. Both matrices are further described in sections 2.1 and 2.2. Afterward, the test data and the evaluation criteria are specified.

2.1. GREIT-like Matrix based on real-world data

For calculating a GREIT-like Matrix based on realworld data, the point-like conductivity abnormality is approximated by a cylindrical PLA-target with a conductivity close to $0 \,\mathrm{Sm^{-1}}$ and a diameter of $10 \,\mathrm{mm}$ (see Fig. 1). A phantom tank is filled with saline $(5.37 \,\mathrm{Sm^{-1}})$, and a positioning system places the PLA target in 1247 different positions, which are equally distributed in the tank. This is repeated 10 times to generate the dataset. The measurements were conducted by the EIT device "EIT32" of Sciospec Scientific GmbH with 16 electrodes, the adjacent stimulation and measurement pattern, a frequency of 1 kHz, and a current of 1 mA. In addition to the target measure-



Fig. 1: Measurement setup.

ments, 100 measurements of the tank without a target were averaged to generate time-differential measurements. The ground truth images are derived from the target position and geometry. The matrix was calculated with these ground truth images and the time-differential measurements as described by Adler et al. [4].

2.2. pyEIT Reconstruction Matrix

pyEIT is a framework for EIT applications in Python developed by Liu et al [6]. It provides methods for forward and inverse solving of the EIT problem, which also includes the GREIT algorithm for image reconstruction. The GREIT matrix is based on simulated EIT data with 16 electrodes and the adjacent stimulation and measurement pattern.

2.3. Testdata

The performance of the two matrices is evaluated on different time-differential test datasets. First, datasets recorded at our phantom tank are used. This includes measurements of the 10 mm target and of cylindrical PLAtargets with a diameter of 20 mm, 40 mm, 60 mm and 80 mm. For these datasets, only one target was placed in the tank at a time. For the 10 mm target, measurements at 1247 different positions were recorded. For the larger targets, the number of positions was limited to 308 due to the size of the targets and, therefore, less available space in the tank. Additionally, measurements are recorded where the $20\,\mathrm{mm}$ and the $60\,\mathrm{mm}$ target are placed in the tank simultaneously. Since the positioning system, which was used before, is only able to position one target, the targets are placed by hand, and therefore, no exact ground truth is available. The targets were placed approximately 15 cm, 7.5 cm, and $0.5\,\mathrm{cm}$ apart from each other. Second, the matrices are validated on tank measurement from another tank setting available on EIDORS [7]. In this dataset, plastic and metal targets were placed in a tank in different arrangements. There is no information on the size of the targets or the radius where they are positioned, only on the relative angle of the targets to each other. Therefore, no exact ground truth is available.

2.4. Evaluation criteria

The reconstructed images are evaluated qualitatively and quantitatively. The qualitative evaluation is conducted by visual comparison. The visibility of the target, the agreement with the ground truth, and the differences between the two matrices are inspected. Quantitatively, they are evaluated by the Figures of Merit (FOM) introduced by Adler et al. [4]. The amplitude response (AR) represents the ratio of pixel amplitudes between the reconstructed image and the ground truth. The position error (PE) quantifies the positional difference between the actual and reconstructed target locations. The Resolution (RES) compares the size of the reconstructed target relative to the overall tank size. Ringing (RNG) indicates the extent to which the amplitude of pixels surrounding the target negatively overshoots. Lastly, the shape deformation (SD) measures how the shape of the reconstructed target deviates from the original target's shape. All metrics should be uniform and as close to zero as possible, except AR, which should be close to one. PE is given in pixel, all other metrics are unitless. The FOMs can only be calculated if the ground truth is available.

3. Results

Figure 2 shows reconstructions of the 10 mm target. For the tank matrix, a target is visible and fits the ground truth in shape and size in every image. When using the pyEIT matrix, a target is visible in every image, but the target position differs more from the ground truth, and the edges of the targets are less sharp. Especially targets closer to the center of the image appear larger than the ground truth. This enlargement is also visible for the tank matrix but to a smaller extent. The quality difference is also represented in the FOMs. The tank matrix achieves better FOMs than the pyEIT matrix in all metrics except ringing (compare corresponding entries in Figure 4). Especially for the position error, the tank matrix is superior to the pyEIT matrix.



Fig. 2: Reconstructions of the $10 \,\mathrm{mm}$ Target. The red circle indicates the ground truth.

When using bigger targets, the increase in size is visible in the images for both matrices. The reconstructions with the tank matrix still appear more precise, especially at the edges of the target, since it fits the ground truth better. For both metrics, the position accuracy visually decreases for larger targets, which is reflected in the FOMs as well.



Fig. 3: Reconstructions of larger targets. The red circle indicates the ground truth.



Fig. 4: FOMs of reconstructions of different target sizes compared for the tank matrix and the pyEIT matrix.

Figure 4 presents the average FOMs for the different target sizes and the two matrices. In general, the tank matrix outperforms the pyEIT matrix for every FOM and every target size except for ringing. However, there are some

differences between the FOMs in how much they differ between the two matrices. For AR, the results are closest together. For both matrices, holds that the larger the target is the larger the AR. The difference in PE is the largest of all FOMs. The tank matrix achieves a much higher accuracy in the target position than the pyEIT matrix. The PE also indicates that the position accuracy decreases for larger targets, which was also visible in the images. The RES represents the visible target enlargements in the pyEIT reconstruction with a higher value for the minimal resolution. RNG is the only FOM where the pyEIT matrix achieves better results than the tank matrix. However, the RNG has a higher variability between the different target sizes for the pyEIT matrix than for the tank matrix. The shape deformation improves for bigger targets reconstructed by the pyEIT matrix, which is not the case for the tank matrix, which stays at a low SD level.

When applying the matrices to a scenario where two targets are placed in the tank, the targets are distinguishable with the tank matrix in all three situations (see Figure 5). Additionally, their size difference can be seen in the first two images. In the last image, the smaller target is only represented in a lower intensity and not in a size difference. For the pyEIT matrix, the two targets can not be recognized in any case. For the first case, it can be assumed that two targets are present, but they are not clearly visible. For the last two cases, there is just one abnormality in the center of the image.



Fig. 5: Reconstructions of two targets in one tank.

Lastly, the matrices are tested on data from a tank experiment available on EIDORS [7]. The tank matrix shows a better performance on this data as well. For every situation, the targets can clearly be distinguished, and the conductivity difference between the saline background and the plastic or metal target is represented correctly (see Figure 6). The latter is valid for the pyEIT reconstruction as well, but here, the two targets can not be separated when they are at a 45-degree angle to each other, so they are very close to each other.

4. Discussion

In general, the tank matrix outperforms the pyEIT matrix for every tested situation and almost every FOM. The



Fig. 6: Reconstruction of an external dataset.

performance increase may be caused by the better adaptation of the tank matrix to the real tank setting since the simulation cannot integrate all variables like the electrode impedance or special characteristics of the EIT device. Even on data that is collected in a different EIT setup, the reconstructed images exhibit a better quality when using the tank matrix. This leads to the conclusion that there are even more factors that differ between simulation and reality.

The sharper edges of the reconstructed targets are a main factor in the improved visual quality. These sharp edges can be the result of the chosen weight matrix, which is used in the calculation of the reconstruction matrix [4] and defines the size of the transition zone between the target and the background. A smaller zone leads to sharper edges but also to increased ringing (i.e. overshoot), according to Gibb's Phenomenon [8]. Therefore, the reconstructions of the pyEIT matrix express a lot less ringing since the edges are less sharp. The sharper edges could also contribute to the ability to distinguish between two targets when utilizing the tank matrix. Especially when the targets are closer together, the tank matrix is superior to the pyEIT matrix, where the targets can not be separated.

For both matrices, the reconstruction quality decreases for targets close to the center of the tank. This decrease might be mitigated when using a different stimulation and measurement pattern since the adjacent pattern is known for suboptimal results in the center of the tank [9].

5. Conclusion

This paper presents a comparison between the GREIT reconstruction matrix provided by pyEIT and a custom

GREIT-like matrix based on real tank measurements. The matrices were tested on different datasets from tank experiments, which include single cylindrical PLA targets, two PLA targets in the same tank, and data recorded in a different tank setup. In all tested cases, the performance of the custom reconstruction matrix exceeds the performance of the pyEIT matrix. The main difference is that the edges are sharper, and the matrix is especially beneficial for two targets close together. In general, this study shows that for the GREIT algorithm, it is beneficial to rely on real tank data and not only on simulated data to improve the reconstruction performance. This suggests that the same could hold for other data-based reconstruction algorithms like algorithms using Machine Learning, which should be investigated in further research.

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Design and experimental verification of novel types of microwave applicators for use in cardiology

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Abstract. This study aims to design and experimentally validate new types of microwave applicators suitable for the treatment of cardiac arrhythmias. Two types of applicators were designed, fabricated and tested on an agar phantom of muscle tissue. Optimization of shape and dimensions was based on numerical simulations employing the finite element method implemented in Sim4Life software. The results show that the proposed applicators are suitable to be used in the treatment of cardiac arrhythmias, both in terms of efficiency and ability to create the desired shape of ablation zone.

Keywords

Atrial fibrillation, finite element method, intracavitary applicator, microwave ablation, numerical simulation.

1. Introduction

These days, thermoablation is widely employed in cardiology for treatment of symptomatic forms of arrhythmias. The objective of this technique is to induce irreversible damage to a specific area of myocardium, which subsequently heals as a scar, thereby isolating pathological impulses from the surrounding tissue [1]. The lesion formation is facilitated by coagulative necrosis resulting from tissue heating to a minimum temperature of 50 °C [2]. Thermoablative methods include not only microwave ablation but also radiofrequency ablation, cryoablation, and laser ablation [3]. At present, the most commonly used method for treating arrhythmias is radiofrequency ablation. This technique achieves tissue heating through the flow of current between the catheter electrode and a ground electrode placed on the patient's back [4]. However, this ablation modality is associated with a high probability of arrhythmia recurrence [5] and may lead to severe complications such as pulmonary vein stenosis or esophageal fistula due to insufficient control over the lesion formation [6]. An increasingly prevalent alternative to thermal methods is electroporation, which, rather than inducing thermal necrosis, triggers apoptosis in individual cells [7]. However, recent research indicates that even microsecond pulsed fields can generate ablation temperatures that lead to tissue necrosis and the associated

inflammatory response [8, 9]. Furthermore, evidence suggests that irreversible damage to a significant number of red blood cells is present. Consequent hemolysis potentially leads to renal failure in some patients [10]. Microwave energy presents an alternative to these approaches but is primarily utilized in oncology for the treatment of cancerous diseases [11-15]. Historically, microwave ablation has already proven effective for treating arrhythmias in cardiology [16-18].

The main objective of this study is to present new types of microwave applicators that are sufficiently impedance-matched and capable of creating an ablation zone shape that meets specific therapeutic requirements. A spiral applicator with a wide aperture will be designed for the treatment of ventricular tachyarrhythmias. Additionally, a loop-type applicator will be developed to create a lesion around the pulmonary vein circumference. Numerical simulations will be performed aiming at optimizing dimensions of applicator antennas to achieve a sufficiently low reflection coefficient and appropriate SAR distribution at the selected operating frequency of 2.45 GHz. Based on the simulation results, the applicators will be manufactured, and their properties will be tested through measurements using an agar phantom mimicking biological tissue.

2. Materials and methods

2.1 Design of applicators

In the context of arrhythmia treatment, successful outcomes depend on the generation of a sufficiently deep lesion that penetrates the entire thickness of the myocardial wall, thereby effectively isolating the pathological tissue. In addition, the design must ensure that the targeted area reaches a temperature of at least 50 °C to induce thermal necrosis [19]. The depth of heating is influenced by several factors, including the frequency of the microwave radiation [20], the dimensions of the applicator, and the dielectric and anatomical characteristics of the surrounding tissue [21]. A major challenge in achieving effective ablation with sufficient lesion depth is the dissipation of heat via blood flow in well-perfused organs [19]. Another issue

arises from power losses, particularly the heating of the supply line [22].

The predominant technological solution of intracavitary applicators involves applicators based on modified coaxial transmission lines, which are favored for their flexibility and small dimensions, making them well-suited for catheter-based applications [16, 18, 19]. These applicators are capable of achieving penetration depths on the order of millimeters [23]. The radiating element does not necessarily need to conform to the dimensions of the catheter, provided it is appropriately constructed from a shape-memory material [17]. In this study, two types of coaxial intracavitary applicators were designed and tested. The first type, featuring a spiral structure, is intended for the ablation of ventricular arrhythmias. This design was inspired by a study [16], in which a similar applicator was tested at a frequency of 950 MHz. According to the authors, its advantage lies in the ability to create wide and deep lesions, thus shortening the duration of the ablation procedure and improving treatment efficiency. The second type of applicator utilizes loop structure to create a lesion around the pulmonary vein for the treatment of atrial fibrillation. This design was inspired by study [24] introducing a loop-shaped applicator with similar purpose. Schematic representations of both applicators are shown in Fig. 1.



Fig. 1. Design of applicators: (a) spiral-shaped applicator; (b) loop-shaped applicator.

2.2 Numerical simulations

The dimensions of the radiating structures were optimized using numerical simulations conducted in the Sim4Life software. То compute distribution of electromagnetic field, Sim4Life employs the Finite Difference Time Domain (FDTD) method [25]. The model of selected coaxial cable RG-174 was created using several concentric cylinders. The antenna of the spiral applicator was modeled using an Archimedean spiral and the antenna of the loop applicator was created using an arc. The electromagnetic energy source was defined as a waveguide source, which excites a TEM wave traveling toward the terminating structure of the coaxial line. Eventually, the applicators were applied to the surface of the cardiac tissue model. Myocardium thickness was chosen as 15 mm considering that the thickness of the cardiac chambers is highly variable, ranging from 1 mm at the cardiac apex to 15 mm at the obtuse margin [26]. Each element of the model was assigned parameters from the Sim4Life database [27], which contains various types of tissues and inorganic materials with defined dielectric properties.

Each resonator can operate at multiple resonant frequencies at integer multiples of the wavelength in the tissue [28]. For the initial simulations, the length of the radiating structure was chosen to achieve one of these theoretical maxima.

In terms of energy transfer efficiency, the dependence of the reflection coefficient modulus on frequency was evaluated, with the aim of achieving the lowest possible values. For different radii of the spiral and loop structures, this dependence is shown in Fig. 2. For both types of applicators, sufficiently low reflection coefficients were achieved at the operating frequency, with the spiral applicator achieving -16 dB and the loop applicator reaching -44 dB.



Fig. 2. Simulated reflection coefficients for different radii of radiating structures: (a) spiral applicator; (b) loop applicator.

Along with the reflection coefficient, the spatial distribution of the Specific Absorption Rate (SAR) was also evaluated during the simulations. The SAR distribution was determined as the output of a harmonic simulation performed using a sinusoidal excitation signal at the working frequency. The distribution of SAR around the radiating structures is depicted in Fig. 3. The figure suggests that for both applicator types, a significant amount of energy is absorbed in the region in front of the radiating structures.



Fig. 3. SAR distributions: (a) spiral applicator; (b) loop applicator.

2.3 Experimental evaluation of applicators

Both applicator types were manufactured using flexible coaxial cable RG-174. The radiating elements were formed by removing the surface insulation and outer conductor from a segment of the cable, with the length of the exposed section optimized based on numerical simulations. The modified distal segment of the coaxial cable was then shaped into either a spiral or loop, depending on the applicator type. The length of the spiral structure was chosen to be 44 mm, and the loop structure was selected to be 34 mm.

Properties of manufactured applicators were tested in vitro, performing measurements on an agar phantom. Initially, the reflection coefficient in the frequency range from 2 to 3 GHz was measured using a microwave vector analyzer Agilent Technologies E5062A. The applicator was mounted using a laboratory stand to ensure its contact with the surface of the agar phantom. The blood around the applicator was replaced with tap water. Based on the reflection coefficient measurements, it was found that for the loop applicator, resonance occurred above the operating frequency of 2.45 GHz. Thus, it was necessary to manufacture this applicator again, with the length of the terminal structure extended to 40 mm. After this modification, the measured reflection coefficient approached the simulation results. The measured dependence of the reflection coefficient modulus on frequency in the range from 2 to 3 GHz is shown in Fig. 4. This figure also compares the measured reflection coefficients for the optimized applicators with the previous simulation results. For the spiral structure of length 44 mm and loop structure of length 40 mm, a minimum reflection coefficient of -15 dB and -40 dB was achieved, respectively.



Fig. 4. Comparison between simulated and measured reflection coefficients: (a) spiral applicator; (b) loop applicator.

To characterize the distribution of the Specific Absorption Rate (SAR), the temperature distribution within the agar phantom was measured. Given that the internal temperature of the human body is approximately 37 °C, a temperature increase of 13 °C is required to achieve the ablation effect. In the laboratory conditions, the initial temperature of the phantom was 21 °C, thus it was necessary to heat it to at least 34 °C. The agar phantom was heated using a 120 W microwave power from an electromagnetic power generator by Sairem for 20 seconds. After switching off the generator, the phantom was sliced and the thermograms were taken as soon as E60 thermal possible using the FLIR camera. Thermograms for both applicator types are shown in Fig. 5. In case of the spiral applicator, the maximum temperature achieved in the cross-section was 32 °C, and for the loop applicator, it was 34 °C. The depth of the lesion was approximately determined based on the distribution of maximum temperatures in the thermogram. For the spiral antenna, the maximum heating depth reached 10 mm, and in case of the loop antenna, it reached 7 mm. At the end of the experiment, the relative permittivity as a function of frequency was measured for the agar phantom and tap water.



Fig. 5. Thermograms of the fantom section: (a) spiral applicator; (b) loop applicator.

3. Discussion

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The primary objective of this study was to design, fabricate, and evaluate novel microwave applicators designed for the treatment of different types of cardiac arrhythmias. The dimensions of the radiating structures of both applicators were optimized using the Sim4Life simulation software. The experimental results demonstrated that both types of applicators achieved sufficiently low reflection coefficients (below -10 dB) indicating effective energy transfer. The distribution of the Specific Absorption Rate (SAR) predicted the highest energy absorption above the radiating structures of both applicators, corresponding to the regions where the desired ablation effect was expected to occur. To achieve the required temperature increase of 13 °C, relatively high-power settings were necessary. Possible contributing factors to the observed power requirements include rapid cooling of the phantom, which may have hindered the accurate recording of the actual temperatures, and power losses in the feeding coaxial cable, which became noticeably heated during the experiment. The power loss due to cable attenuation, specified as approximately 1 dB/m for the RG-174 coaxial cable, would correspond to an insertion loss of approximately 0.5 dB for a 0.5 m feed cable, representing a power loss of around 10 %.

Regarding the lesion depth, the spiral applicator achieved a maximum heating depth of 10 mm, while the loop applicator achieved a depth of 7 mm. This outcome is consistent with the original hypothesis that the spiral applicator would generate a deeper lesion suitable for the treatment of ventricular arrhythmias, whereas the loop applicator, designed for the treatment of atrial fibrillation, requires a shallower lesion to achieve transmural ablation. These results are in line with those observed in other studies investigating the microwave ablation effects. Notably, the study by Chiu et al. [18] reported a lesion depth of 9 mm after 30 seconds of heating bovine heart tissue at 80 W, which is comparable to the results obtained in this study.

4. Conclusion

Microwaves present a safer and more efficient alternative, especially due to their ability to reduce side effects and minimize arrhythmia recurrences, as the size and depth of the resulting lesion can be more precisely controlled. The findings from this study indicate that the designed applicators are sufficient and effective in generating the desired lesion morphology, thereby suggesting their use in catheter ablation procedures for arrhythmia treatment.

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Hyperspectral Photoplethysmography Imaging

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Abstract. Photoplethysmography imaging (PPGI) is a technique for remote blood volume pulse (BVP) estimation. While most PPGI methods rely on RGB cameras optimized for human vision, hyperspectral imaging (HSI) enables a more detailed exploration of multi-wavelength approaches for BVP extraction. This study investigates spectral band fusion strategies to enhance heart rate (HR) estimation by employing a hyperspectral camera (350—1002 nm, 164 channels). Experimental results from three subjects show that a linear weighting method significantly enhances signal-tonoise ratio over baseline monochrome imaging and traditional RGB-based PPGI methods. Despite hardware constraints, this demonstrates the potential of hyperspectral data for optimizing non-contact vital sign monitoring.

Keywords

hyperspectral imaging, photoplethysmography, optimization, signal fusion

1. Introduction

Photoplethysmography Imaging (PPGI) is a technique for measuring blood volume pulse (BVP) signals from the skin from a distance by using cameras. Similarly to its contactbased counterpart, the photoplethysmogram (PPG), PPGI relies on the changing light absorption characteristics of skin dependent on the blood flow in the microvascular bed. Instead of using a controlled light source, ambient illumination is used and a region-of-interest (ROI) for signal extraction must be selected. PPGI may provide heart rate (HR) measurements, oxygen saturation, blood pressure and spatiotemporal dynamics of cutaneous perfusion [1]. Its robustness for real-world application was proven for example, by estimating HR in critical care patients achieving measurement errors within 5 BPM of an ECG reference HR over a period of 83% of total recording time [2]. The first baby steps in PPGI were done using an industrial near-infrared camera [3]. Quickly methodology adopted RGB cameras for their wide availability in consumer cameras [4] and because the multiple color channels (wavelengths) could be exploited for reducing motion and illumination changes by employing blind-source separation [5] and later other robust signal processing techniques [6, 7]. In early research by Hertzman [8], who coined the term "photoplethysmog-



Fig. 1. Penetration depths of different wavelengths on face and arm skin (skin image adapted from Servier Medical Art, licensed under CC BY 4.0)

raphy", the spectral properties of light were not considered. Instead, emphasis was placed on maximizing signal amplitude, primarily by using high-power light sources such as automobile headlight bulbs. Since then, particularly with the advent of PPGI, research has been conducted to identify optimal wavelengths and effective wavelength combinations to estimate BVP, which will be discussed in the following paragraph.

Mono-, Multi- and Hyperspectral Pulse Estimation Monospectral estimation uses a single band of the light spectrum. Historically, the origin of the PPG signal was thought to come from the arteries below the dermis. Hence, the penetration depth of the used wavelength was considered a major confounder to signal strength. One of the early works [9] summarizes that light with a longer wavelength, i.e. infrared, penetrates deeper into the skin and may go through the dermis and into subcutaneous tissue (see Figure 1). Beyond penetration depth, other factors influencing signal quality include the absorption characteristics of key chromophores such as hemoglobin and melanin. However, they found that the 510-590 nm band exhibits the maximum amplitude of pulsation inside the 420 to 940 nm range independent of skin color. Corral et al. [10] verified these findings using a spectrometer with 10 Hz sampling rate for HR and found a second suitable band in 800-925 nm. Accordingly, the first work employing RGB cameras for PPGI identified the green channel as producing the strongest signal [11]. Today, most consumer devices, such as smartwatches, use green light, while in clinical applications a red/infrared PPG light probe is often used because it is capable of picking up signals from the deeper arteries and facilitates blood oxygenation measurements via the ratio-of-ratios method [12].

While the research on the optimal single wavelengths has settled, the usage of combinations of different wavelengths still largely depends on the predefined wavelengths originally optimized for the human visual system (classical RGB). Multispectral imaging captures a limited number (typically three to twelve) of distinct relatively narrow spectral bands [13]. This technique allows for the generation of parametric images that map the distribution of skin chromophores [14]. Most contact-based multi-wavelength PPG systems use only three to four wavelengths [15]. Traditionally color channel combinations in PPGI have been used to reduce the influence of illumination changes (specular effects) [6, 7] and motion [16]. Kado et al. [17] combined NIR and RGB imaging to fuse spatial and spectral HR estimates using a histogram-based approach. Their method demonstrated higher accuracy than previous methods under varying lighting conditions, including TV-induced illumination changes. A different problem where multiple wavelengths can come in handy is blood pressure estimation, for which the pressure inside a single artery must be estimated. However, the measured PPG signal cannot be attributed to a single origin, but is a superposition of pulse wave functions with different waveforms and phase shifts. Liu et al. [12] present a multi-spectral PPG method exploiting the wavelength dependence of light penetration in skin tissue to provide depth resolution of skin blood pulsation. They used two and three different wavelengthsto extract the BVP through a multilayer light-skin interaction model, enabling them to separate pulsation from the subdermal plexus from pulsation originating from other layers. Blackford et al. [18] developed a multispectral imaging system featuring a 12-camera array with narrowband filters (50 nm) covering the 400-750 nm range at 120 FPS. Their system also incorporated a dual RGB/NIR imager (1024×768 resolution, 30 FPS) and a highresolution spectrometer (1.5 nm, 400–1162 nm). Although they demonstrated the feasibility of HR extraction from each spectral channel, no further data evaluation was provided.

Hyperspectral imaging (HSI) extends multispectral capabilities by capturing a broad spectrum with high spectral resolution. Besides hemodynamic monitoring [19], HSI has been applied in fields where only single snapshots are required, including tissue oxygenation mapping [20], fluorescence angiography [21], remote skin assessment [22], and blood component analysis (e.g., hemoglobin, platelets, and bilirubin) [23]. [1] propose hyperspectral reconstruction from RGB for PPGI to overcome HSI limitations using deep learning. [24] analyse NIR bands for PPGI with a hyperspectral camera with the goal to select a promising single or dual channel system resulting in 799 nm and 861 nm as the optimum.

Due to the high cost and the limitations in spatial and temporal resolution, hyperspectral imaging has not been used to analyze the fusion of different spectral bands for PPGI. This study takes an initial step in addressing this gap.



Fig. 2. Setup consisting of the hyperspectral camera (HSI) with paired monochrome camera, white reference plate, and two wide spectrum high intensity white LED lights.

2. Methods

2.1. Measurement Setup

Our setup consists of a hyperspectral camera paired with a registered monochrome camera (Cubert Ultris X20P) that can take full spectrum snapshots (global shutter) with a frequency of 4 Hz. It provides 164 channels with a spectral resolution of 14 nm evenly spaced between 350 and 1002 nm at 12 bit with a spatial resolution of 410 x 410 that can be upscaled to 1886 x 1886 via software. As light source, two wide-flat spectrum LED light bars for HSI (Effiflux¹, 31 W) with 400-1000 nm are used and other sources of light are minimized. As reference sensor, the finger PPG of a patient monitor (General Electrics) was used. We recorded 160 seconds of data from three subjects. The subject's head rested in left lateral position on a bed with a face-to-camera distance of ca. 85 cm while keeping a kneeling position. A distance calibration of the hyperspectral camera was performed before each recording to ensure precise spatial alignment of the different channels.

2.2. Processing and Evaluation

Our goal is to find the optimal wavelength combination for extracting HR for hyperspectral imaging. We select three rectangular ROIs l on the forehead of each subject and segment the intensity signal

$$I_l(\lambda, t) = \sum_{(x,y) \in \text{ROI}_l} I(x, y, \lambda, t)$$
(1)

in 30 second segments with 15 seconds overlap. λ refers to a spectral band centered around the wavelength λ . The reference heart rate HR_{ref} is computed by averaging the HR estimated by the patient monitor inside the 30 second segment.

We implement three comparison methods for computing the BVP signal from the spectral signal. The baseline

¹Effiflux, EFFI-FLEX-HSI-X2-400-910-970-KIT-ELS



Fig. 3. Pulse signal power spectrums of linear method and baselines

method computes $S_{\text{baseline}} = \sum_{\lambda} I_l(\lambda, t)$ imitating the signal measured by a monochrome camera. For readability, we drop l and t. Then we implement two well known methods from the literaturate, the green channel and POS [7], for hyperspectral cameras. For that, we convert I to sRGB space using a Matlab toolbox [25]. S_{green} and S_{POS} are simply computed from the RGB signal using the respective methods. We developed two approaches for combining the hyperspectral channels that can be expressed as

$$S_{\rm BVP}(t,w) = \sum_{\lambda} w(\lambda) I_l(\lambda,t), \tag{2}$$

namely a greedy approach that discretizes $w_{\text{greedy}}(\lambda) \in \{-1, 0, 1\}$ and a *linear weighting* approach allowing $w_{\text{linear}}(\lambda) \in \mathbb{R}$. The greedy approach models three possible states of a spectral signal: It may provide no pulse information (0), significant pulse information (1) or pulsatile information with an inverted phase (-1). The linear weighting is a generalization of that and can be thought of as an extension to similar weighted approaches such as POS [7], CHROM [6], and O3C [26] to the hyperspectral domain. The optimization objective is to maximize the SNR of the BVP signal defined by [6], which we adjust to the frequency band [0.4,2] Hz to limit the frequency accorrding to the sampling rate:

$$\mathbf{w} = \arg \max \mathrm{SNR}(S_{\mathrm{BVP}}(\mathbf{w}), f_{\mathrm{s}}, \mathrm{HR}_{\mathrm{ref}}). \tag{3}$$

For the greedy approach, we can simply compute all possible w. For the linear approach, we use an optimization algorithm (*optimproblem*, MatlabR2022b). We can increase the computation speed by precomputing the power spectra of noise and signal for each λ , as this is a linear operation. Using the optimization, we calculate separate w for all segments, ROIs, and subjects to perform statistical analysis and achieve more robust results. We also save the optimization on its specific segment to evaluate how it generalizes to the other recordings.

3. Results and Discussion

Fig. 3 shows the fourth segment of the first ROI of the first subject that resulted in $\mathbf{w}_{linear}^{[optim]}$ with the highest SNR over



Fig. 4. Average of the 10 weights with the highest SNR for both optimization approaches. The grey area shows one standard deviation.



Fig. 5. Improvement of SNR compared to baseline for the reference methods, our combination of wavelength, and the weights that achieved the hightest SNR on the signal they were optimized for.

all segments. We can also see for the second segment of ROI 2 that this weight generalizes well and results in a slightly more pronounced peak around the HR when compared to POS and significantly higher SNR than the baseline. We validate the consistency of the estimated weights for both the greedy and linear approach by averaging the ten weights that resulted in the highest SNR for their respective segment (Fig. 4). Interestingly, linear and greedy weights show a similar pattern over the spectrum, with positive weights in the green and infrared parts of the spectrum and negative weights in the red. Consistent with [10], the calculated weight is highest around 580 nm. Compared to the baseline, all implemented methods improve the SNR significantly (Fig. 5). We can also see that the greedy method achieved a higher SNR on the segments it was optimized on, whereas the $\mathbf{w}_{linear}^{[optim]}$ generalized better to other segments and individuals, resulting in a slightly higher average SNR than POS.

This study has several limitations. First, we were unable to optimize the SNR based on skin reflectance, which would have eliminated the influence of the camera's spectral sensitivity and the emission spectrum of the light source. Instead, signals were computed directly from raw spectral power. Additionally, only the greedy optimization approach reliably reaches the global optimum, whereas the linear weighting method may converge only to a local optimum. This was evident when applying $\mathbf{w}_{linear}^{[optim]}$ to recordings

that exhibited low SNR during optimization yet achieved a higher SNR afterward. Further research on the optimization and combination of different wavelengths is required. A key hardware limitation was the camera's low frame rate. To cover HR up to 120 BPM and ensure reliable results, a frame rate of at least 8 Hz would be necessary. One potential solution could involve upsampling using an RGB camera, which will be part of future research.

4. Conclusion

Optimizing linear weights applied to hyperspectral bands for extracting PPGI signals has the potential to enhance SNR and inform the development of next-generation PPG hardware. However, the POS algorithm, designed to work with standard RGB cameras optimized for visual perception and cost efficiency, can be shown to utilize the light spectrum nearly as effectively.

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An active model of the respiratory system as a phantom for the forced oscillation technique

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Keywords

Model of pulmonary system, Arduino Uno, linear actuator, forced oscillation method, Tremoflo C-100, 3D print

1. Introduction

Respiration is a vital physiological process. Any disorders affecting the respiratory system can significantly impact health and quality of life [1].

The Forced Oscillation Technique (FOT) provides a passive alternative by analyzing the mechanical properties of the respiratory system using acoustic pressure waves [2]. Devices like the Tremoflo C-100 (Thorasys Thoracic Medical Systems Inc., Kanada) [3] measure respiratory impedance at different frequencies, offering valuable insights into airway resistance and reactance [4], [5]. Research suggests that FOT is particularly sensitive to changes in peripheral airways, making it a promising tool for early disease detection [4].

This study aims to develop an active respiratory system model that enables standardized breath simulation for FOT testing. The model will allow for controlled variations in physiological parameters and will be validated using the Tremoflo C-100 to ensure measurement consistency.

2. Methods

An active model of respiratory system model was designed to simulate standardized breathing patterns for Forced Oscillation Technique (FOT) measurements. The model consisted of a linear actuator, an Arduino Uno microcontroller, and a 3D-printed mechanical syringe, which together generated controlled airflow to mimic human respiration.

The automation of breathing was achieved through an H-bridge motor driver connected to the Arduino, allowing precise control over the actuator's movement. A custom C++ program regulated the actuator's motion, enabling adjustments to key parameters such as breath volume, fre-



Fig. 1: Photo of a model.

quency, and resistance. This ensured repeatable and standardized breathing cycles, essential for accurate measurements.

For data collection, the model was connected to the Tremoflo C-100 device, which measured respiratory impedance at various oscillation frequencies. Multiple trials were performed under different settings to evaluate the model's flexibility and reliability. The recorded data included resistance (R_{rs}) and reactance (X_{rs}) curves, which were analyzed to assess the consistency of the simulated breathing patterns.

Statistical methods, such as mean and standard deviation calculations, were applied to compare the measurements across different conditions. The results were examined to determine the accuracy and reproducibility of the model, ensuring its suitability for FOT-based respiratory system assessments.

3. Results

The study investigated the impact of individual components on resistance (R_{rs}) and reactance (X_{rs}) curves. The results showed that the parabolic resistor (Rp) significantly influenced both parameters. A larger Rp led to a higher resistance curve and a lower reactance curve, meaning that adjusting Rp allowed for shifting these curves closer or further apart. Additionally, the position of Rp played a crucial role—placing it closer to the Tremoflo device increased resistance and decreased reactance due to reduced airflow.



Fig. 2: Model with 54 L chamber and different Rps

In contrast, the position of the glass chamber had no measurable effect on resistance or reactance, indicating that its placement within the model does not influence the impedance measurements. Similarly, the length of the tube and the duration of inhalation had minimal impact on the recorded values, suggesting that these parameters do not significantly alter the model's impedance characteristics.

The consistency of the results was verified through 30 repeated measurements on the same model, followed by a comparison with a calibration syringe. The resistance variability for the 3D-printed syringe ranged between 0.1% and 3.2% across all frequencies, indicating high reliability. In contrast, the calibration syringe showed a wider resistance variability, ranging from 0.2% to 8.5%. These findings suggest that the 3D-printed syringe provides more consistent impedance measurements, making it a more suitable choice for standardized respiratory simulations.

Overall, the findings confirm that Rp size and placement are key factors in controlling impedance curves, while chamber positioning, tube length, and inhalation duration have minimal impact.

4. Discussion and conclusion

The study successfully developed an active respiratory system model capable of simulating standardized breathing patterns for Forced Oscillation Technique (FOT) testing. The model's automation, controlled via Arduino Uno and a linear actuator, ensured consistent breath cycles with adjustable parameters. The measurements obtained using the Tremoflo C-100 demonstrated high reproducibility, con-

firming the model's reliability for impedance-based respiratory analysis. However, certain limitations were identified. At higher frequencies, minor actuator response delays were observed, potentially affecting impedance measurements. At lower frequencies, slight variations in impedance readings suggest the possibility of air leakage in the system. The mechanical components, particularly the actuator and syringe system, may introduce small inconsistencies in airflow generation over extended test periods. Despite these limitations, the model provides a valuable tool for respiratory research, particularly in validating FOT-based diagnostic techniques. This study confirms the feasibility of using an active breathing model for FOT testing. The model demonstrated consistent and adjustable breathing patterns, with impedance measurements aligning with expected physiological responses. While minor technical challenges were noted, they can be addressed in future refinements. The findings suggest that such a model could be a useful tool for further respiratory studies, aiding in the development and validation of noninvasive diagnostic methods.

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Model of Applicator for Regional Hyperthermia based on eight "Bow-tie" Antennas

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Abstract. This article deals with the design and implementation of an applicator for regional hyperthermia based on an array of eight Bow-tie antennas. The applicator is designed and simulated using the Sim4Life electromagnetic field simulator. The primary focus is on operating frequency of 434 MHz, as we want to radiate about 2 to 4 cm deep inside the tissue.

The main objective is to develop an applicator that demonstrates an optimal reflection coefficient (|S11| parameter) and a suitable specific absorption rate (SAR) distribution for effective treatment. In contrast to traditional wire dipoles, the Bow-tie antennas are expected to offer a broader bandwidth, enhancing their performance.

The applicator and a corresponding phantom model, designed to simulate human tissue, are fabricated and experimentally evaluated to validate the computational results. The reflection coefficient of each antenna is measured individually before their connection together with the microwave radiation generator. The temperature distribution within the phantom is recorded using an infrared (IR) camera, and the acquired data are subsequently analyzed to assess the system's performance.

Keywords

Microwave hyperthermia, applicator, Bow-tie, electromagnetic field, phantom.

1. Introduction

Microwave hyperthermia is a therapeutic method that uses a non-ionizing electromagnetic field for tumor treatment. Pathological tissue exhibits greater sensitivity to elevated temperatures compared to physiological tissue. This property enables controlled heating to temperatures between 41 and 45 °C, inducing apoptosis in tumor cells and preventing their further proliferation. This relatively straightforward method, based on localized thermal heating, has the potential to treat certain oncological diseases. Moreover, microwave hyperthermia can be combined with other oncological treatment modalities, such as radiotherapy and chemotherapy. Further details can be found in references [1], [2] and [3]. In this study, we focus on regional hyperthermia and the design of a novel applicator. While numerous applicators have been developed for regional hyperthermia, our proposed applicator aims to achieve higher efficiency over a broader bandwidth compared to conventional wire dipole designs.

2. Effective penetration depth

One of the key parameters in regional hyperthermia is the effective penetration depth. To determine the appropriate type of therapy, it is essential to understand both the depth and the focus of microwave energy radiation.

The penetration depth is influenced by three primary factors: the frequency of the electromagnetic field, the aperture velocity of the applicator, and the dielectric properties of the tissue. The effective penetration depth is defined as the distance at which the intensity of the electromagnetic field decreases to 1/e of its surface value, where $e \approx 2.718281$. It can be expressed mathematically as:

$$d = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

Where f stands for frequency, μ is permeability, and σ is conductivity of the tissue. So, for 434 MHz, the effective penetration depth is about 2 to 4 cm [4] [5] [6].

Dielectric properties							
Material or background	ε _r []	σ [S/m]	μ[]	ρ [kg·m ⁻³]			
Air	1	0	1	1.2			
Distilled water	76.70	0.00005	1	1000.0			
Polyactic acid (PLA)	2.70	0.00050	1	1240.0			
Biological tissue	56.86	0.80511	1	1090.4			

 Tab 1. Dielectric properties of materials and background for bandwidth 434 MHz in Sim4Life [7] [8] [9].
3. Simulation and design

Initially, a trustworthy model was designed to simulate the propagation of the electric field and SAR using the Sim4Life simulation software. The applicator was optimized to achieve the best possible reflection coefficient (|S11| parameter) at the operating frequency of 434 MHz, minimizing energy losses.

The proposed applicator consists of eight Bow-Tie antennas arranged in a symmetrical octagonal configuration. Each antenna is mounted within a specially designed holder, which is sealed enough to contain distilled water along with the phantom, which substitutes the water bolus.

2

The Bow-Tie antenna and the balun are characterized by specific geometric parameters, illustrated as in Figures and 1 2. These parameters include: width w, outer height h, inner height c, outer rounding of the edges o, inner rounding of the edges *i*, distance between the Bow-tie arms d, for the balun length l, outer width b_1 and inner width b_2 [10].

For the single 434 MHz Bow-Tie with optimized parameters:

w = 36 mm,	h = 20.6 mm
c = 6.3 mm,	o = 8 mm
i = 3 mm,	d = 2.5 mm
l = 40 mm,	$b_1 = 14 \text{ mm}$
$b_2 = 2.3 \text{ mm},$	

we got the $|s11| \approx -42$ dB.

Fig. 1. Model of a single Bow-tie antenna.



Fig. 2. Model of a balun designed for the 434 MHz Bow-tie Antenna.



Fig. 3. Reflection coefficient for single Bow-tie Antenna on bandwidth 200 - 700 MHz from the simulation.

Figure 4 presents the final model of a single Bow-Tie antenna designed for simulation testing. A water bolus, with dimensions $100 \times 100 \times 40$ mm (represented by the blue block), is placed on the antenna, along with a biological tissue phantom with dimensions $100 \times 100 \times 50$ mm (represented by the orange block). The antenna and balun are enclosed and secured within a custom-designed holder, intended for future fabrication via 3D printing.



Fig. 4. Complex model of single Bow-tie Antenna with balun, PLA holder, water bolus and biological tissue.



Fig. 5. SAR distribution of single Bow-tie, XZ plane.

For the applicator, a matrix structure was designed, including a cylindrical phantom with a diameter of 10 cm and a height of 9.5 cm. The antennas are mounted in a 3D – printed holder, as shown in Figure 6. The holder is designed to be filled with distilled water as a water bolus.



Fig. 6. Complex model of the Applicator with water bolus and a cylindrical phantom., XY plane and XZ plane.

Because of the interaction between the Antennas in the matrix, the reflection coefficient for each active Bow-tie has changed, see Figure 7.



Fig. 7. Reflection coefficient for all active antennas in the matrix.

The next Figure shows SAR distribution in the cylindrical phantom of the biological tissue in XY plane. Energy is focused on the center of the phantom.



Fig. 8. SAR distribution inside of the cylindrical phantom of the biological tissue, XY plane.

4. Realization and testing

The 3D-printed components of the applicator were fabricated and assembled separately. Each Bow-Tie antenna is constructed from a 0.5 mm copper plate, shaped according to the optimized design from simulations. An SMA connector is mounted at the end of the balun on each antenna.



Fig. 9. One of the manufactured Antennas.



Fig. 10. Manufactured Applicator (Matrix of 8 Bow-Tie Antennas).

Reflection coefficient was measured to verify the functionality of the Antennas sepparately. The results are shown in the following Figure.



Fig. 11. The |s11| parameter of each Antenna measured sepparately from the analyzer.

Later on, the applicator was connected to the microwave generator. A single input was evenly split into eight outputs of identical length to prevent phase shifting. To achieve a sufficient temperature increase, the phantom was exposed for 10 minutes. The microwave hyperthermia system ALBA, which was utilized in this study, delivered an average power of 78 W to the applicator, while the average reflected power was 8 W. Which means, the phantom absorbed approximately 42 kJ of energy.



Fig. 12. Hyperthermic system ALBA with our connected Applicator on the right, IR camera with the monitor on the left.

The temperature distribution of the phantom was measured using an IR camera. The first thermogram represents the phantom before exposure, while the second thermogram captures a cross-section of the agar phantom at the region of highest energy deposition. The recorded temperature difference reached 6 $^{\circ}$ C.



Fig. 13. IR view of the Applicator filled with distilled water and agar phantom before the exposure on the left, slice of the phantom after the exposure on the right.

5. Conclusion

A novel applicator for regional microwave hyperthermia, based on eight Bow-Tie antennas, was developed. Using Sim4Life software, the applicator was designed for an operating frequency of 434 MHz. The antenna parameters were optimized to achieve a reflection coefficient below -10 dB. Simulations were conducted to analyze and optimize the electric near-field propagation and SAR distribution.

The Applicator was manufactured according to the calculated design parameters. The reflection coefficient was verified using a vector analyzer.

The hyperthermic system ALBA was used as the microwave generator, with an agar phantom serving as a substitute for biological tissue. During a 10-minute exposure, the phantom absorbed 70 W of power. These results indicate that the designed applicator meets efficiency requirements and, theoretically, could be adapted for therapeutic applications.

For future research, incorporating a water bolus in the form of a water cushion could get the results more to clinical conditions in microwave hyperthermia. Another area of investigation involves developing a more complex phantom with specified tissue properties, as these factors may influence the reflection coefficient of the applicator. Compared to simple wire dipoles, an antenna matrix based on Bow-Tie antennas offers a broader bandwidth, potentially improving impedance matching and overall efficiency.

The matrix of eight Bow-Tie antennas is particularly advantageous for adjusting the focal position of the energy absorption by manipulating the phase shift and amplitude of each antenna.

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Pulse to Tone Dialling Converter

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Abstract. Historic telephones use pulse dialling, which is less and less supported by modern systems. To keep these phones usable, a converter was developed in this work, which intercepts the pulse dialling from the phone and emulates a tone-dialling phone on the line side. This converter is plugged between phone and connection socket, and can be supplied with power from the telephone line. The resulting device works reliably, with the only major drawback of a relatively high current consumption (about 1 mA). This is noticeable in the form of noise on the line, but the issue can be eliminated by using an external power supply.

Keywords

Historic telephones, signalling technology, converter.

1. Introduction

Historic rotary phones use the pulse dialling method, for which the support in modern telephone systems, routers etc. is increasingly dropped. Furthermore, you navigate through many automated hotlines by entering numbers, and most of these systems do not understand pulse dialling. Since those old phones are still of interest to enthusiasts (such as the first author), and commercially available solutions are either expensive or out of stock, the implementation of a converter, that picks up the pulse signals from the historic phone and translates them to the more modern tone dialling, was tendered as a project seminar assignment. The work presented here is the third iteration of this project.

2. Fundamentals

2.1. Pulse dialling

Pulse dialling was invented around 1900, and replaced manual switching by telephone operators as it was common until then. The dialled digits are communicated by shortly interrupting the telephone line the corresponding number of times (e.g. nine interruptions for the digit nine), which is performed mechanically by the rotary dial (see Fig. 1). To encode the digit "0", ten interruptions are widely used. Originally, the switch site interpreted these pulses by moving an electromechanical arm (in two directions) one step at each pulse, in order to reach the desired contact on an opposite contact board. Later on, the pulses were processed electronically. The duration of each interruption is 60 milliseconds followed by 40 milliseconds of waiting time, while between the digits, a break of 200 milliseconds must be left to enable the system to recognise when one digit ends and the next begins. [1] [2]



Fig. 1. Functional principle of a rotary dial.

2.2. Tone dialling

Tone dialling was introduced in the early 1960s, as it offered faster handling compared to rotary dials. Here, the digits are selected using buttons, and are encoded by a superposition of two monofrequent tones, which is transferred over the phone line equally to speech. At the switch site, the respective frequencies are recognised and interpreted like two-dimensional coordinates. The assignment between frequency pairs and digits can be seen in Tab. 1. [2] [3]

Frequency	1209 Hz	1336 Hz	1477 Hz
697 Hz	1	2	3
770 Hz	4	5	6
852 Hz	7	8	9
941 Hz	*	0	#

Tab. 1. Assignment between frequency pairs and digits [3].

3. Materials and Methods

3.1. Microcontroller platform

The pulse to tone converter was realised based on an MSP430G2553 microcontroller from Texas Instruments, since this microcontroller family is widely used at the institute and also has low energy consumption, which is relevant for this project since one of the goals was to supply the converter from the phone line. A so-called *LaunchPad* kit was chosen, which, in addition to the microcontroller itself, includes the essential wiring to run it and also a USB programmer/debugger. Access to the microcontroller's I/O ports is provided conveniently through pin headers (see Fig. 2).



Fig. 2. MSP430 LaunchPad (downloaded from geizhals.de)

On the software side, the Integrated Development Environment *Energia* is available for MSP430 devices, which provides them with a user-friendly set of C++ instructions mostly identical to the popular *Arduino* platform (see *https://energia.nu*). Due to the high degree of abstraction (and thus the high number of layers), firmwares based on the Energia libraries have a lot of overhead compared to directly accessing the microcontroller's registers, but as the intended application is small, Energia was still chosen in favour of rapid development and understandable code.

3.2. Testing environment

In order to test the converter's functionality during development without potentially damaging a productive setup, a used *Eumex 401* telephone system (shown in Fig. 3) was bought, which comes with four internal lines able to call and speak to each other. They support both pulse and tone dialling, but it must be explicitly configured (from a tone dialling phone featuring the keys * and #, or a PC connectable via USB) which method is used on each line. Two rotary phones were used as testing devices, one of which was connected to a pulse dialling line, while the other was connected to a tone dialling line with the converter in between. [4]



Fig. 3. *Eumex 401* telephone system (modified from [4]), used here for testing. The internal lines (used by the devices in green) can call each other. A PC (shown in orange) can optionally be connected for configuration.

4. Implementation

4.1. Overall system design

The goal was a converter that is simply pluggable between telephone and junction box, without having to modify either of them. An additional aim, in order to avoid cable clutter, was to supply the converter with power from the telephone line. The design, depicted in Fig. 4, was based on the expertise of existing do-it-yourself solutions, see [5], [6] and [7].



Fig. 4. Pulse to Tone converter schematic.

4.2. Detailed implementation

Normally, an analog phone is connected with two wires, denoted in Fig. 4 as L_a (which is connected to a negative DC supply voltage on the system's side) and L_b (ground). In addition to the supply voltage, L_a also transmits the speech and the ringing signal (both AC) and the dialling pulses. The latter are not supposed to get beyond the converter, as they might interfere with the tone dialling otherwise. This was achieved with a workaround adapted from [7]: Old phones come with another wire W_2 , which transmits everything *but* the dialling pulses. (Originally, this was for an additional bell. To prevent it from pinging while dialling, the pulse dialling interrupter was bypassed for its con-



Fig.5. Detailed schematic of the converter (TAE denotes the phone line, explanation see below).

nection.) Connecting W_2 to the phone line instead of L_a ensures undisturbed transmission of the tone dialling, while L_a is connected to the microcontroller for registering the pulse dialling. The microcontroller then generates the according tones and feeds them back into the phone line through a coupling capacity. As the telephone line (in contrast to the microcontroller) works with a negative supply voltage, the tones are fed into the ground wire $L_b,$ which is not a problem when superimposing an AC signal on a DC voltage.

Fig. 5 shows a more detailed view of the converter circuitry. On the left side, by an LF33CV voltage regulator, the supply voltage from the phone line is converted to the 3.3 V required by the microcontroller. The input is protected by the 27 V Zener diode $Z_{\rm SR}$ and stabilised by the capacitor $C_{\rm SR1}$ - which is particularly important during dialling, since $L_{\rm b}$ and W_2 are then short-circuited due to the internal wiring of the telephone (see [7]).

On the right side, a voltage divider (R_2 and R_3) converts the pulses generated by the phone to a range between 0 V and 3.3 V compatible with the microcontroller. The 3.3 V Zener diode Z_1 protects the microcontroller from overvoltage (such as the ringing signal, which is about 100 V_{pp}).

In the middle, the MSP430 microcontroller detects the pulses by polling the digital input pin 1.5, and outputs the according tones. It was experimentally found out that the tones do not necessarily have to be sinusoidal, since the telephone system also recognises square-wave tones as long as they have the appropriate frequency. As this simplifies the circuitry enormously, the tones are thus just generated using two digital outputs (pin 2.5 and 2.6). In order to achieve the required superposition of two tones, these are then interconnected (behind two resistors R_K which prevent short-circuits if one pin is HIGH and the other LOW). Finally, the resulting dialling tone is fed into the line through the coupling capacitor C_K .

A circuit board containing all the peripheral components was designed and etched in-house, onto which the MSP430 LaunchPad can be plugged, see Fig. 6. This was installed in a suitable aluminum housing. The phone can be connected either via a TAE socket (the telephone plug system common in Germany) or a screw terminal (which was added because old phones often come without a plug, since in their days it was common practice to screw telephones permanently to the wall socket). The outgoing TAE plug is finally to be connected to the telephone system, emulating a tone dialling phone. Optionally, an external power supply can be connected to a USB socket. See Fig. 7.



Fig. 6. Finished converter interior.

5. Result and Conclusion

This project resulted in a reliably working pulse to tone dialling converter, which can be powered by the telephone line. The advantage of this work over [5] and [6] is that no intervention in the telephone is necessary, while the circuit is much simpler than in [7]. A remaining drawback is the



Fig. 7. Finished converter exterior.

relatively high power consumption (about 1 mA), which is either noticeable in the form of noise when making calls or can be avoided by switching to an external power supply.

6. Outlook

A short-term improvement to the microcontroller firmware that will be addressed in the next iteration is the switch from the current poll loop to an interrupt-based solution for counting pulses. The poll loop leads to the high power consumption mentioned above. In addition, the rectangular tones currently used do work, but are not particularly pleasant acoustically. A switch to sinusoidal tones (using digital-analogue conversion or filters) could therefore be considered. The disadvantage of this, however, would be that it would complicate the circuit considerably.

A long-term issue is that analogue tone dialling is nowadays already being replaced by digital Voice over IP protocols, so that it seems sensible to extend the converter by such a protocol. A literature review is therefore planned to find out to what extent there are manufacturer-independent standards here. In any case, this would involve switching to a more powerful microcontroller with an Ethernet interface, including Power over Ethernet if independence from an external power supply is to be kept.

As an additional luxury, the converter could also be equipped with a display and extended to provide the convenience that we are now used to from modern phones, e.g. a display of the calling number or information about missed calls. Furthermore, it would make sense to search for a solution independent of the external bell line, as there might be phones around which do not have it. To get even *very* old phones on board - those from the days even before rotary dials - one could add the option of dialling directly with the converter.

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1

Design and Implementation of a Broadband Wilkinson Power Divider

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Abstract. This project presents the design and implementation of single-section and multi-section microstrip Wilkinson power dividers operating at a center frequency of 2.4 GHz. The single-section design achieves a transmission bandwidth from 1.5 GHz to 3.0 GHz, while the multi-section design extends it from 670 MHz to 3.2 GHz, demonstrating enhanced performance for broadband applications. The designs are validated through measurements of return loss, isolation, and power division, confirming their effectiveness for signal distribution in microwave circuits.

Keywords

Microwave power divider, Wilkinson power divider, impedance matching, isolation, broadband, signal splitting, multi-section design, transmission lines, Chebyshev matching.

1. Introduction

A power divider is a passive device that takes an input signal and splits it into two or more output signals with reduced power levels. The Wilkinson power divider is widely used in RF and microwave applications for its ability to split an input signal into equal-amplitude, in-phase outputs while ensuring impedance matching and high isolation. The Wilkinson divider is preferred for low input power due to its compact design and low insertion loss. It employs quarter-wavelength ($\lambda/4$) impedance transformers with a characteristic impedance of $\sqrt{2Z_0}$ and a 2Z₀ isolation resistor to minimize signal interference within a narrow bandwidth. Wilkinson power dividers are extensively utilized in microwave circuits due to their simple structure, high isolation between output ports, and excellent impedance matching at all ports, making them popular in communication systems. First introduced in 1960 [1], the initial designs had a narrow bandwidth, with optimal performance only at the center frequency. To enhance bandwidth, multi-section configurations were introduced in 1968 [2], significantly improving performance. Originally, Wilkinson power dividers were designed for equal power distribution. However, in 1965, an unequal power divider was developed [3], utilizing even-odd mode analysis for design optimization. This approach was later applied to multi-section dividers in 1971 [4].

Despite their structural simplicity, designing Wilkinson dividers remains complex. Over the years, various design methodologies have been introduced to achieve different bandwidths and power division ratios [5]. These dividers have been implemented on different transmission line structures as well as in coupled and separated configurations [6,7].

2. Characteristics of the Wilkinson Power Divider

The Wilkinson Power Divider (WPD) is a three-port network that is designed to be lossless in the ideal case when the output ports are properly matched. In this setup, only reflected power is dissipated as heat by a resistor in between the output ports. The primary function of this divider is to split the input power into two or more signals that are in phase and have the same amplitude [8].

In microwave circuits, power transmission is typically expressed in logarithmic scale (dB). In a three port WPD, the input power is evenly distributed between both output ports, with each receiving half of the total input power [9]. Ideally, in a lossless system, this would result in a power reduction of 3 dB per output branch. However, in practical implementations, transmission lines introduce losses, causing the delivered power to slightly deviate from the ideal -3 dB level [10]. In WPDs, the input transmission line has a characteristic impedance of Z₀, and each output port is designed to be matched to Zo. However, from the input's perspective, the impedance of each output branch appears as 2Z₀, leading to a mismatch that would cause reflections and reduce power transfer efficiency. To mitigate this issue, a single-section quarter-wavelength $(\lambda/4)$ impedance transformer with a characteristic impedance of $\sqrt{2Z_0}$ is used to ensure smooth impedance matching between the input and output ports, enabling efficient power division while maintaining isolation between output ports.

A single-section line with $Z=\sqrt{2}Z_0$ of characteristic impedance and quarter wave line length is added between the T-junction point and the output ports [10]. A general schematic view of the designed single-section WPD is shown in Figure 1 where the transmission line width of $W_{11}=1.85$ mm results in a 50 Ω characteristic impedance and $W_{12}=1.0$ mm results in 70.7 Ω . Since it has low losses at high frequency range, Rogers 4003C substrate material with a permittivity of $\varepsilon_r = 3.55$, a thickness of H=32 mils (0.813 mm), and a loss tangent of tan $\delta=0.002$ was taken from Rogers Data Sheet. At the center frequency of 2.4 GHz, the length of the paths resembling the quarter wave transformers was optimized to be 19.2 mm using Keysight Advanced Design System (ADS) software. Using the footprint of the 0603 resistors the spacings are set to be 1.4 mm.



Fig. 1. A general schematic view of the designed single section Wilkinson power divider with equivalent microstrip width W_{11} =1.85 (mm) and W_{12} =1.0 (mm), X=32.35 (mm), Y=49.78 (mm)

The multi-section Wilkinson power divider follows the same configuration as the single-section design. However, additional sections are incorporated sequentially by introducing quarter-wave transformers in each section. The quarter-wave line impedances must be calculated to gradually match the input impedance to the output impedance as shown in Figure 2. This gradual impedance matching enhances broadband transmission compared to the single-section divider. As a result, the guided wave from the input port to both output ports indicates that the transmission coefficients S_{21} and S_{31} demonstrate a wider usable bandwidth, thanks to enhanced impedance transition and reduced reflection losses, as shown in Figure 2.



Fig. 2. A general schematic view of the designed multi section Wilkinson power divider with equivalent microstrip width W_{10} =1.858 (mm), W_{11} =1.5354 (mm), W_{12} =1.0067 (mm), W_{13} =0.6116 (mm), X=63.8 (mm), Y=45.74 (mm)

To calculate each line's impedance, *binomial matching* or *Chebyshev matching* for broadband applications can be used [6]. Equation (1) shows a typical Binomial quarter wave transformation. For the N-section Wilkinson power divider the transmission line impedances are determined by

$$Z_{i} = Z_{0}e^{\frac{1}{2}\ln(\frac{T_{N}(X)}{T_{N}(X_{i})})}$$
(1)

Where,

Z_0	System impedance (usually 50 Ω)	
-------	---	--

- $T_N(X)$ Chebyshev polynomial of order N (where N is the number of sections)
 - X Normalized variable representing either position (in a multi-section impedance transformer) or frequency (in a broadband matching network)
 - *X_i* Specific value of X, corresponding to a given section in the impedance transition

Since a 3-section divider is used, the Chebyshev Polynomials for N=3 become [6]

$$T_0(X) = 1 \tag{2}$$

$$T_1(X) = X \tag{3}$$

$$T_2(X) = 2X^2 - 1 \tag{4}$$

$$T_3(X) = 4X^3 - 3X \tag{5}$$

Where the factor of *X* is calculated by equation (6).

$$X = \cosh\left(\frac{1}{N}\operatorname{arcosh}\left(10^{\frac{RL}{20}}\right)\right) \tag{6}$$

The calculation depends on the return loss RL (dB) and the number of sections N. If different RL value is chosen (e.g., 20 or 30 or 40 dB), the calculation results will change as well. The goal is to design the sections with -30 dB return loss.

Impedance line transformers for 3 sections (N=3) are shown in Tab.1.

Impedance line section (Ω)	Equivalent microstrip width (mm)
$Z_0 = 50$	$W_{10} = 1.858$
$Z_1 = 56.123$	$W_{11} = 1.5354$
$Z_2 = 70.71$	$W_{12} = 1.0067$
$Z_3 = 89.09$	$W_{13} = 0.6116$

Tab. 1. Line impedance transformers for 3 sections (N=3).

3. Experimental Results

To validate the design, two 3-port Wilkinson power dividers with a separate layout are analyzed based on their scattering parameters up to 8 GHz. Figures 3 and 5 illustrate the measured S-parameters of the fabricated WPDs. Due to transmission line losses, if a reference of -3.4 dB is considered, the single-section design achieves a transmission bandwidth spanning from 1.5 GHz to 3.0 GHz, as depicted in Figure 4. In comparison, the multi-section design extends the bandwidth from 670 MHz to 3.2 GHz, as presented in Figure 6. This result demonstrates that the multi-section configuration nearly doubles the bandwidth relative to the single-section counterpart, emphasizing its superiority in broadband applications. The comparison between measured and ADS-simulated design is shown in Figure 7. Due to parasitic effects, a shift in the resonance frequency can be observed. The physical dimensions of both devices and their relative bandwidths (with respect to the mean frequency) are presented in Table 2.



Fig. 3. Frequency response of the fabricated single-section divider



Fig. 4. $|S_{31}|$ from measurement of the single-section divider



Fig. 5. Frequency response of the fabricated multi-section divider



Fig. 6. $|S_{31}|$ from measurement of the multi-section divider



Fig. 7. $|S_{11}|$ comparison of the measured and ADS-simulated single- and multi-section Wilkinson power dividers

Design	Frequency range (GHz)	Mean frequency (GHz)	Relative BW	Size (cm ²)
single- section	1.5 - 3.0	2.25	66.7%	16.10
Multi- section	0.67 - 3.2	1.935	130.7%	29.21

Tab. 2. The relative bandwidth and the device size



Fig. 8. Single-section Wilkinson power divider



Fig. 9. Multi-section Wilkinson power divider

4. Conclusion

Power dividers and combiners are essential components in RF and microwave systems, enabling dividing and combining of signals with minimal loss and distortion. They are commonly designed using microstrip technology, which offers a compact and efficient way to integrate these components on a substrate. A well-designed power divider should ensure matched condition, providing equal power distribution to each output port while minimizing reflections. Isolation between ports is crucial to prevent signal interference and the device should ideally be lossless, maintaining signal integrity across the frequency range.

In this paper, two types of Wilkinson power dividers one as a single-section used for narrow band applications and another as a multi-section Wilkinson power divider used for broadband applications have been successfully designed and fabricated for a center frequency of 2.4 GHz The singlesection Wilkinson power divider provides excellent isolation, a low return loss, and a narrower bandwidth compared to the multi-section design, but its bandwidth can be improved using multiple sections at the cost of adding complexity.

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Subjective test methodology design for spatial audio transmission

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Abstract. Spatial audio with relative head position tracking (i.e. headtracking) is lacking a set of basic parameters requirements that are necessary to achieve a full immersive user experience. We focus on theory and practice of the spatial audio system and its potential critical points of transmission which potentially can disrupt the user's immersive experience. We concentrate on how latency between the current head position and the reproduced sound affects the immersive effect and to obtain a minimal threshold which is necessary to maintain this effect. Our aim is to design a subjective test method to acquire parameter requirements for individual listening situations and scenarios which are necessary for the upcoming technology of the anticipated codec IVAS from 3GPP which will standardize the algorithms and software for transmission of spatial audio with headtracking.

Keywords

Binaural audio, spatial audio, immersive audio, relative head position tracking, headtracking, subjective test methods, latency in relative position.

1. Theory and practice of spatial audio with headtracking

Spatial audio with headtracking works by acquiring the relative angular head position by the headtracker and rerendering the binaural audio using the user's HRTF (headrelated transfer function) rotated by these angles in real time. Extending the audio playing system by headtracking the user will get a more natural headphones listening experience by simulating an actual space with separated signal sources.



Fig. 1. HW system for spatial audio with headtracking.

This technology allows users to experience new depth of listening experience by placing the sound sources in the virtual sound space based on user's position and movements and also to improve comprehensiveness in critical environments or videoconferences by spatial separation of the sound sources (voices) avoiding for example the Cocktail party effect.

There is a long awaited release of the new IVAS codec (from 3GPP consortium) that will standardize the algorithms and software for transmission of spatial audio with headtracking.

2. Parameters

To acquire the full experience of the spatial audio, the system needs to fulfill number of practical parameters required for the user's subconscious spatial audio experience. The main parameters are acoustic sound quality (the bandwidth and amplitude bit resolution of the reproduced audio signal), the precision of the sound position placement and sharpness of the position (how precisely we can place a signal source in the virtual space and how sharp we actually perceive the position), and latency between the change of angular position and the actual re-rendered audio being reproduced (especially for example in a typical application with Bluetooth headphones), where high latency can completely disrupt the user's subconscious spatial audio experience.

Since latency is closely linked to the system HW and SW requirements (because of the high computational demand for real-time binaural audio rendering). The latency is difficult and expensive to minimize and there is low research knowledge which would set the minimal requirements sufficient to sustain the intended immersive effect. Therefore it is our topic of research to design a testing methodology which would evaluate the user's perception of spatial audio.



Fig. 2. Photo of the headphone with Supperware head tracker setup.

It is expected that the minimal requirements for audio system's response latency will be different for different use cases. The user has a different minimal latency threshold when listening to background audio while doing other activities (for example listening to music while cooking), when being active in the virtual space (for example during videoconference with multiple participants to avoid the Cocktail party effect), when position of the signal source indicates relevant important information (for example air traffic controller or while playing VR games). Our research aims to identify and separate these cases and with subjective methods obtain the latency threshold values.

3. Testing methods

Testing methods are essential to obtain objective useful information of subjective parameters. Our plan is to base the testing methodology on modified ITU-T P.800 Methods for subjective determination of transmission quality and ITU-R BS.1534-3 Method for the subjective assessment of intermediate quality level of audio systems. First we set up the experimental environment consisting of the spatial audio system (headphones with headtracker) connected to a computer running number of audio samples with different latency. The participant will listen to the short sample with pre-set latency and evaluate the spatial experience on a scale from one (the repositioning of the signal sources is disturbing) to five (full immersive experience, feeling like the signal source is staying in the same position from the original user's position). Statistically sufficient amount of responses (typically 24-36 votes for each use case) will be evaluated.

Currently we have all the functional blocks necessary for the actual experiment working. We set up a headtracker from Supperware with its *Supperware Binaural Plug-in* for DAW (Digital workspace station) affected by a delay Plugin with precisely settable latency time and we are working on setting up a semi-autonomous system for playing the sample sets with randomly set latencies. The first experiments are planned for the second quarter of 2025.



Fig. 3. Supperware Binaural Plug-in user interface.

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Effects of hybrid turbulence modelling on aeroacoustic noise generation in automotive door gaps

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Abstract. With the rising popularity of quiet electric vehicles in transportation, one of the primary sources of acoustic noise arises from aeroacoustic mechanisms, such as vortex shedding at an automotive door gap. A detailed computational fluid dynamics (CFD) simulation of a simplified vehicle door gap geometry is presented. Due to their enhanced computational efficiency, Hybrid Reynolds-Averaged-Navier-Stokes (RANS)-Large-Eddy-Simulation (LES) turbulence modelling methods are increasingly adopted in industry and research, and it is crucial to understand their impact on aeroacoustics compared to pure LES simulations. A thorough evaluation of the transient flow fields and their statistics allows us to study the effects of different turbulence modelling techniques on the aerodynamics of the cavity. By analyzing the acoustic field using dynamic mode decomposition, we can link tonal sound emissions to their corresponding generation mechanisms, offering the path to optimize door gap geometries during future vehicle design to reduce passenger and community noise.

Keywords

Compressible flow, Turbulence modelling, Door gap, Aeroacoustic feedback, DMD

1. Introduction

Aeroacoustic noise has a significant impact on passenger comfort in the automotive sector. With the increasing proportion of electrified vehicles, the internal combustion engine, previously a primary acoustic noise source, is becoming less significant. This shift means that the effects of aeroacoustic noise generated by the aerodynamic flow are becoming more apparent. A cavity with a lip serves as a generic model for a vehicle door gap, where acoustic feedback interacts with the surrounding flow field. In Figure 1, the different noise generation mechanisms and transfer paths of a schematic door gap are shown. Rockwell and Naudascher [1] initiated the classification of cavity noise into three categories, namely fluid-dynamic, fluid-resonant, and fluid-elastic. Fluid-dynamic noise (e.g. Rossiter modes) arises from aerodynamic feedback mechanisms, while fluidresonant noise stems from acoustic resonances, such as Helmholtz resonance or geometrical domain resonances. Fluid-elastic represents noise generated by the coupling of vibrating surfaces of the cavity walls. This fluid-structure interaction mechanism is neglected due to the assumption of a rigid cavity. The considered geometry (see Figure 2) is a benchmark case originally experimentally and numerically investigated during the third and the fourth Computational Aeroacoustics (CAA) Workshop on Benchmark Problems by NASA [2, 3].



Fig. 1. Schematic drawing of a vehicle door gap including the aerodynamic excitation through boundary layer fluctuations, as well as acoustic mechanisms. This figure was extracted from [4].





2. Simulation setup

The compressible conservation equations of fluid mechanics are solved using ANSYS Fluent 2024 R1, where air is modelled as an ideal gas under ambient conditions (p = 101325 Pa, T = 300 K) and a constant dynamic viscosity of $\mu = 1.7894 \text{ kg}/(\text{m s})$. A pressure-based solver utilizing the PISO algorithm is employed, with second-order discretization in both space and time.

The studied cavity geometry is depicted in Figure 2. No-slip, impermeable smooth walls are prescribed at solid boundaries, while spanwise periodicity is imposed to approximate an infinitely long domain. A pressure outlet with non-reflecting boundary conditions (NRBCs), based on characteristics, mitigates spurious wave reflections. At the inlet, a turbulent boundary layer velocity profile, obtained from a precursor flat plate simulation, is imposed, with an NRBC applied to suppress acoustic reflections. A hybrid multi-block grid ensures efficient resolution, featuring smooth coarsening away from the cavity region. The mesh is designed for the freestream velocity of 50 m/s, satisfying the requirements of Stress-Blended Eddy Simulation (SBES), a hybrid RANS-LES turbulence model [6]. SBES blends the k-omega-SST RANS [7] model near walls with the WALE [8] subgrid-scale LES model in the core flow, balancing accuracy and computational efficiency.

The governing equations for compressible flow are the conservation laws of mass, momentum, and energy. The conserved variables are the density ρ , the momentum density ρu , and the total energy density ρE . Assuming that conductive heat flux q follows Fourier's law, $\mathbf{q} = -k\nabla T$, the conservation equations can be expressed as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau}$$
(2)

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\rho \mathbf{u} E + \mathbf{u} p) = \nabla \cdot (k \nabla T) + \nabla \cdot (\mathbf{u} \cdot \boldsymbol{\tau})$$
(3)

The Reynolds-Averaged-Navier-Stokes (RANS) equations are obtained by time-averaging the conservation equations

$$\frac{\partial \overline{\rho}}{\partial t} + \nabla \cdot \left(\overline{\rho} \,\overline{\mathbf{u}}\right) = 0 \tag{4}$$

$$\frac{\partial(\overline{\rho}\,\overline{\mathbf{u}})}{\partial t} + \nabla \cdot (\overline{\rho}\,\overline{\mathbf{u}}\overline{\mathbf{u}}) = -\nabla\overline{p} + \nabla \cdot \left(\overline{\boldsymbol{\tau}} - \overline{\rho}\,\overline{\mathbf{u}'\mathbf{u}'}\right)$$
(5)

$$\frac{\partial(\overline{\rho}\overline{E})}{\partial t} + \nabla \cdot \left[\overline{\rho}\overline{\mathbf{u}}\left(\overline{E} + \frac{\overline{p}}{\overline{\rho}}\right)\right] = \nabla \cdot \left[k_{\text{eff}}\nabla\overline{T} + \overline{\mathbf{u}}\cdot\overline{\tau}\right]$$
(6)

with the Reynolds stress tensor $\mathbf{u}'\mathbf{u}'$. The components of the viscous stress tensor $\overline{\tau}_{ij}$ assuming a Newtonian fluid follow as

$$\overline{\tau}_{ij} = \mu \left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) - \frac{2}{3} \mu \left(\frac{\partial \overline{u}_k}{\partial x_k} \right) \delta_{ij}$$
(7)

Using an eddy viscosity model, the turbulent shearstress tensor τ_t , as well as the Reynolds stress tensor $\overline{\mathbf{u}'\mathbf{u}'}$ are described by

$$\boldsymbol{\tau}_t = -\overline{\rho} \, \overline{\mathbf{u}'\mathbf{u}'} = \mu_t \left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) - \frac{2}{3} \overline{\rho} k \delta_{ij} \qquad (8)$$

In stress-blended eddy simulation [6], RANS turbulence models and LES are combined by merging the respective shear-stress tensor τ of both approaches

$$\boldsymbol{\tau}_t = f_b \boldsymbol{\tau}_t^{\text{RANS}} + (1 - f_b) \boldsymbol{\tau}_t^{\text{LES}}$$
(9)

using the blending function $f_b \in [0, 1]$. The value of the blending function is dependent on different parameters. It is influenced mostly by the wall distance, the local grid resolution and the characteristics of turbulence. When eddy viscosity models are employed for the RANS part, the blending can be done directly using the eddy viscosity ν_t

$$\nu_t = f_b \nu_t^{\text{RANS}} + (1 - f_b) \nu_t^{\text{LES}} \tag{10}$$

Two additional transport equations have to be solved for the used $k - \omega$ -SST RANS turbulence model [7], which allows calculation of the eddy viscosity ν_t^{RANS} . The scalar transport equations are for the turbulent kinetic energy k and the specific turbulent dissipation rate ω . For the LES, the eddy viscosity ν_t^{LES} is calculated by a wall-adapting local eddy-viscosity (WALE) subgrid-scale model [8]. To evaluate the performance of the SBES approach in predicting the turbulent structures and the resulting aeroacoustic noise, a comparative pure LES study using the same subgrid-scale model as in the LES part of the SBES simulation was also performed. The details of both simulations are summarized in Table 1. By comparing both simulations, the impact of the turbulence modelling technique on the flow field and the emitted aeroacoustic noise can be investigated.

Туре	δ	$oldsymbol{U}$	Δt	Steps	$h_{ m core}$
	(mm)	(m/s)	(μs)		(h)
SBES	9.68	50	20	14000	17422
LES	9.68	50	20	20000	42660

Tab. 1. Overview of both CFD simulations. The specified processor hours $h_{\rm core} \approx N_{\rm core} \cdot t_{\rm run}$ are estimated by the number of processor cores $N_{\rm core}$ and the simulation run time $t_{\rm run}$ on the cluster (The computations where performed on the Vienna Scientific Cluster (VSC) 5, using compute nodes equipped with 2xAMD Epyx Milan, and 512 GB of RAM, each).

Table 1 also shows that the SBES simulation needs around 1.2 $\frac{h_{core}}{step}$ which is more computationally efficient when compared to the pure LES simulation's $2.1 \frac{h_{core}}{step}$. This results in a speedup of 72% for the SBES simulation, cutting down the simulation time significantly.



Fig.3. The averaged vorticity $\overline{\omega}$ and the directly resolved Reynolds stresses $\overline{u'_i u'_j}$ observed in the SBES and the comparative LES simulation. The Figure was adapted from [5].

3. Flow field and acoustic signature

To compare the flow field and turbulent fluctuations of both simulations, the time-averaged vorticity $\overline{\omega}$ and the Reynolds stresses $u'_i u'_i$ are shown in Figure 3. In LES, largescale turbulent structures within the boundary layer are directly resolved, enabling direct interaction between the turbulent boundary layer and the vortex-shedding mechanism. In contrast, the SBES approach employs a RANS-modeled boundary layer, where fluctuations are only captured statistically. These differences become apparent when comparing the statistics in the turbulent boundary layer and the shear layer over the cavity. In Figure 4, we display the instantaneous vorticity field ω in a timestep of the SBES simulation. When comparing both the Reynolds stresses and the vorticity a unperturbed vortex shedding mechanism can be observed in the SBES simulation, which is not found for the LES. The differences in turbulence modelling of the boundary layer can have a significant impact on acoustic noise emission due to differing structures of the vortex shedding mechanism. Unperturbed vortex shedding in the SBES allows the excitation of multiple acoustic modes, whereas the process perturbed by resolved turbulent fluctuations leads to fewer (more broadband) modes. This also explains the difference of excited modes in the corresponding pressure level spectra in Figure 5.

The first tonal peak in the spectrum of both simulations indicates that the flow oscillates in the 1st Rossiter mode. Rossiter modes are self-sustained oscillations caused by the interaction between shear layer instabilities and the acoustic feedback of the cavity. The frequency of the *n*-th Rossiter mode can be analytically estimated using the free stream velocity U, the cavity length $L_{\rm M}$, the Mach number M and two empirical constants α and κ_v by

$$f_{\mathbf{R}_n} = \frac{U}{L_{\mathbf{M}}} \frac{n - \alpha}{M + \kappa_v^{-1}}, \qquad n \in \mathbb{N}^+$$
(11)

In addition to the dominant 1st Rossiter mode (1654 Hz), other tonal peaks can also be found in the SBES simulation. Their origin is identified using DMD and presented in the next section. The spectrum shows that the peak frequency of the first Rossiter mode is consistent between methods, confirming that the main flow features remain similar regardless of the turbulence modelling approach used. The additional peaks observed in the SBES simulation are not excited in the LES study. As explained above, these discrepancies are primarily attributed to differences in boundary layer modelling and the vortex shedding perturbed by them.



Fig. 4. The instantaneous vorticity field ω in a sample timestep of the SBES simulation together with velocity vectors.



Fig. 5. Pressure level spectra for both simulations compared to the experimental data of Henderson [3]. The reference pressure $P_{\rm ref} = 2 \cdot 10^{-5}$ Pa was used for the decibel scale.

4. Acoustic mode extraction using DMD

We employ a DMD analysis to understand the sound generation mechanisms and the tonal noise emissions of the cavity. DMD [9] is a data-driven technique that uses snapshots $\mathbf{V}^N = \{\mathbf{v}_1(x,t_1), \mathbf{v}_2(x,t_2), ..., \mathbf{v}_n(x,t_n)\}$ of field quantities and separates them into spatio-temporal modes

$$\mathbf{\Phi}_i(x,t) = \exp(\sigma_i t + \mathrm{i}\omega_i t) \mathbf{\Psi}_i(x) \tag{12}$$

each with a corresponding frequency ω_i and an exponential growth or decay rate σ_i . Theoretically it tries to approximate the in general nonlinear dynamics $f(\mathbf{v}_i)$ using a linear operator \mathbf{A} , such that

$$\mathbf{v}_{i+1} = \mathbf{f}(\mathbf{v}_i) \quad \rightarrow \quad \mathbf{v}_{i+1} = \mathbf{A}\mathbf{v}_i$$
(13)

The operator is used to model the transition from the state matrix of the first (n - 1) snapshots \mathbf{V}_1^n to the state matrix of the last (n - 1) snapshots \mathbf{V}_2^n resulting in

$$\mathbf{V}_2^n = A \mathbf{V}_1^n \tag{14}$$

The decomposition is achieved by splitting the matrix of the first (n-1) snapshots \mathbf{V}_1^n using a singular value decomposition (SVD)

$$\mathbf{V}_1^n = \mathbf{U} \boldsymbol{\Sigma} \mathbf{V}^* \tag{15}$$

to obtain the reduced operator A

$$\tilde{\mathbf{A}} = \mathbf{U}^* \mathbf{V}_2^n \mathbf{V} \boldsymbol{\Sigma}^{-1} \tag{16}$$

The eigenvalues $\lambda_i = \sigma_i + i\omega_i$ and eigenvectors $\boldsymbol{\xi}$ of the reduced operator enable the computation of the dynamic modes Ψ_i by

$$\Psi_i = \mathbf{U}\boldsymbol{\xi} \tag{17}$$

By analyzing the different dynamic modes of the pressure, vorticity, and velocity fields, we can verify the origin of emitted tonal sounds. Here, we investigate the three tonal modes already prominently represented in the acoustic spectrum. Analyzing the DMD modes corresponding to the expected frequencies allows us to display fluid dynamic and acoustic phenomena. The emission of pressure waves of the three modes is qualitatively shown in Figure 6. As stated earlier, the first tonal mode corresponds to the first Rossiter mode. As expected, the corresponding dynamic mode of the pressure field shows a periodic convection of the vortex. The second tonal mode, the Helmholtz mode, represents oscillating fluid in the cavity neck. The peak at $f_{\rm H} = 2154 {\rm Hz}$ is attributed to this Helmholtz resonance, validated through an additional frequency domain acoustic simulation using the finite element software openCFS [10]. In the validation simulation, we find a Helmholtz resonance at a frequency $f_{\rm H,val} = 2080$ Hz. This resonant peak is comparable to the one from Henderson [3] (2016 Hz). The third and last investigated tonal mode is identified as a geometric mode of the cavity.

$$f_{\rm Cy} = \frac{c}{4\sqrt{\left(D + 0.5D_{\rm M}\right)^2 + L_{\rm M}^2}} = 2823\,{\rm Hz}$$
 (18)

This mode corresponds to a quarter wavelength resonator, the dominant geometric mode for deep cavities.



Fig. 6. The normalized DMD pressure modes for the SBES simulation at frequencies of the first Rossiter mode ($f_{R_1} = 1660$ Hz), the Helmholtz mode ($f_H = 2160$ Hz) and the geometric depth mode ($f_{Cy} = 2840$ Hz). This Figure was adapted from [5]

5. Conclusion

In this study, we examined the aeroacoustic characteristics of a generic deep cavity with an overhanging lip, modelling an automotive door gap subject to an incoming airflow at a free-stream velocity of 50 m/s. This configuration was initially explored in the Third Computational Aeroacoustics (CAA) Workshop on Benchmark Problems by NASA [2, 3]. The complex interaction between the turbulent boundary layer and the generated acoustic waves gives rise to a strong feedback mechanism, influencing shear layer instability and leading to acoustic noise emission. The present work fo-

cused on capturing the intricate structures of the compressible turbulent flow and studying their dependence on turbulence modelling techniques. A hybrid RANS-LES SBES, as well as a pure LES approach, was employed to resolve large-scale turbulence in a three-dimensional domain, providing a high-fidelity representation of the flow field. The dominant influence of the resolved boundary layer fluctuations of the different approaches on the vortex shedding mechanism and the subsequent excitation of acoustic modes was shown. For the SBES simulation, an unperturbed vortex shedding mechanism led to acoustic modes which were not excited in the LES. Furthermore, Dynamic Mode Decomposition (DMD) demonstrated its effectiveness in identifying the source mechanisms of aeroacoustic noise by correlating tonal peaks with their physical origins. Overall, this study provides new insights into the flow-induced noise mechanisms in automotive door gaps, highlighting their sensitivity to turbulence modelling. The findings contribute to a greater insight into automotive acoustics and may inform future noise mitigation strategies in engineering applications.

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SOA Protection Circuit for eFuses

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Abstract. This article outlines the design and methodology of a novel Safe Operation Area protection circuit which can be used in integrated circuit of electronic fuses (eFuses). The circuit solution has been designed and used specifically in a 100 V, 20 A eFuse, currently being developed, in 180 nm BCD technology of STMicroelectronics, used in newly being developed server platforms. An emphasis has been put on reasonable complexity and variability of the solution that can match Safe Operation Area curves of various power MOSFETs in order to fully use them in terms of maximal allowed power dissipation.

Keywords

SOA, protection, electronic fuses.

1. SOA curves

Power (MOSFET) transistors play a role in a variety of electronic devices and systems, and their safe operation is of particular interest. A characteristic defining the operating limits of power transistors is the Safe Operating Area (SOA), which determines the maximum power dissipation that a power transistor can withstand without experiencing damage.

In addition, power transistors are not self-protecting components, which leaves them prone to overload. Such overloads can arise due to various conditions, such as short circuits, voltage spikes, or excessive power dissipation. Therefore, to prevent the destructive effects of these circuits employ overloads, protection sensors to continuously monitor the operating parameters of the transistor. If the monitored parameters suggest that the transistor is operating outside of its SOA, the protection circuits take action to prevent potential damage. The monitored parameters may include overcurrent and overvoltage conditions, as well as thermal conditions.

However, a challenge arises in that the SOA is not defined by a linear relationship between the drain current I_D and the drain to source voltage V_{DS}. In addition, the time of withstanding these conditions must be considered as well. A power transistor is capable of withstanding much higher power dissipation for short time periods than the power dissipation defined for DC condition. As an example, SOA characteristics of IRF630 MOSFET [8] can be used, depicted in Fig. 1. The plot represents a relation between the drain current I_D and V_{DS} voltage that limits the maximal allowed power dissipation for the given time period. Operation of the transistor within the area restricted by the curves is supposed to be handled without a change of the transistor specification or damage. On the other hand, crossing the line might lead to irreversible changes of the transistor or even to its complete damage and the behavior of the transistor is not guaranteed by the manufacturer.





The first part of the characteristic for low $V_{\rm DS}$ values is determined by the R_{DSon} limitation of the transistor when operated in linear region. Therefore, this line follows ohm's law. When the transistor gets operated in saturation region, the restriction is given by several effects. For very short pulses it can be possible to see the limitation caused by the maximal drain current rating of the transistor. For longer pulses, it may not be possible to reach the maximal drain current because the SOA curve may be limited by the power dissipation itself. Mainly for low to mid V_{DS} values, the maximal power dissipation may be approximately a constant value. For high V_{DS} values, the maximal power dissipation might be lowered due to secondary effects, including temperature instability [1, 4]. As a factor engaged in these effects, a positive temperature coefficient of the drain current can be named [1 - 7]. Another important factor is the way of the transistor mounting [4]. These secondary effects are difficult to be simulated, computed. For this reason, the SOA curves in this region are based mainly on measurement.

Operation of the power transistor in saturation region is common in modern electronic devices such as integrated circuits of electronics fuses (eFuses). During the soft startup up phase, which can take milliseconds, the power transistor is operated with high V_{DS} . Also, during the short event occurrence, the output voltage decreases rapidly, creating high V_{DS} again. On the other hand, when this happens, the eFuse is already handling the short event and the power transistor is being turned off.

Therefore, there is a need for a protection circuit that addresses these issues – one that can handle high voltages, is compact, provides flexibility, and is easy to tune/program for different applications, thereby overcoming the common designs issues.

2. SOA Protection Circuit

The goal of the proposed novel solution is to define a relation between the drain current of the power transistor and its V_{DS} voltage which determines the maximal allowed power dissipation. Ideally, this defined behavior should allow to use the ability of the power transistor as fully as possible without crossing its SOA curves. This circuit also takes in account the time duration of the power dissipation. The emphasis has been put on great variability and tunability to match SOA curves of various power transistors. To the author's best effort, no other state-of-the-work dealing with theses issues has been found. The solution has been filed to US patent office (patent pending) [9].

The circuit solution has been designed and used specifically in a 100 V, 20 A eFuse, currently being developed, in 180 nm BCD technology of STMicroelectronics.



Fig. 2. Functional diagram of the proposed SOA protection circuit.



Fig. 3. Principal of $V_{\rm DS}$ voltage sensing circuit.

For easier understanding, it is suitable to divide the circuit into two main parts – the shaping part and the timing part, depicted in Fig. 2. The function of the shaping part is based on a non-inverting amplifier circuit with a variable gain. The gain of the amplifier is modified according to $V_{\rm DS}$ of the power transistor. $V_{\rm DS}$ sensing circuit, principally depicted in Fig. 3, uses a p-channel transistor $M_{\rm S1}$ together with resistor $R_{\rm VDSSNS}$ to create a current proportional to $V_{\rm DS}$ voltage of the power transistor $M_{\rm POWER}$.

As a non-inverting input signal of the amplifier, $V_{\rm ISNS}$ voltage is used. This sensing voltage represents a voltage proportional to current $I_{\rm PWR}$ through the power transistor $M_{\rm POWER}$. This voltage comes from a precise load current monitoring circuit that is generally used in eFuses for multiple purposes. This circuit processes $I_{\rm COPY}$ current through the copy transistor $M_{\rm COPY}$ and delivers $I_{\rm SNS}$ current in a k factor proportion to the power transistor current $I_{\rm PWR}$ and converts it to $V_{\rm ISNS}$ voltage with a suitable gain G, using a resistor $R_{\rm SNS}$ as the converter. Therefore, this voltage can be expressed as:

$$V_{\rm ISNS} = R_{\rm SNS} \, I_{\rm SNS} = R_{\rm SNS} \frac{I_{\rm PWR}}{k} = G \, I_{\rm PWR} \tag{1}$$

Following the shaping circuit, the timing circuit is present. It composes of a circuit which acts as an operational transconductance amplifier OTA – its output current is given by its differential input voltage V_{DIFF} , either in sinking or sourcing direction, the relation between the differential voltage and the output current I_{OTA} is given by the transconductance as:

$$g_{\text{mOTA}} = \frac{I_{\text{OTA}}}{V_{\text{DIFF}}} = \frac{I_{\text{OTA}}}{V_{\text{ISNSADJ}} - V_{\text{REF1}}}$$
(2)

The I_{OTA} current is capable of charging/discharging the capacitor C_1 . As result, when $V_{ISNSADJ}$ crosses the defined reference voltage V_{REF1}, an overload situation occurs, for further reading let us call this situation as "DC overload". This situation represents the DC SOA curve crossing. At this point, there is no action applied on the power transistor by the protection circuit so far. Firstly, the capacitor C_1 has to be charged to a value of the reference voltage V_{REF2} before the output comparator can trigger the fault event/turn-off procedure. Therefore, this timing circuit allows to cross the DC SOA curve for short time periods and maximizes the use of the power transistor. The shorter the time of the overload condition, the higher the overload is allowed – according to the SOA curves. In addition, since the OTA is capable of discharging the capacitor C_1 by sinking the current, it acts as an integrator and makes averaging of the overloads which can occur in a pulsed waveform rather than just a single event as well. The voltage across the timing capacitor C1 at the time *T* can be expressed as:

$$V_{C1}(T) = \frac{g_{\text{mOTA}}}{C_1} \int_0^T (V_{\text{ISNSADJ}} - V_{\text{REF1}})(t) dt$$
(3)

2.1 SOA Shaping Circuit

A simplified schematic implementation of the shaping part of the circuit is depicted in Fig 4. It consists of an operational amplifier connected as a non-inverting amplifier. The non-inverting input is V_{ISNS} voltage proportional to the current through the power transistor. The feedback network is created by resistor R_F and a parallel connection of N circuitry sections with resistors R₁ to R_N. Each section uses a current derived from a p-channel current mirror consisted of M₀ to M_N transistors. The feeding current of this mirror is current I_{VDSSNS} proportional to the V_{DS} of the power transistor. The mirrored currents through transistors M₁ to M_N are scaled with suitable mirroring factors, the highest current flows through M1, then descending to the lowest current flowing through M_N. The lower part of each section consists of a mirrored reference current I_{REF} through the mirror of M_{x_A} and M_{x_B} while the drain current of M_{x_B} creates a current branch with the corresponding upper transistor M_x of the mentioned mirror of M_1 to M_N . Assuming transistor M_{x C} disconnected by an open switch SW_x , the current branches of M_x B and M_x create "current comparators". If the current through M_x reaches the current set by $M_{x\ B},$ the gate voltage of transistor M_{x_D} reaches high rail and the transistor is turned on, operated in linear region, so it acts as a resistor with its R_{DSon} value. In that situation, resistor Rx is connected through RDSon of MxD to GND and the particular section is "activated". Therefore, it serves in the feedback loop of the operational amplifier. Otherwise, the resistor is in a high-impedance state and is practically floating with no effect.



Fig. 4. Simplified schematic of SOA shaping circuit.

With increasing V_{DS} of the power transistor, I_{VDSSNS} rises. Because of the different scaling of M₁ to M_N, the sections are activated one by one. For the lowest V_{DS} , only the first section is activated, then the other sections are added/activated with higher V_{DS} , until reaching activation of the last section for the highest range of V_{DS} voltages. Therefore, the higher the V_{DS} , the more resistors R_x are connected in parallel, so the total resistance in the lower part of the feedback path gets lower resulting in a higher gain of the non-inverting amplifier. The gain can be expressed as:

$$\frac{V_{\text{ISNSADJ}}}{V_{\text{ISNS}}} = 1 + \frac{R_{\text{F}}}{\frac{R_1}{a_1} \parallel \frac{R_2}{a_2} \parallel \cdots \parallel \frac{R_N}{a_N}}$$
(4)

where
$$a_i \in (0,1 >, a_i = f(V_{DS}) \text{ or } a_i \in \{0,1\}, a_i = f(V_{DS})$$

Therefore, the DC overload occurs at lower power transistor drain current I_{PWR} for higher V_{DS} voltages. An example simulation plot of the gain of the non-inverting amplifier vs V_{DS} voltage is depicted in Fig. 5. A relation between I_{PWR} and V_{DS} voltage that represents the DC overload is plotted in the simulation result in Fig. 6. A similar simulation scenario is plotted in Fig. 7 as a power dissipation (product of V_{DS} and I_{PWR}) that represents the DC overload. For these examples, five sections of the shaping have been used. Activation of each section can be seen, separated by the discontinuity on the curves. So far, the open switches SW_x have been considered. Assuming them closed, transistor M_{x C} is then diode connected. Because of this, the branch of M_{x_B} and M_x does not act purely as a current comparator. The diode of $M_{x C}$ sinks the difference between currents of M_{x B} and M_x, resulting in continuous behavior that sort of "interpolates" the previous discontinuous curves. This can be seen also in the mentioned figures.



Fig. 5. SOA shaping – sim. example of gain of the non-inverting amplifier vs $V_{\rm DS}$ voltage.



Fig. 6. SOA shaping - sim. example relation of I_{PWR} and V_{DS} representing DC overload.



Fig. 7. SOA shaping - sim. example relation of P_{OFF} and V_{DS} representing DC overload.

The circuit provides a high degree of adjustability in terms of the SOA curve. Resistors $R_1, R_2, ..., R_N$ may be trimmable, this trimming is used to tune the SOA curve. Also, the scaling factors of the transistors $M_1, M_2, ..., M_N$ may be adjusted by trimming to shift the SOA curve to a desired range/shape, alternatively, a trimming can be implemented in the lower side of mirrors M_{x_A} and M_{x_B} .

2.2 SOA Timing Circuit

The simplified structure of the SOA timing circuit is depicted in Fig. 8. It uses a symmetrical OTA stage but also it contains additional current mirroring branches for sinking (M_{12}, M_{14}) and for sourcing (M_{13}, M_{15}) and several switches M_{16} - M_{19} . At any given moment, only one of these two branches is active/enabled, depending on the polarity between $V_{ISNSADJ}$ and V_{REF1} which is monitored by additional comparator E_1 . For instance, when $V_{ISNSADJ}$ is higher than V_{REF1} , the sourcing output branch of M_{15} is enabled, thus the switches M17, M18 are on and switches M16 and M_{19} are off. Otherwise, when $V_{ISNSADJ} < V_{REF1}$, the sinking branch of M_{14} is enabled, thus the switches M_{17} , M_{18} are off and switches M₁₆ and M₁₉ are on. One of the ways to increase the linearity is to use a source degeneration by resistor R₁. The resistor creates a local negative feedback, so the linearity is increased as a result. The cost for that is a reduction of transconductance g_{mDIFF} of the differential pair. Also, the source degeneration leads to a higher level of the input noise. On the other hand, these facts do not represent disadvantages for the given application.



Fig. 8. Simplified schematic of OTA used in SOA timing circuit.

To achieve high variability of the overall transconductance of the OTA, electrical trimming of the mirroring factors of mirrors of M₃ a M₅, respectively M₄ and M₆ has been implemented. Since the overall transconductance g_{mOTA} is given simply as:

$$g_{\text{mOTA}} = \frac{I_{\text{OTA}}}{V_{\text{DIFF}}} = \frac{I_{\text{OTA}}}{V_{\text{ISNSADJ}} - V_{\text{REF1}}} = g_{\text{mDIFF}}$$
(5)

Where k represents the total mirroring factor of the drain currents of the differential pair with transconductance g_{mDIFF} to its output branch.

Finally, an example plot of the allowed power dissipation for the given duration of time is depicted in Fig. 9. There are several curves for different V_{DS} values of the power transistor. The simulation has been done in a

following way. For each given value of the V_{DS} , a particular step of constant I_{PWR} has been applied and the time from the biggening of the step of I_{PWR} to the triggering of the output comparator (SOA fault signalization), monitoring the C_1 voltage, T_{OFF} has been measured. For each measured value of the time T_{OFF} , a power dissipation given as $P_{\text{OFF}} = V_{\text{DS}} I_{\text{PWR}}$ has been plotted. As observed, the allowed power dissipation is decreased for higher V_{DS} according to the shaping part of the circuit. For short periods, higher power dissipation is allowed according to the timing part of the circuit. It can be seen that for low values of V_{DS} and for low values of T_{OFF} , the power dissipation does not rise. This behavior is caused by the limited dynamic range of the current sensing block. In that case, the I_{PWR} is too big so that V_{SNS} is at its limit value and is saturated, so it does not rise anymore with rising I_{PWR} . The curves have a hyperbolic trend of 1/x function. Since it can be derived from equation (3) that it holds:

$$V_{\rm ISNSADJ} - V_{\rm REF1} \sim \frac{1}{T_{\rm OFF}}$$
(6)

The minimal T_{OFF} is limited by the maximal current of the OTA and/or reaching the maximal possible voltage by the output of the shaping block – its limited dynamic range. A "less hyperbolic" shape can be achieved by lowering the OTA transconductance, on the other hand, simply decreasing of the transconductance of the OTA by, for instance, lowering its mirroring ratios leads to increasing of the minimal T_{OFF} as well. In that case, a whole dynamic range would need to be increased as well to cope with this. This plot in Fig. 9 can be also transformed to a relation between I_{PWR} vs V_{DS} with the T_{OFF} as a parameter. The curves for constant T_{OFF} can be read from the plot, such curves for four chosen T_{OFF} parameters are depicted in Fig. 10.



Fig. 9. SOA protection – example of allowed power dissipation for given time duration.



Fig. 10. SOA protection – example of I_{PWR} vs V_{DS} for given overload period.

2.2.1 SOA Timing Circuit – Pulsed Overloads

So far, it has been considered to have the same transconductance of the OTA for both sourcing and sinking directions. In that case, the timing circuit makes averaging of the overload condition, as already explained, given by equation (3). When it comes to pulsed overload waveforms, it may not be fully desirable to compute true averaging since the heating effect is influenced by many complex factors. Thermal capacitances of a die and a case, such as mounting of the power transistor, can be named as an example. Simply put, the cooling down may be a longer process than heating up. Therefore, for suitable prolonging the discharging phase, a simple additional discharge circuit is depicted in Fig. 11. Between the charging capacitor and the output of the OTA, a resistor R_{DIS} is added which prolongs the discharging time with a suitable trimmable resistance.



Fig. 11. Principle of the additional discharge circuit for SOA timing.

3. Conclusion

A novel implementation of SOA protection for power MOSFETs has been introduced. It allows great tunability and variability to match SOA curves of various transistors in order to fully use their power capabilities. Besides shaping of DC SOA curves, a SOA timing restrictions problematics is address in the implementation as well. No other circuit dealing with these issues among state-of-the-art articles has been found.

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Characterisation of a Low-Cost Acoustic Chamber

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Abstract. Anechoic chambers are often necessary for acoustic measurements, but can be expensive. This paper documents the characterisation of a low-cost flexible anechoic chamber of type Studiobox Premium through acoustic measurements. The characterisation is performed with three measures: (i) the reverberation time in the chamber following ISO 3382-2, (ii) the sound insulation from the outside to the inside of the chamber following ISO 16284-1, and (iii) the environmental correction K_2 of a sound power measurement following ISO 3744. The reverberation time is smaller than 0.2 s for third-octave bands from 250 Hz to 10 kHz. Considering the wall thickness of 14 cm–19 cm, the sound insulation of more than 35 dB above 160 Hz is satisfying. Due to the size of the acoustic chamber, the requirements of ISO 3744 are violated regarding the distance between the sound source, the microphones, and the chamber walls. However, the results presented serve as a first quantification of the chamber's acoustic properties. For third-octave bands from 125 Hz to 10 kHz, the environmental correction K_2 (following ISO 3744) is smaller than 4 dB, thus fulfilling the requirements for a class 2 sound power measurement. From these results, the acoustic properties of the anechoic chamber can be assessed, which is necessary for future measurements planned in the acoustic chamber.

Keywords

Acoustics; Acoustic Chamber; Sound Power; Sound Insulation.

1. Introduction

The *Studiobox Premium* chamber is a modular acoustic enclosure for rapidly implementing an environment that is "acoustically treated" [1]. The chamber is assembled from 28 panels, as depicted in Fig. 1. The outer dimensions of the chamber are 2.7 m in width, 3.28 m in length, and 2.3 m in height with a chamber wall thickness of 14 cm to 19 cm. The chamber is set up in a room-in-room configuration, where the inner room is the acoustically treated chamber and the outer room contains the control station. A top-view sketch of the room-in-room configuration is provided in Fig. 4. Inside the chamber, a floor made from Sylodyn [2] with a thickness of 3 cm is laid to dampen vibrations. This equipment was recently set up at *Graz University of Technology* from a second-hand source. Due to the transportation and relocation of the acoustic chamber, material defects may have occurred. Therefore, similar to [3], the proposed paper documents characterisation measurements to assess the rebuilt chamber's in-situ acoustic properties. The characterisation measurements allow for quantifying the chamber's acoustic attributes regarding the acoustic field's properties. These measurements serve as future reference about whether the acoustic chamber complies with particular research requirements.



Fig. 1. The acoustic chamber of type *Studiobox Premium* set up in its new location at Graz University of Technology.

To quantify the sound transmission between neighboring rooms, ISO 16283-1 specifies a measurement method for the airborne sound transmission [4], and ISO 16283-2 for the structure-bound transmission paths [5]. While these methods are originally intended for neighboring rooms, they are applied to the present room-in-room configuration, as we can also see in [3]. Furthermore, as the structural vibrations are damped by the Sylodyn flooring [2] in the chamber, only airborne sound transmission (ISO 16283-1) is investigated in the present study [4]. ISO 3744 defines class 2 and 3 engineering methods for a free field over a reflecting plane, which are used in the paper at hand [6]. Class 2 and 3 measurements rely on a comparison method, where the emitted acoustic power of a reference sound source (RSS) is measured in situ. It is compared to a reference sound power measurement under free-field conditions provided in the RSS data sheet. From the difference between the in-situ and reference measurements, the environmental correction K_2 is calculated. Thus, K_2 quantifies the deviations of the in-situ sound field from

free-field conditions. In [7], another chamber of the same type is used to measure the acoustic pressure emitted from a vibrating structure in the free field.

The chamber's reverberation time T_{30} is estimated by a sound insulation measurement based on the ISO 16283-1 is performed [4]. The acoustic characteristics deduced from the obtained third-octave values for the K_2 coefficient based on the ISO 3744 standard [6] are discussed and compared to the results in [8] following the 1. class standard ISO 3745 [9]. The measurements have been conducted as part of a bachelor's thesis [10].

This paper is structured as follows. In Sec. 2, the measurement methods used for the characterisation of the acoustically treated chamber are described. In Sec. 3, the measurement results are explained. A discussion and conclusion are provided in Sec. 4.

2. Characterisation methods for an acoustically treated chamber

2.1. Reverberation time

The estimation is based on ISO 3382-2 reverberation time measurement in the receiver room, which is performed for third-octave frequencies ranging from a center frequency of 53 Hz to 10 kHz, with a sound level decay drop of 30 dB [11]. A *Müller-BBM PAK* acoustic measurements system with six G.R.A.S. 46 AE 1/2" free-field microphones is used, as specified in Tab. 2. Furthermore the microphonesource configuration presented in Fig. 4 inside the chamber is adopted, such that the microphone positions M_6 — M_{11} are used. A detail photograph is depicted in Fig. 2a.





(a) Detail of the measurement setup for reverberation time.

(b) Detail of the measurement setup for SPL outside the chamber at microphone position M_5 .

Fig. 2. Measurement setups for (a) reverberation time and (b) sound insulation measurements.

The *Müller-BBM PAK* acoustic measurement system records third-octave band filtered impulse response functions that are used to calculate the energy decay curves in dB for each third-octave frequency band [12, Eq. (1)]. The excitation signal is a sinusoidal sweep. A linear regression line is computed to best match the energy decay curve between 5 dB and 35 dB below the stationary level. The time between

these two levels is the reverberation time $T_{30}^i(f_j)$ for the *i*-th microphone position and the *j*-th third-octave band. The reverberation times are averaged across the microphone positions to achieve a global reverberation time in the acoustic chamber

$$T_{30}(f_j) = \frac{1}{N_{\rm mic}} \sum_{i=1}^{N_{\rm mic}} T_{30}^i(f_j) \,. \tag{1}$$

The resulting reverberation time $T_{30}(f_j)$ in the acoustic chamber is depicted in Fig. 3.



Fig. 3. Reverberation time T_{30} in the acoustic chamber measured according to ISO 3382-2 [11].

Microphone Position	x in m	y in m	h in m
M_1	3.35	0.52	1.35
M_2	5.35	2.36	1.11
M_3	7.78	1.40	1.17
M_4	6.51	4.46	0.65
M_5	3.45	5.20	1.39
M_6	1.37	2.07	1.75
M_7	1.67	3.67	0.62
M_8	2.31	2.94	1.17
M_9	3.30	3.46	0.67
M_{10}	3.47	2.10	1.39
M_{11}	2.70	1.92	0.56
Source Position	_		
S_1	0.60	0.50	1.25
S_2	8.10	3.25	1.25
S_3	0.97	4.07	1.25

Tab. 1. Microphone and source positions. Positions M_6 — M_{11} and S_3 are used for reverberation time measurements, and M_1 — M_{10} with S_1 and S_2 are used for the sound insulation measurements.

2.2. Sound insulation

The standard ISO 16283-1 provides a method to determine the airborne sound insulation in buildings, i.e., between neighbouring rooms [4]. In contrast to the usual application, this paper applies the method to determine the sound insulation of the outer room to the inside of the acoustic chamber. The basic measurement setup is depicted in Fig. 4: $N_{\rm mic} = 5$ microphones are placed inside and outside the acoustic chamber, respectively, with two source positions outside and one source position in the acoustic chamber. A photograph of one exemplary microphone position M_5 is depicted in Fig. 2b. While the sound source (i.e., the loudspeaker as specified in appendix A) is repositioned for each measurement, it is not necessary to reposition the ten microphones. The excitation signal is white noise. The acoustic chamber is considered to



Fig. 4. Top view of the room-in-room configuration with microphone and sound source positions for the sound insulation measurement.

be the receiver room, and the outer room is considered to be the sender room in the sense of ISO 16283-1 [4]. Three measurements are performed sequentially, as follows. Firstly, a sound pressure level measurement of the background noise is performed using the microphone positions in the sender room $(M_1 - M_5)$ and in the receiver room $(M_6 - M_{10})$ as depicted in Fig. 4. No source is active during this first measurement. Secondly, a sound power level measurement is performed using the same microphone positions and the source positions S_1 and S_2 as depicted in Fig. 4. A dodecahedral loudspeaker (Norsonic Nor267) is used as a sound source, as listed in Tab. 2. Finally, a reverberation time measurement is conducted with the source at position S_3 and the microphone positions at M_6 through M_{11} . All microphone and source positions are depicted in Fig. 4 and listed in Tab. 1. For each of the three measurements, the measured quantity is the thirdoctave band averaged sound pressure level at the microphone positions $L_{p}^{i}(f_{i})$, where i is the microphone index and f_{i} is the respective third-octave band center frequency.

The level difference $D(f_j)$ between sender and receiver room yields [4, Eq. (1)]

$$D(f_j) = L_1(f_j) - L_2(f_j)$$
(2)

where $L_1(f_j)$ is the averaged sound pressure level in the source room while the source is operating, and $L_2(f_j)$ is the averaged sound pressure level in receiver room with the source operating in the source room. These are calculated from the measured third-octave band averaged sound pressure levels, such that

$$L_{k}(f_{j}) = 10 \log_{10} \left(\frac{1}{N_{\text{mic}}} \sum_{\forall i \in \mathcal{N}_{\text{mic}}^{k}} 10^{\frac{L_{p}^{i}(f_{j})}{10}} \right), \quad (3)$$

with $k \in \{1, 2\}$.

For k = 1, Eq. (3) yields the averaged sound pressure level in the sender room (i.e., outside of the acoustic chamber) with $\mathcal{N}_{\rm mic}^1 = \{1, 2, 3, 4, 5\}$. With k = 2 and

 $\mathcal{N}_{\mathrm{mic}}^2 = \{6, 7, 8, 9, 10\}$, the average sound pressure level in the receiver room (i.e., in the acoustic chamber) is obtained. From the level difference $D(f_j)$, the standard sound level difference $D_{\mathrm{n}T}(f_j)$ can be calculated with [4, Eq. (2)], such that

$$D_{nT}(f_j) = D(f_j) + 10 \log_{10} \left(\frac{T_{30}(f_j)}{T_0}\right) \, \mathrm{dB} \qquad (4)$$

where $T_{30}(f_j)$ is the reverberation time in the receiver room as described in Sec. 2.1, and T_0 is a reference reverberation time. According to [4], T_0 can be set to 0.5 s for residential units. However, the acoustic chamber does not constitute a residential unit and exhibits significantly lower reverberation times as Fig. 3 illustrates. Therefore, $D_{nT}(f_j)$ is evaluated for reference reverberation values of $T_0 \in \{0.25 \text{ s}, 0.5 \text{ s}, \min(T_{30}(f_j))\}$. The effect of the variation of T_0 can be seen in Fig. 7, and it is essentially a parallel shift of the $D_{nT}(f_j)$ along the vertical axis. The apparent sound reduction index R' of the chamber is computed with [4, Eq. (3)], such that

$$R'(f_j) = D(f_j) + 10\log_{10}\left(\frac{S}{A}\right) \,\mathrm{dB} \tag{5}$$

where S is the area of the common partition, and $A = 0.16V/T_{30}(f_j)$ is the equivalent absorption area of the receiving room.

2.3. Environmental correction K_2 of class 2 sound power measurements

In ISO 3744, a method for measuring the sound power emitted from an around source is standardised for an "essentially free field over a reflecting plane" [6]. To do so, ten microphones are placed in defined hemispherical positions around the sound source, as depicted in Fig. 5. Due to the spatial restrictions in the chamber, the following different radii of the hemisphere are compared: $r \in \{0.5 \text{ m}, 0.75 \text{ m}, 1.0 \text{ m}\}$. The measurement microphones record third-octave bandaveraged sound pressure levels. The "reflecting plane" required in [6] is achieved by placing rigid, smooth wooden panels on the floor of the chamber, as depicted in Fig. 6. A reference sound source (RSS) is placed at the location of the device under test (see Fig. 6), and the sound power level L_W^* according to ISO 3744 (without any correction) is obtained. The environmental correction K_2 is the difference between the measured sound power level L_W^* (adjusted by the background noise correction term) and the reference sound power level of the RSS $L_{W,(RSS)}$ under free-field conditions, which is known from its data sheet, such that

$$K_2 = L_W^* - L_{W,(RSS)} \,. \tag{6}$$

3. Results and discussion

3.1. Sound insulation

The measured level difference D, the apparent sound reduction index R', and the standardised level difference D_{nT}



Fig. 5. Positioning of the microphones for the Sound Power Measurement based on ISO 3744 [6] for distances of 0.5 m, 0.75 m, and 1.0 m (non-standard distances).



Fig. 6. Setup of sound power measurement of the RSS with a distance of 0.75 m.

are depicted in Fig. 7. For D_{nT} , three different reference reverberation times have been used, as described in Sec. 2.2. Expanding on [3], the approach to calculating the D_{nT} for acoustically treated rooms is further developed. Three different reference reverberation time values are used for the calculations and plotted in Fig. 7 reassuring good insulation of the chamber.

3.2. Environmental correction *K*₂

The limited space of the chamber imposes constraints on the standardised measurement distances according to ISO 3744 [6]. For the 0.5 m measurement, the distances are marginally acceptable. For the 0.75 m measurement, the narrow pair of the chamber walls make it infeasible to meet the requirements – transducers could not be placed at least twice the DUT-to-microphone distance from each wall. Each microphone is positioned at an acceptable distance from the small source, but the required distance from the chamber walls is surpassed by 0.5 m. For the 1 m measurement, the distance from reflecting surfaces crosses the required margin by 1.75 m for each transmitter. Henceforth, the measurements



Fig. 7. Level difference D, apparent sound reduction index R', and standardised level difference D_{nT} for different reference reverberation times T_0 .

conducted at distances 0.75 m and 1 m are merely based on the given standards, while the 0.5 m marginally complies with standards margin [6]. These values are used for calculating the K_2 coefficient as presented in Fig. 8. The chamber in [8] achieves a K_2 correction that fits the class 1 standard of ISO 3745 starting from the center frequency band of 400 Hz. Considering that the chamber at hand has a volume less than one-tenth of the chamber in [8], the K_2 correction meeting the class 2 requirements of ISO 3744 above the 200 Hz frequency band represents a significant achievement for economically equipped acoustic chambers[9, 6].



Fig. 8. Environmental correction K_2 for microphone distances of 0.5 m, 0.75 m, and 1.0 m.

4. Conclusion

From the reverberation time measurement in the chamber, it is evident that for third-octave bands above approximately 200 Hz, the reverberation time is below $0.2 \,\mathrm{s}$. The sound insulation from outside the acoustic chamber to its inside can be quantified with the level difference D. Considering the wall thickness of $0.12 \,\mathrm{m}$ and the modular construction of the chamber, the sound level difference values of more than 30 dB for $f_j > 250 \text{ Hz}$ are noteworthy. The environmental correction K_2 of class 2 sound power measurement complements these results. For third-octave bands above 200 Hz, the acoustic chamber can be used for class two sound power measurements. If class three measurement results are sufficient, the lower frequency limit is 100 Hz. However, due to space restrictions, it is impossible to fully comply with the standard's specifications [6] for sound power measurements.

In summary, the acoustic chamber seems promising for various types of acoustic measurements that require an essentially free field. Future use cases of the acoustic chamber may include psychoacoustic measurements with a test person and multiple stimuli (e.g., for experimental setups investigating the effect of traffic noise on humans), sound pressure emission measurements similar to [7], or speech science experiments requiring a quiet environment.

A. List of used equipment

Table 2 lists the equipment used to perform the measurements described in Sec. 2.

Equipment	Туре	Quantity
USB Audio interface	RME Babyface Pro	1
Dodakaeder speaker	Norsonic Nor276	1
Measurement microphones	G.R.A.S 46 AE 1/2" free-field	10
Data acquisition system	PAK Movile MKII	1
Measurement computer	Lenovo Thinkpad W520	1
Reference sound source	Brüel & Kjær RSS 4204	1
Microphone calibrator	Brüel & Kjær Type 4231	1

Tab. 2. Equipment used to measure the reverberation time, the sound insulation, and the environmental correction K_2 .

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Designing a Miniaturized Fluxgate using Flip-chip Technology

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Abstract. This work presents a novel approach to designing a miniaturized fluxgate magnetic sensor using flip-chip technology. The design consists of two chips bonded together using flip-chip technology, with a racetrack-shaped core in between. Metal layers of the chips and the bonds between the chips form a solenoid coils around the core. To maintain an acceptable fabrication cost, the top and bottom chips should be identical so that we can use multiple chips of the same layout rather than fabricating two different layouts. The layout must, therefore, be perfectly symmetrical, which makes the design challenging. We present the steps for the design and verification of such a symmetrical layout.

Keywords

Fluxgate, flip-chip, magnetic sensor, IC design, CMOS

1. Introduction

A miniaturized fluxgate was presented by our team last year [1]. It uses wire bonding technology to create the solenoid coils, as depicted in figure 1a. While the device performs well, the wire bonding process is time-consuming and therefore not suitable for mass production. In this paper, we propose using flip-chip technology for the next design iteration, as shown in figure 1b.

The new design consists of two chips bonded together. In order to reduce fabrication costs, the top and bottom chips are supposed to be identical. The layout must therefore be perfectly symmetrical, which is a challenge for the IC design. This paper presents the steps of design and verification of the symmetrical layout.

2. Designing basic pattern of the coils

Before we begin to design the layout, we need to figure out which positions of the bonding pads are compatible with the requirement of symmetry. This is done by an iterative process in which various patterns of bonding pads are tested.



Fig. 1: Comparison of micro-fluxgate designs

I created a simple graphical program to help with this task. In this program, the user places pads on the bottom chip and the program automatically generates the corresponding pad on the top chip. The same is true for drawing traces connecting the pads. Example of such drawing is shown in figure 2. Blue color indicates the bottom chip, which is drawn by the user. Red color indicates the top chip, which is generated by the program based on the bottom chip.

At this step of the design process, we don't yet consider the actual dimensions of the pads and traces. The main goal is to find a symmetrical pattern. After the design is finished, the program exports the layout to a file which can be imported into KiCAD PCB design software.

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Fig. 2: Basic pattern of the symmetrical coils, as designed in the custom-made program.

3. Scaling the design

In the KICAD layout, the simplified design is extended by adding more coil turns while maintaining the original pattern. The density of the coils shall be as high as possible while keeping minimum dimensions and spacing of the pads. Minimum spacing and maximum width of metal traces is taken into account when drawing connection between the pads. This design is done for the bottom chip only (bottom layer). After this design is finished, the top chip is created by mirroring the bottom chip (using Python script that acts on the PCB layout file). If the design is correct, the mirrored top layer should fit onto the bottom layer. Example of the layout in KiCAD is shown in figure 3.

KiCAD offers a tool for exporting 3D models of the layout. This tool is used to export the coil structure as a STEP file which can be further processed in a mechanical CAD software (Autodesk Fusion). Post-processing mainly consists of merging all traces and vias into a single solid object and adding cubes with flat faces to the ends of the coils (current terminals are assigned to those faces in FEM simulation settings). The 3D model is shown in figure 4.



Fig. 3: Layout in KiCAD



Fig. 4: 3D model exported from KiCAD

4. Verification of the design using FEM

After post-processing the 3D model in a mechanical CAD software, the model is imported into a FEM simulation software Ansys Maxwell. Each coil is simulated separately, by applying current to the coil terminals and using magnetostatic simulation to calculate the magnetic field created by the coil. At this phase, the main purpose of the simulation is to ensure that:

- The coils form a continuous conductive path without open circuits.
- There is no short circuit, or section of coil that is bypassed and have no current flowing through it.
- No branching or merging of the coil path.
- The magnetic field created by the coils has correct orientation.

5. Conclusion

The workflow for designing a miniaturized fluxgate using flip-chip technology was presented. The design was created in KiCAD and verified using FEM simulation.



Fig. 5: FEM simulation of the coil structure; Field created by excitation coil (4 serially connected segments) is shown.

As per previous experience, it is not a good idea to try to directly convert KiCAD layout to GDSII format for chip layout, it is better to only transfer the coordinates of pads and do the routing manually in chip EDA software [2]. Given that the layout consists of regular patterns, re-drawing the layout in the chip EDA software should be relatively easy.

The 3D model of the layout may be further used for more detailed simulations, such as simulating eddy currents in the core to optimize position of the excitation coil to minimize current required for saturating the core. This will require some post-processing of the 3D model, for example changing the distance between top and bottom layer to match the actual gap between the chips and replacing the hollow vias exported by KiCAD with solid connections to reduce complexity of the model.

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Temperature Compensated Power Detectors for L- and S-Band Radiometer Applications

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Abstract. This paper deals with the design, fabrication, and verification of power detectors for radiometer applications using discrete Schottky diodes. Special emphasis is taken to design a circuit with high temperature stability and sensitivity. A formulation for the most sensitive biasing point is found by applying the Bode Fano criterion on the power transfer to the diodes' differential resistance together with maximizing the sensitivity. The diodes are configured as a voltage doubler circuit. For temperature compensation a reference diode pair is introduced. The temperature compensated difference voltage is amplified using a low drift high precision operational amplifier.

Keywords

Power Detector, Schottky Diode, Bode Fano Criterion, Temperature Compensation, Radiometer

1. Introduction

1.1. Microwave Radiometers

Microwave radiometers are passive, sensitive measurement systems that aim on measuring the black body radiation in the microwave regime. According to Planck's law, the power radiated by an ideal black body at thermal equilibrium temperature of T in a bandwidth of B is given by

$$P = kTB \tag{1}$$

with k being the Boltzmann constant [1]. A typical total power radiometer consists of an antenna, a band pass filter, a low noise amplifier stage, and a power detector circuit followed by an integrator as shown in Fig. 1.



Fig. 1. Total power radiometer block diagram as in [2]

Crucial figures of merit to determine the performance of a radiometer are the noise figure of the LNA stage and the sensitivity of the power detector [3]. Radiometers are used in

many different fields such as e.g. radioastronomy as well as environmental, military, and medical applications [1, 3, 4].

1.2. Powerdetectors

Power measurement and therefore detectors are used in many Radio Frequency (RF) applications like receivers and transmitters for automatic gain or level control purposes to comply with governmental standards as well as in measurement equipment [5]. Recent research focuses on Monolithic Microwave Integrated Circuits (MMICs) and integrated power detectors for power control [6, 7, 8]. Power detectors can be distinguished as calorimetric, bolometric, and diode power detectors [1, 9] depending on the phenomena exploited e.g. thermoelectric, thermistors, or the nonlinear behavior of semiconductor devices [5, 9, 10].

Diode based power detectors can generally be described as nonlinear two port devices with a high frequency input and a direct current (DC) output. Depending on the operating range of the nonlinear element, the output voltage will either be proportional to the amplitude of the input signal (*envelope* detection) or the power of the input signal (*square law* detection) [11]. A common and simple architecture is shown in Fig. 2 [11]. A Schottky diode including the bias supply is used in the square law detector region to efficiently convert the input RF voltage $v_{\rm RF}$ to a proportional DC output voltage $V_{\rm out}$.



Fig. 2. Diode detector including a bias network with steady state bias currents as in [11]

2. Theory on Diode Detectors

Following the derivation of Sorrentino [11], the sensitivity of a quadratic diode detector, as shown in Fig. 2, is given as

$$\gamma_{\rm det} = 2 \frac{I'_0 + I_{\rm S}}{(nV_{\rm T})^2} \frac{r_{\rm d}^3 \cdot \text{Re}(Z_{\rm G})}{|Z_{\rm G} + R_{\rm S} + r_{\rm d}|^2}$$
(2)

with I'_0 the modified bias current, I_S the saturation current, n the ideality factor, V_T the thermal voltage, r_d the differential resistance, R_S the parasitic series resistance of the diode and Z_G the generator impedance. The sensitivity is the most important measure as it relates the output DC voltage V_{out} to the input power P_{in} as described in eq. (3) [11].

$$V_{\rm out} = \gamma_{\rm det} P_{\rm in} \tag{3}$$

2.1. Temperature Effects

As the diode detectors shall be used in radiometric applications, special emphasis needs to be taken on the temperature properties. Even more so because the diode characteristics itself are highly temperature dependent as can be seen from the temperature dependencies included in the Shockley equation [12]

$$I_{\rm D}(V_{\rm D},T) = I_{\rm S}(T) \cdot \left(e^{V_{\rm D}/nV_{\rm T}(T)} - 1\right)$$
 (4)

where

- $V_{\rm T}(T)$ is the thermal voltage given as $V_{\rm T}(T) = \frac{kT}{a}$
- and $I_{\rm S}(T)$ is the reverse bias saturation current which is exponentially dependent on temperature.

$$I_{\rm S}(T) = I_{\rm S}(T_0) e^{\left(\frac{T}{T_0} - 1\right) \frac{V_{\rm G}(T)}{n V_{\rm T}(T)}} \left(\frac{T}{T_0}\right)^{\frac{X_{\rm T,i}}{n}}$$
(5)

With the quantities T - Temperature [K], q - elementary charge, $I_{\rm S}(T_0)$ - saturation current at temperature T_0 , $V_{\rm G}$ - bandgap voltage, and $X_{\rm T,i}$ - temperature exponent of the saturation current.

Investigating the temperature influence on the sensitivity of the detector, one finds $V_{\rm T}(T)$ as well as the influences of the saturation current $I_{\rm S}(T)$ and the differential resistance $r_{\rm d}(T)$ due to the fact that the differential resistance is temperature dependent itself

$$r_{\rm d}(T) = \frac{\mathrm{d}V_{\rm D}(T)}{\mathrm{d}I_{\rm D}} \approx \frac{nkT}{qI_{\rm D,O}(T)}|_{I_{\rm D,O}\gg I_{\rm S}}.$$
 (6)

Using these equations to plot $\gamma_{det}(T)$ for a detector using a single SMS3293 Schottky diode (which will also be used later on), Figure 3 is obtained. It is apparent that the lower the bias current $I_{D,O}$, the higher is the sensitivity. However, the temperature dependence of the sensitivity is more pronounced. Furthermore, it can be seen, that at the



Fig. 3. Simulated influence of Temperature T[K] on the detectors sensitivity $\gamma_{\rm det}$ for different bias currents

intersection point, the sensitivity has degraded significantly due to the temperature's influence.

To obtain a stable sensitivity with respect to temperature, the bias point needs to be chosen as a compromise between maximum sensitivity and minimal temperature dependence. To compensate for the DC offset voltage due to the biasing current, a second diode pair within the same package (and therefore similar temperature and properties), will be integrated into the circuit. A differential amplifier is used to boost the output voltage to a range, where it can then be sampled by an Analog-to-Digital Converter (ADC) or measured using a voltmeter.

2.2. Optimum Bias Point

To obtain maximum output voltage for a given input power, it is not only necessary to maximize the sensitivity as given in eq. (3), but also the available input power $P_{\rm in}$ by matching the detectors impedance to the system impedance over a wide bandwidth [9]. This is necessary due to the broadband nature of the noise signal being used in the available radiometer setup. The LNAs have a limited bandwidth in the L-band from 1.1 GHz to 1.65 GHz and in the S-band from 3.25 GHz to 4.25 GHz. This fact leads to a necessary matching bandwidth of ≈ 550 MHz for the L-band and ≈ 1 GHz in the S-Band detector.

Using the diodes parasitic equivalent circuit and extracting the parasitic descriptions into the matching network as well as assuming that the load resistance $R_{\rm L} \gg r_{\rm d}$ and $X_{C_{\rm L}} \approx 0$ yields the reduced matching setup shown in Fig. 4. This concludes to the necessity of matching the parallel circuit consisting of the differential resistance and the junction capacitance, by using a passive, ideally lossless matching network. The parasitics network influences on the possible bandwidth of the matching is very limited as it consists of nearly lossless components [13]. Given that the parasitics are lossless themselves, they can be compensated by the matching network without any influence on the possible bandwidth of the matching circuitry. The bandwidth is



Fig. 4. Reduced matching problem of the diode detector using the equivalent circuit and including the parasitics of the diodes

fundamentally defined by the Bode-Fano conditions for an R-C load as in eq. (7).

$$\int_0^\infty \ln(\frac{1}{|\Gamma|} d\omega) \le \frac{\pi}{RC} \Rightarrow B \ln(\frac{1}{|\Gamma_{\max}|}) \le \frac{\pi}{RC}$$
(7)

Assuming that the reflection coefficient Γ of the detector input is smaller than a Γ_{max} for a given matching bandwidth of *B* and respective load of a parallel R-C and using the equation from [11] for the available DC power by substituting the RF power to the detector with the available RF-Power to the internal diode, eq. (8) can be obtained.

$$P_{\rm av,DC} = \left(\frac{1}{8} \frac{1}{I_0 + I_{\rm S}} \frac{1}{nV_{\rm T}} \left(1 - \Gamma_{\rm max}\right)^2\right) \cdot P_{\rm av,RF}^2 \quad (8)$$

Substituting also the reflection coefficient Γ_{max} by eq. (7), the optimum bias point can be found according to the maximization of the available DC power as given in eq. (9).

$$\max_{I_0} \left(\frac{1}{8} \frac{1}{I_0 + I_{\rm S}} \frac{1}{nV_{\rm T}} \left(1 - \exp \frac{\pi B}{r_{\rm d}(I_0)C_{\rm j}(I_0)} \right)^2 \right) \quad (9)$$

Solving eq. (9) numerically for SMS3923 and BAT15 Diodes leads to a single optimum bias points of 10.43×10^{-6} A and 1.49×10^{-6} A respectively.

3. Fabrication and Measurements

In total, there were four diode detectors fabricated on 20 mil RO4003c substrate and compared regarding their temperature stability as well as their output response. An sample Printed Circuit Board (PCB) is shown in Fig. 5.

The input impedance matching of the L-band detectors is found to be less than $-3 \,\mathrm{dB}$ in a frequency band from 1.07 GHz to 1.51 GHz (for the BAT15 diodes) and from 1.28 GHz to 2.0 GHz for the SMS3923 diodes as a compromise to fulfill optimum bias conditions. For the S-Band detectors, the matching was found to be less than $-3 \,\mathrm{dB}$ in a frequency band from 2.8 GHz to 4.0 GHz (for the BAT15 diodes) and from 3.3 GHz to 3.6 GHz for the SMS3923 diodes using optimum bias conditions.



Fig. 5. Photograph of diode detector PCB on Rogers 4003C using SMS3923 Diodes matched for L-Band

Sweeping the applied signal power using an E4438C signal generator from HP/Agilent at the desired center frequencies of the L- and S-Band detectors (1.375 GHz and 3.75 GHz), respectively, and monitoring the output voltage with a Gossen Metrahit 15S Multimeter yields the output voltage curves shown in Fig. 6 in a logarithmic scale with sensitivities displayed in Tab. 1. The minimum detectable power is evaluated for when the output voltage can be sampled by an ADC or equivalently exceeds the offset by 1.53 mV.



Fig. 6. Output voltage vs. input power for L- and S-band without offset

	Sensitivity $\gamma[^{mV/\mu W}]$		
	SMS3923 BAT15		
L-Band	56.2	55.8	
S-Band	5.62	15.6	
	Minimum Power $P_{\min}[dBm]$		
	SMS3923	BAT15	
L-Band	-44	-44	
S-Band	-40	-34	

 Tab. 1. Sensitivity and minimal detectable power of the diode detectors

For the temperature dependence, a climate chamber of type KWP 130/40-180 DU by Weiss Technik GmbH was used. By plotting the output voltage normalized on the voltage for temperature of 25°C, all detector circuits can be compared.

Up to 60°C all circuits show a deviation of less than 0.5%/K



Fig. 7. Normalized output voltage vs. temperature for both L- and S-band detectors and input powers of $P_{\rm in} = -20 \, \rm dBm$ and $-30 \, \rm dBm$

with the best stability seen in the L-band BAT15 detectors. Furthermore, it can be concluded from Fig. 7 that the temperature dependence varies only slightly with respect to the input power.

Validation of the detectors performance using noise power created by a 346B noise source from Keysight, a broadband amplifier and a stepped attenuator for varying the input power shows that the detector response is even better by at least $0.66 \,\mathrm{dB}$ for powers greater than $-45 \,\mathrm{dBm}$, compared to when the power is present in a single center frequency. This can be explained due to the average matching being better than at the center frequencies and by the power present in the transition areas of the L- and S-band filters.

4. Conclusion

Within this research, an optimization problem for the trade-off between power matching and detector sensitivity was found and experimentally validated for two different Schottky diodes. This approach can be extended to all detector circuit topologies (single or voltage doubler architectures) using diodes as the nonlinear element for converting the RF-Power into a proportional DC voltage. Temperature stability was achieved by using a reference diode pair in conjunction with a differential amplifier. The temperature stability was found to be less than 0.5%/K and the minimal detectable power is $-56 \, \text{dBm}$.

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Transistors Based on the Nitride Semiconductor Heterostructures

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Abstract. GaN based depletion and enhancement mode high electron mobility transistors (HEMT) were prepared and studied with the AlGaN/GaN heterojunction as the main channel. The e-mode operation was achieved by the addition of the Mg doped p-GaN suppression layer above the AlGaN blocking layer. Prepared samples were characterised by the van der Pauw method, output and transfer, and CV measurements. Furthermore, the diffusion of Mg was studied using the SIMS method. Enhancement mode operation was successfully achieved for the p-GaN variant. Current collapse degradation was observed in positively biased samples. Mg diffusion was successfully stopped by the addition of the absorption layer of the undoped GaN under the p-GaN layer.

Keywords

GaN, e-HEMT, Mg doping, MOVPE, ALD, IIInitrides, Wide band gap semiconductors

1. Introduction

The GaN is a promising material for semiconductor devices for high-frequency and power electronics. As a wide band gap material, it has a high breakdown voltage and can withstand higher electrical loads. Its intrinsic and strain induced polarisation allows for the creation of high electron mobility transistors (HEMT) with the channel formed by two-dimensional electron gas (2DEG) confined at the heterojunction of two GaN-based alloys. By employing the polarisation effects, the transistor structure can be created without doping the semiconductor (Fig. 1). This allows to avoid the efficiency losses caused by the impurity scattering.

Basic AlGaN/GaN heterojunction HEMTs have the 2DEG channel present without any applied bias, resulting in depletion mode or normally on characteristics. This is disadvantageous for applications that require to be fail-safe. Various modifications to the structures can be utilised to obtain enchantment mode operations: recessed gate [1], fluorine implantation [2], barrier layer thinning [3], p-GaN capping

[4], InGaN capping [5], cascode configuration with Si MOS-FET. In this paper, the p-GaN layer configuration is studied.

Mg doped p-GaN layer is deposited over the AlGaN layer during the sample growth, lifting the threshold voltage above zero, resulting in normally off behaviour. However, introduction of magnesium into the structure may lead to contamination of the main channel by diffusion of Mg impurities into it. This problem is intensified by the high temperature annealing that is required to activate Mg as an acceptor. As grown, it remains passivated by hydrogen.

To prevent the contamination of the channel heterojunction, an additional layer of undoped GaN was added beneath the p-GaN layer to act as an absorbent for diffusing magnesium.



Fig. 1: Band diagram of the AlGaN/GaN heterojunction

2. Fabrication process

Two different HEMT heterostructures were prepared using the metal organic vapour phase epitaxy (MOVPE) method on sapphire substrates. Sample a) depletion mode HEMT with simple GaN/AlGaN heterojunction in Fig. 2a, b) modification of the first structure by the addition of the
p-GaN layer on top with an absorption layer beneath it (Fig. 2b).



(b) Enhancement mode HEMT



Both samples incorporated a back barrier structure formed by the AlGaN barrier below the GaN channel to electrically isolate the growth layer near the substrate.

To form a gate oxide following the MOVPE growth, the sample was covered with a 10 nm thin Al_2O_3 layer, by means of thermal atomic layer deposition using Trimethylaluminum as a precursor and H_2O vapor as a co-reactant. Precursors were pulsed for the duration of 120 ms followed by a 2 s purge of N_2 . The substrate temperature was maintained at 300 °C.



Fig. 3: Fabrication steps for the circular transistor

After the heterostructure growth, circular transistor (Fig. 3 and 5) and van der Pauw (VdP) structures were fabricated on the split samples. Additionally, one sample of the enhancement mode structure was etched to remove the p-GaN suppression layer for direct observation of the main channel.

Fabrication of the transistors consisted of four steps. 1) etching of the ohmic contact pits; 2) ohmic contact deposition; 3) annealing of the ohmic contacts; 4) gate contact deposition (Fig. 3). The chosen circular transistor topology allowed for bypassing the isolating mesa etching around the transistors, as the active area was fully enclosed between the source and drain contacts.

To ensure direct contact with the 2DEG channel, the ohmic contacts were placed in the etched pits to the depth

of the AlGaN/GaN heterojunction. A four-layer Ti/Al/Ti/Au composition was used for drain and source ohmic contacts. Two-layer Ni/Au gate contacts were deposited on Al_2O_3 (see Fig. 4). Both contact types were deposited using ebeam evaporation method. Ohmic contacts were annealed at 800 °C in a vacuum.



Fig. 4: Fabricated circular transistor cross section



Fig. 5: Optical image of the developed circular transistors

3. Measurement and results

Van der Pauw method measurements for the depletion mode sample (a) show a high mobility of electrons and high carrier concentrations indicating the presence of 2DEG in the unpowered state. The second sample (b) shows high resistivity and concentration, and mobility below the detection level, indicating that the main channel was successfully suppressed with a p-GaN layer. Sample with etched p-GaN returned back to the depletion mode, with characteristics similar to the first sample suggesting that the Mg diffusion did not reach the AlGaN/GaN heterojunction and was stopped by the absorption layer.

Sample	Sheet resistivity (Ω)	$\begin{array}{c} \text{Mobility} \\ (cm^2/(V \cdot s)) \end{array}$	Carrier density (cm ⁻²)	Polarity
p-GaN	$2.473\cdot 10^{10}$	-	-	-
no p-GaN	717	1442	$6.041 \cdot 10^{12}$	n
etched p-GaN	597	1731	$6.037\cdot10^{12}$	n

Tab. 1: Results of Van der Pauw measurements

It can be noted that the etched sample has a higher mobility (see Tab. 1), which can be attributed to the lack of the GaN cap passivation layer present in the first sample.

To evaluate the performance of the fabricated transistors the output, transfer, and CV characteristics were measured. The characteristics presented below were measured for transistors of the same geometry for both samples: drain diameter of 400 μ m, gate length of 10 μ m and 5 μ m spacing between the gate and ohmic contacts.

The threshold voltage for the first sample $V_{\rm th}$ = -7 V to close the transistor corresponding to the depletion behaviour can be seen in the transfer characteristics (see Fig. 7). The gate to drain leakage at $V_{\rm DS}=0$ V is around $I_{\rm GD}$ = 113 nA for $V_{\rm G}$ = -10 V.



Fig. 6: Output characteristics of the normally-on HEMT



Fig. 7: Transfer characteristics of the normally-on HEMT

The sample with p-GaN layer (Fig. 8 and 9) functions as an enhancement mode device with threshold voltage around $V_{\rm th}$ = 3 V. However, the value of the threshold voltage for the normally-off device is unstable and shifts with repeated use to the higher values. The same effect can be seen in the output characteristics, whereas a trend for the decrease in saturation current can be observed.

For $V_G = 10$ V the $I_{GD} = 26$ nA, which is lower due to the larger distance between the gate and the channel. The I_{DS} leakage in the off state remained under 50 μ A. The output characteristics (see Fig. 8) do not show a linear rise from the zero which can be attributed to the comparatively large spacing not covered by the gate. In the spacing area, the 2DEG remains suppressed by the p-GaN creating a parasitic element in series to the active zone.



Fig. 8: Output characteristics of the normally-off HEMT



Fig. 9: Transfer characteristics of the normally-off HEMT

3.1. CV meauserment

The capacitance voltage characterisation was performed for both transistor types. Attained results of the threshold voltage $V_{\rm th}$ (see Fig. 10 and Fig.11) correspond well to the transfer measurements (Fig. 7 and 9).



Fig. 10: CV profile of the depletion mode HEMT



Fig. 11: CV profile of the enhancement mode HEMT

3.2. Mg diffusion

The composition of the p-GaN e-HEMT was further studied with secondary ion mass spectrometry (SIMS). The measured composition depth profile (see Fig. 12) shows that Mg diffusion from the suppression layer did not reach the channel heterojunction. The GaN absorption layer between the AlGaN and p-GaN layers has successfully absorbed the majority of diffused Mg. A small amount of Mg impurities can be observed in the top of the AlGaN blocking layer. However, the transport measurements (see tab. 1) do not show a decrease in mobility or concentration for the etched sample.



Fig. 12: Composition depth profile of p-GaN HEMT

4. Conclusions

We were able to successfully fabricate both depletion and enhancement mode GaN MIS HEMTs. The diffusion of Mg from the p-GaN layer to the 2DEG channel was prevented using an absorption layer of undoped GaN. The available structures can be improved by selective etching of spacings not covered by the gate to minimise their impact. The SIMS measurements show an uneven distribution of the Mg doping near the surface, which can trap the charge below the gate, leading to the observed current collapse. The instability of normally off HEMT $V_{\rm th}$ remains a major issue that requires further development of the technology.

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Digitally programmable symmetrical power pulse generator using SiC power switches

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Abstract. Design, realization, and characteristics of a power pulse generator using silicon carbide (SiC) power switches are presented. The generator is used to generate symmetrical output pulses with adjustable voltage, frequency, and other parameters. The generator is controlled by a microprocessor with an integrated FPGA. All generator parameters like switching frequency, duty cycle, dead times, output voltage, or maximum values of output voltage and current can be all digitally set from the PC over a serial line. The output voltage can be set in a 150 V - 600 V range for each pole, meaning V_{pp} is set between 300 V - 1200 V. Prototype of the proposed generator was constructed, using adjusted half-bridge topology for DC-DC converter and 3-level T-type topology for power stage, with SiC transistors and rectifier diodes. Finally, the prototype was tested with different values of output voltage and power up to 500 W.

Keywords

pulse generator, DC-DC converter, 3-level, SiC, digitally programmable, symmetrical output

1. Introduction

Symmetrical pulse generators are commonly used laboratory and industrial devices for many applications, such as ultrasonic probe driving, semiconductor devices testing, short circuit and isolation testing, and more. There are not many symmetrical generators on the market for voltages up to 1 kV, let alone programmable ones. Generators on the market often don't have their own voltage source and are for lower power use [1]. This article describes the design of a laboratory pulse generator, including a DC-DC converter, power stage, and control with digitally set parameters, including output voltage, frequency, duty cycle, and more. The output voltage can be set from 150 V to 600 V for positive and negative poles, reaching a maximum V_{pp} of 1.2 kV. For the converter and power stage, new power switches based on SiC are used to achieve higher efficiency and signal quality [2]. In the end, experimental results and measurements are described.

2. Design of the Generator

2.1 DC-DC converter

This converter was designed for a symmetrical 500 W load. It is powered from a 320 V source, simulating rectified main line voltage. To achieve a symmetrical output voltage, a modified half-bridge topology was used, as shown in Fig. 1.



Fig. 1 Used modified half-bridge topology.

Thanks to this topology, the symmetrical output voltage is created. Furthermore, current flows through both output poles, no matter which transistor (T1, T2) is switched on. This helps to reduce the output voltage ripple. With this topology, voltage on the primary side winding of the transformer is halved. To reach 600 V on the output for both poles, the transformer ratio needs to be 1:4 for both secondary windings. For the primary side winding, six turns were made, therefore $N_p = 6$ and $N_s = 24$. To construct the transformer, a toroidal core from a Vitroperm 250 F material was used. For the output rectifier, 1.2 kV SiC Schottky diodes were used. For simplicity, the same 1.2 kV SiC transistors are used for the DC-DC converter and the power stage.

2.2 Power stage

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For the generator power stage, a 3-level T-type topology was used, as shown in Fig. 2. With this topology, it is possible to switch positive, negative, or zero voltage to the connected load [3]. To make the switching of positive and negative 600 V possible, 1.2 kV SiC transistors were used.



Fig. 2 3-level T-type power stage topology.

2.3 Generator control and setting

For the generator control, an ARM microcontroller with an integrated FPGA is used. All functional parameters like frequency, dead times, duty cycle, output voltage, maximum output voltage and current values, can be set from a computer over the serial line. They are saved in the microcontroller and automatically loaded at the start, even without a connected computer. The DC-DC converter can run either with strict set parameters or with real-time PID regulation, using measured output voltage for closed-loop feedback. If the measured voltage or current exceeds the maximum set values, the generator stops operation. In PID-regulated mode, the converter can adapt to a dynamic load in real time. For the generator power stage, important parameters like frequency, duty cycle, and dead time can be set. It can also operate in continuous or burst mode, with an adjustable number of pulses. In Fig. 3, there is a block diagram of the generator control and measurement of voltage and current.



3. Experimental results

3.1 Generator prototype

For the generator prototype, one board with control circuits and a half-bridge topology was designed, which is shown in Fig. 4. The same board was used for both, the DC-DC converter and the power stage. For the power stage, one additional board with two anti-serial connected transistors was used to create the 3-level topology. Block diagram of the generator connection is shown in Fig. 5. In Tab. 1, there are parameters of the constructed generator prototype.



Fig. 4 Prototype board with control circuits and half-bridge topology.



Fig. 5 Generator connection block diagram.

Input voltage	320 V	
Symmetrical output V _{pp}	300 V – 1200 V	
Max output power	500 W	
Output frequency	15 kHz – 100 kHz	
Duty cycle	2 % - 98 %	
Operational mode	Continuous / Burst	

Tab. 1 Generator prototype parameters.

3.2 Generator testing

Before the whole generator was constructed, the DC-DC converter was tested independently with a symmetrical resistive load, which was connected between the positive and negative output. The converter was tested with different frequencies and voltages up to 600 V for both poles. In Fig. 6, example waveforms of the DC-DC converter for $V_{pp} = 1200 \text{ V}$, $f_s = 50 \text{ kHz}$, and $R_z = 2.5 \text{ k}\Omega$ are shown, where yellow is the primary side voltage, blue is the primary side current, and green is the converter positive output voltage.



Fig. 6 DC-DC converter example waveforms, $V_o = 600$ V, $f_s = 50$ kHz, $R_Z = 2.5$ k Ω .

The constructed generator was tested with different types of loads, mainly resistive and piezoelectric. Waveforms from testing with a resistive load of 1.8 k Ω and output values $V_o = 600$ V, $f_s = 50$ kHz, and D = 0.45 are shown in Fig. 7, where yellow is the load voltage, blue is the current of the load and green is the output voltage of the DC-DC converter.

The main use of the generator was to test and drive different types of sonotrodes on their dominant resonant frequency. For impedance matching, a coil with multiple windings and different inductance values was connected in series with the sonotrode. To prevent saturation, a core with an adjustable air gap was used. In Fig. 8, there are waveforms on the connected sonotrode on its resonant frequency, where yellow is the voltage on the sonotrode, blue is the current of the sonotrode, green is the positive output voltage of the DC-DC converter, and pink is the current drained from the converter. Generator parameters were set to $V_o = 600$ V, $f_s = 21.5$ kHz, and D = 0.25.



Fig. 7 Resistive load, $V_o = 600$ V, fs = 50 kHz, D = 0.45, Rz = 1.8 k Ω .



Fig. 8 Piezoelectric load, $V_0 = 600 \text{ V}$, $f_s = 21.5 \text{ kHz}$, D = 0.25.

4. Conclusion

In this paper, the design of a digitally programmable symmetrical pulse generator prototype was described. The generator consists of a DC-DC converter and a 3-level power stage. The DC-DC converter is designed with an adjusted half-bridge topology, using SiC transistors and rectifying diodes. This topology makes it possible to generate symmetrical positive and negative voltage using only one transformer. Furthermore, both output poles are active during each switching cycle, reducing output voltage ripple. Converter can run with set parameters, or with realtime PID regulation. Output V_{pp} can be set between 300 V and 1200 V. The generator power stage is designed with a 3-level T-type topology, which makes it possible to switch positive, negative, and zero voltage to the connected load. The power stage can operate in continuous or burst mode with an adjustable number of pulses. Output parameters like

switching frequency, duty cycle, or maximum voltage and current values can also be set.

The generator was tested mainly with resistive and piezoelectric load, with different output frequencies, voltages up to 1200 V_{pp} , and power up to 500 W, in continuous and burst modes. Example waveforms of DC-DC converter and power stage output were shown. The generator is fully functional and can be used for many different applications.

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Real–Time Data Capture with TI mmWave Radars

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Abstract.

In recent years, the popularity of robots and autonomous driving vehicles has steadily increased. One of the fundamental needs of such applications is the information about the robot's surroundings (obstacles, walls, other robots, etc.) and its location. Among the most common sensors for Simultaneous Localization And Mapping (SLAM) are LiDAR and various types of cameras. The Frequency Modulated Continuous Wave (FMCW) millimeter wave radar is an emerging sensor in this field thanks to its ability to function in vision-denied environments, where optical sensors fail. One of the most popular platforms is the Texas Instruments (TI) AWR/IWR device family. Although supplementary tools and hardware to facilitate the development of radar processing algorithms are offered, as of the author's current knowledge, no tool that provides access to real-time data is currently provided. In this paper, methods of capturing the radar data are described, and modifications to the current tools are proposed. The modified tools are tested and verified.

Keywords

AWR1642BOOST, radar, mmWave, FMCW, DCA1000EVM, real-time data capture, raw ADC capture, UART, Ethernet.

1. Introduction

The mmWave Frequency Modulated Continuous Wave (FMCW) radar has become one the ubiqitous sensors with broad range of applications across industries. Some of the main applications include Advanced Driver–Assistance Systems (ADAS), traffic monitoring, pedestrian detection, vital signs recognitions (breathing, heart rate monitoring, blood pressure detection, etc.), human posture and gesture recognition, surface sensing and material classification, object detection and tracking in robotic systems and many more [1]. Thanks to its ability to function in all–weather situations, unfavorable lighting conditions, or vision–denied environments, it has become one of the emerging sensor in the field of environment sensing applications.

One of the few wide-spread platforms used to develop radar applications are the evaluation kits from Texas Instruments (TI) [1]. Authors of [2] proposed a realtime obstacle-detection system for autonomous unmanned aerial systems (UAS). The system was based on the AWR1843BOOST evaluation board and the ZED 2 stereoscopic camera. Bansal et al. [3] introduce a novel concept of Cross Potential Point Clouds to solve the problem of noise and sparsity in radar point clouds by using the spatial diversity of multiple radars. Their platform was equipped with two IWR1443BOOST radars, a 16 channel Ouster LiDAR and an Intel RealSense D415 Camera. Kwon et al. [4] propose a method for performing SLAM in indoor environments using only radar as the sole sensor. A cascaded array of four AWR2243 radar chips was used with the antennas spanning in both horizontal and vertical directions.

One of the features that facilitates the development of such systems is the possibility to evaluate the proposed methods on a personal computer (PC) prior to embedding the algorithms into the radar's firmware. Such approach enables easier debugging, tuning and visualiation of the processed data. Although TI offers accompanying hardware and software for data capture, it does not officially support real-time data processing on the host PC. Since most systems require the measurements in real time for decision making processes (eg. steering, braking, path planning, etc.), there is a need for such a feature. The aim of this work is to modify the currently available tools to provide the user with the option for real-time processing. Two methods for alternative data capture are presented and verified.

2. Data structure

The basic structure used in radar processing is called the radar cube. The term refers to the organization of radar data from one radar frame. It represents the space-time snapshot of the scene observed by the radar. It is composed of multiple sampled chirps that are organized by the time they were received and by the antenna that received them. The upper part of the Figure 1 depicts one of the possible data arrangements. Rows represent the individual chirps (the chirp is retransmitted multiple times within one frame), columns contain the Analog-to-Digital Converter (ADC) samples of the chirps and the third dimension represents the receiving antennas. Common way of processing the cube is to apply the Fast Fourier Transform (FFT) to extract the range, velocity and bearing information about the targets (lower part of Figure 1). These transformations are often called Range FFT, Doppler FFT and Angle FFT. Each slice across the antenna dimension of the processed radar cube is called the range–Doppler heat map that contains the information about the speed and range of the targets. This heat map is often used to separate targets in the range/velocity domain by using various detection methods such as variants of the Constant False Alarm Rate (CFAR) algorithm.



Fig. 1. Raw and transformed radar cube

3. Official methods

3.1. Using the dedicated data capture card

The official method to acquire unprocessed ADC data is to use the DCA1000EVM data capture card. It connects to the radar evaluation board, captures the data generated by the radar and sends it to the host PC over a gigabit ethernet connection using the User Datagram Protocol (UDP). To interface with this card, TI offers the mmWave studio software. This program enables the user to set up the desired chirp profile, timing and to start/end the capturing process. Although the data is captured from UDP packets that are streamed from the capture card in real-time, the software stores the data to a file for offline analysis. Another disadvantage is that the mmWave studio application is available only for Windows PCs.

3.2. Data capture without the dedicated capture card

The support for capturing data without the DCA1000EVM capture card is rather limited. The only supported tool (as of the author's current knowledge) is the mmWave visualizer application that communicates with the radar running the out–of–the–box demo application. The captured data is sent via the Universal Serial Bus (USB) interface, where virtual serial ports are created by the board. However, the data available from the demo application is preprocessed by the radar itself. The raw ADC data is unavailable as well as the radar cube.

4. The alternative approach

4.1. DCA1000EVM CLI tools

Apart from the aforementioned mmWave studio program, standalone Command Line Interface (CLI) tools for configuring and starting/stopping the capture process can be utilized. As these tools are used by the mmWave studio itself for data capture, they exhibit the same disadvantage of storing the data to a file for offline processing. However, the source code is provided, enabling the compilation and usage even for Linux–based systems. The general usage of the tools is depicted in Figure 2. The goal is to modify the code to provide the real–time data for the user while preserving the full functionality of the original program.



Fig. 2. Alternative approach CLI tool capture procedure

4.2. CLI tools modification

There are two programs that run the configuration and data capturing process: DCA1000EVM_CLI_Config and DCA1000EVM_CLI_Record. These programs implement the communication and configuration between the host PC and the data capture card via network sockets. There is an additional RF_API.dll (RF_API.so on Linux systems) library that contains functions for sending and receiving the UDP packets.

If the user intercepts the UDP stream by creating a listener on the host system prior to the execution of the CLI programs, the tools will not receive any packets and will issue a timeout error since the packets would be taken by the user application. To prevent this behaviour, an extra communication socket must be created to retransmit the captured data on a UDP port specified by the user. Since the creation of these sockects is hard–coded into the source code, the following modifications must be made.

First, additional socket was created and configured with the user-specified UDP port in the rf_api.cpp file (port number 5010 was chosen). Next, the code that handles the packet reception (located in recorddatarecv.cpp) was extended to retransmit the incoming packets using the new user socket.

Figure 3 explains the functional diagram of the modified tools. The capture card is connected to the radar via the Low–Voltage Differential Signalling (LVDS) interface that handles the ADC data transfer between the card and the radar. The DCA1000EVM is configured via UDP on the 4096 port and sends the raw ADC data on the 4098 port to the host computer. The incoming packets are processed by the CLI tools and retransmitted to the host on the 5010 port. The radar is configured and started via the serial interface by the host computer (see the third step in the Figure 2).



Fig. 3. Functional diagram of the modified data capturing tools

4.3. UART data capture

The evaluation board features a Universal Asynchronous Receiver–Transmitter (UART) connection that is used to flash the firmware image to the radar, transfer the configuration and even to provide some low–throughput data access. Although it was not the intended purpose of this interface to be used to transfer the radar cube, it can be achieved with certain limitations that will be discussed next. It is important to note that this approach is intended for debugging use only and is not intended as a replacement for utilizing the capture card.

The core of this approach is the mmWave demo application, which is meant to show the basic preprocessed data to the user via a web interface or a standalone visualizer app. It provides the user with a subset of processed data, such as a range-Doppler heat map, range profile, detected targets, etc. Nonetheless, the whole radar cube is unavailable. This is due to the fact that the hard–coded (in the radar's firmware) UART baud rate of 921 600 is not sufficient to transfer the radar cube within the inter–frame period (discussed later). Since the source code of the mmWave demo is available in the Software Development Kit (SDK), it can be altered to provide the radar cube.

The first of the necessary changes is to alter the UART baud rate. An empirical value of 1115200 baud was selected, although the AWR/IWR devices may support larger values. Specifically, the value that controls the UART baud rate is gMmwMssMCB.cfg.loggingBaudRate that is set up in the mas_main.c. The maximum supported baud rate is specified in the device's datasheet and technical reference manuals. For example, the maximum baud rate for the AWR18xx/16xx/14xx/68xx family is 3.125 Mbps [5].

Next, it is necessary to alter one of the Type Length Value (TLV) structures that are sent via UART to the host PC from the radar. By changing the payload length and the address of the data to be sent in the dss_main.c file, the data stored in the shared L3 memory containing the radar cube can be sent.

Since most of the data structures sent by the mmWave demo application are derived from the radar cube, almost any of the structures can be modified without losing data. It is important to note that the radar cube obtained this way does not consist of raw ADC samples but rather individual range profiles. These profiles are calculated by applying range FFT to the ADC data. This calculation is programmed into the demo's firmware and the result is stored in the L3 memory. If raw ADC samples were desired, further changes would have to be made.

Finally, the configuration of the radar must be adjusted so the radar has enough time between frames to send the whole radar cube. The frame period limit of the firmware is 1333 milliseconds, which is enough to transfer a radar cube with 256 samples per chirp, 2 Tx antennas, 4 Rx antennas (8 virtual antennas in total) and 16 chirp repetitions. Other configurations may be possible, however the wole radar cube collected from one frame must fit into the 768 KB L3 memory.

5. Results

For demonstating the output of the modified CLI tools, a script in MATLAB was created to start the capuring process, configure the radar via UART and set up a UDP listener. The configuration mentioned in section 4.3 was used with the frame periodicity set to 100 milliseconds. The data received by the user-defined UDP port was compared with the file recorded by the tools yielding identical results. The raw ADC data from both channels (I, Q) are plotted in the Figure 4. Figure 5 depicts the range–Doppler heat map that was calculated by summing the power spectra across all virtual antennas. This map is sometimes called the detection matrix, because detection algoritms can be applied to this matrix to detect targets in the range–Doppler domain. Figure 6 shows the range–angle heat map for static targets.



Fig. 4. Raw ADC data of a single chirp (16-bit, unscaled)



Fig. 5. Range–Doppler heat map for static scene

6. Conclusion

This article summarizes the available methods for capturing data from AWR/IWR mmWave radar evaluation boards from TI and provides insight how to extend the functionality of available tools to facilitate development of algorithms that depend on the radar data. A cross–platform



Fig. 6. Range-angle heat map for static targets

method for real-time data capture was presented as well as the method for capturing data without the captue card. The methods presented were tested and verified.

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Transnational Flows of Innovation: The Importation of Hydro-Electric Machinery from Paris to Mexico by Barcelonette Entrepreneurs (1890-1910)

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Abstract. This paper examines a historical file from the Archivo Histórico del Agua (AHA) in Mexico City, which documents the importation of hydroelectric machinery from Paris to Mexico at the beginning of the 20th century. The machinery was sent by the French company Société l'Éclairage Électrique and managed by entrepreneurs of Barcelonnette origin. The study explores how transnational networks of trade, technology, and migration played role in shaping Mexico's early hydroelectric infrastructure. Through the detailed translation of original documents written in French, this research reconstructs the economic, technical, and cultural dynamics behind the process. Findings reveal how technical innovation was embedded in a global context of technology transfer while addressing local challenges posed by Mexico's landscape and economy.

Keywords

History of Technology, Industrial heritage, Technical innovation, Hydroelectricity, Late 19th century, Early 20th century, Mexico, Transnational Flows, Barcelonnette's.

1. Introduction

Early 20th century was a critical period in Mexico as it due the government politics sought to modernize its infrastructure and integrate technological innovations into its industrial and urban development. Among these innovations, hydroelectric power played its part, being for the time an efficient source of energy to modernize and develop industry and urban infrastructure. This paper investigates a case of technology transfer in Mexico City by analyzing historical files from the Historical water Archive (AHA) that details the importation of hydroelectric machinery from Paris, facilitated by Mexican entrepreneurs of French origin. This community, also known as *Barcelonnette's*¹, in Mexico were primarily recognized for their success in commercial and textile ventures and acted as cultural and economic intermediaries between Europe and Mexico. Foreign companies, and in this case those from France, played a crucial role in providing technical expertise and equipment. Among them, *Société l'Éclairage Électrique (SLE)* supplied machinery, facilitating the electrification of industrial sites. The Barcelonnette's, a community of French entrepreneurs, acted as intermediaries, integrating electrical technology into Mexico's economic landscape.

Their involvement in this project illustrates the interplay between migration, transnational trade, and technological exchange, within the broader global context of electrification and hydroelectric technology development, investing in this development at the same time as first word countries.

1.1 Theoretical Framework and Methodology

Electrification was in the late 19th and early 20th centuries was not an autonomous process, but one that depended in great measure of the technology imports, knowledge and foreign capital. This phenomenon is called technology transfer, which happens when a country adopts, adapts and develops innovations from another context. In this case, the electrical machinery came from the French company Société l'Éclairage Électrique, which shows how foreign companies played a crucial role in the modernization of Mexico's energy infrastructure. Therefore, the importation of turbines, generators and electrical systems not only represented a technical change, but also influenced the way business and industry were organized in Mexico. Thus, the theoretical framework is

¹ A group of French immigrants from what today is the Alpes de Haute Provence in France.

based on business history, technology transfer and the role of migrant networks in industrialization.

The electrification process in Mexico aligns with broader studies on technological transfer and industrial heritage [1,2]. This research draws on historical technology analysis [3] to examine how imported hydroelectric technology was adapted to local economic and geographical conditions. The role of immigrant entrepreneurs, particularly the Barcelonnettes, is framed within studies on transnational business networks and their impact on industrial modernization.

This research is based on archival analysis of historical documents from AHA, focusing on machinery importation for a hydroelectric plant. Primary sources include procurement records, technical descriptions, and correspondence related to SLE. Secondary sources provide context on the role of Barcelonnettes in Mexico's electrification. The study employs a qualitative approach, integrating bibliographic review with technical analysis of imported equipment to assess its impact on industrial modernization.

2. Historical and Technological Context

2.1 The Expansion of Electricity in Mexico and the Barcelonnette diaspora

The introduction of electricity in Mexico during the Porfiriato² (1876-1911) marked a significant shift towards modernization and industrialization. The State played a central role in this process, facilitating technological transfer through policies such as tax exemptions for machinery imports and construction materials, encouraging industrial development and attracting foreign investment. The government expanded infrastructure by granting concessions for the exploitation of mineral and water resources, which were crucial for electricity production. With the Law for the Promotion of New Industries (1873) and the modification of the Mining Code (1884), private investment in various industries, including textiles, was further incentivized. These measures not only reinforced Mexico's industrial economy but also accelerated the adoption of foreign technologies, transforming the country's productive landscape [4].

Hydroelectric plants, in particular, were a very curious introduction, emerging as a component of this transformation due to the country's water resources [5]. In the beginning of this process, the small hydroelectric plants were essential for early electrification, especially in areas distant from major industrial centers. These plants supplied power to mines, factories and small communities, marking the first steps toward decentralized energy distribution. Many of these projects were financed by local entrepreneurs who relied on foreign technical expertise, highlighting the necessity of financial resources and access to advanced European technology.

Among the most influential business communities in this period were the Barcelonnettes, a group of entrepreneurs from France who established a strong commercial and industrial presence in Mexico throughout the 19th century. Primarily engaged in the textile trade, they founded major department stores such as *Las Fábricas de Francia, El Puerto de Liverpool, and La Ciudad de Londres,* integrating their supply chains from production to retail [6]. By pooling capital and modernizing old factories or establishing new ones, they successfully imported and implemented European technologies, reinforcing their dominance in the textile industry.

The Barcelonnettes' migration was driven by economic crises in their native region and the attractive opportunities presented by Mexico's protected textile industry. Their business networks, built on trust and familial connections, allowed them to navigate the local and international markets effectively. Through strong ties with both French and Mexican entrepreneurs, as well as legal and financial intermediaries, they reached the electricity sector, constructing hydroelectric plants such as *Los Dínamos*³ on the *Magdalena River* to power their textile factories and supply electricity to nearby communities.

Within this group the company to highlight as being the one who ordered the purchase of the technology for the first power plant to generate hydroelectric power from the SLE, was *Meyran, Donnadieu y Cía*, owner of the factories *Santa Teresa, La Magdalena* and a clothing store named "*La Francia Marítima*" [7].

2.2 Société l'Éclairage Électrique

Founded in Paris in 1887 by industrialist Hippolyte Fontaine, *Société l'Éclairage Électrique* quickly established itself as one of the companies in the production of electrical equipment and systems. Specializing in the manufacture of electric motors, dynamos, alternators, and measuring devices, it provided comprehensive solutions for electrification. The company not only was stablished in the French market but also expanded its influence internationally, exporting electrical machinery [8].

² *Porfiriato* is the period when Mexico was under the dictatorship of General Porfirio Díaz, which began in 1876, after a coup d'état, and ended in 1911, with the Mexican Revolution.

³ Set of 4 small hydroelectric plants that were used to supply energy to the textile factories. Each one is called according to its position first, second, third and fourth Dinamo.

As a joint-stock company, it had a capital of 6,000,000 francs. Its administrative offices were located at 27, Rue de Rome, near Gare Saint-Lazare, in the 8th district of Paris, while its construction workshops were situated at 364, Rue Lecourbe, near Gare Grenelle-Ceinture [9].

In this context of international influence, the collaboration between SLE and those of Barcelonnette origin, like Meyran Donnadieu owner of the company with the same name, evidences the interconnection between European capital and Mexican industrial modernization. The Barcelonnette diaspora, active in sectors such as textiles and commerce, facilitated the importation of French technology into the country, ensuring that Mexican factories and in this case, the future hydroelectric plant were equipped with state-of-the-art technology.

In 1918, the *Compagnie Française pour l'Exploitation des Procédés Thomson-Houston* (CFTH) acquired SLE, marking a new phase in the French electrical industry [10]. This integration was led by Lazare Lévi [11], who later became Director General of CFTH, in a context of industrial consolidation during the first half of the 20th century. Through its innovations and collaborations, SLE left a significant mark on the modernization of electrical infrastructure, both in France and abroad, contributing decisively to the global expansion of electrification [12].

2.3 Comparison with Other Cases in Latin America

Making a brief comparison with another example in Latin America, the expansion of hydroelectric power, in Mexico and Colombia followed similar patterns, driven by private entrepreneurs rather than state initiatives in the late 19th and early 20th centuries. In Colombia, the early electrification process was led by local business elites who leveraged their international connections to import the necessary technology and expertise. The Cali N°1 hydroelectric plant, built in 1910 by private entrepreneurs, exemplifies this trend. With a capacity of 50 KW, it used water from the Cali River to drive a Pelton turbine, example of demonstrating an early small-scale hydroelectric power for local industry and infrastructure development. Although in this case, they imported the machinery from North America instead of Europe. This case closely resembles our own, Los Dinamos hydroelectric plants in Mexico, where Barcelonnette entrepreneurs imported European electrical equipment to power their textile factories, reinforcing the role of private investment in early electrification [13].

These cases illustrate how, in different regions, the electrification process was initially shaped by private initiatives and international technology transfer, highlighting the global nature of hydroelectric development and industrial modernization.

3. Analysis of the AHA File

3.1 About the content of the file and Insights from Translation

The analyzed file contains a range of documents, including invoices, correspondence, and contractual agreements, offering a view of the logistical, financial, and technical aspects involved. Notably, the correspondence reveals the negotiations between the company in Mexico was *Meyran, Donnadieu y Cia* and SLE, highlighting the transnational nature of the project.

The translation of the French documents provided insights into the specifics of the machine. For example, detailed descriptions of the equipment's components. Additionally, the financial terms revealed the substantial investment made by Meyran Donnadieu, of 28.460 francs, underscoring their commitment to develop their industry, and by so advancing Mexico's hydroelectric capacity and infrastructure.

OCIÉTÉ "L'ÉCLAIRAGE ÉLECTRIQUE" ienne Sociele Generale d'Electricite 2 .

Fig. 1. Notice of dispatch from SLE to Meyran Donnadieu. [19]

3.2 Imported Electrical Equipment and Its Functions

The analyzed archival documents describe various specialized equipment for generation, distribution, and control used in the hydroelectric plant.

- a. **Excitation and field rheostats:** In the case of a hydroelectric plant, they were used to control the excitation of the electric generators, i.e., the amount of current supplied to the generator coils to produce electricity in a stable manner.
- b. Three-pole circuit breakers: High-capacity switches designed to interrupt electrical currents, in this case, the documents mention circuit breakers with abrupt cut-off, designed to interrupt currents up to 900 amperes and 440 volts, guaranteeing safety and avoiding overloads.
- c. Three-pole and voltmeter switches: Commutators allowed electricity to be routed to different circuits according to operating needs. The voltmeter switch, in particular, facilitated the

measurement of voltage in different phases of the system.

- d. **Ammeters, and voltmeters:** These measuring instruments were essential for monitoring the performance of the electrical system. The ammeter measured the amount of electric current in amperes, while the voltmeter indicated the voltage level.
- e. **Marble distribution panels:** The bases where the electrical equipment was mounted were made of marble due to its insulating properties, which reduced the risk of short circuits and improved the safety of the system.



Fig. 2. Marble distribution panel of the SLE. [20]

- The Main Motor and Its Performance: One of f. the key components in the hydroelectric plant was the motor converting mechanical energy into electricity. According to the documents: It was a three-phase asynchronous motor, Labour system, coupled to a Pelton wheel, operating at 400 volts and 60 Hz. which means it operated on a threephase alternating current system, an industrystandard configuration for its efficiency and ability to maintain a stable power supply. The engine was rated at 300 horsepower (HP) but could reach up to 345 HP in periods of up to 12 hours. Finally, the efficiency of the motor was 91%, indicating that it lost only 9% of its energy in the form of heat or other mechanical losses.
- g. **Safety and Maintenance Elements:** To ensure continuous and safe operation, various protective mechanisms were implemented:
 - Adjustable tension system: Allowed real-time belt tension modifications, preventing premature wear.

- **Foundation and support plates:** The machinery was installed on foundation bases and metal plates to ensure stability and reduce harmful vibrations.
- **Insulated cables and connection terminals:** The use of insulating materials in the electrical connections prevented short circuits and improved the safety of the installation.



Fig. 3. Dynamo F. Labour of the SLE and the interior of the « First Dinamo ». [21]

4. Discussion

4.1 Logistical and Technical Challenges

Transporting hydroelectric machinery from France to Mexico posed significant challenges. The machinery's weight and size required meticulous planning for its shipment across the Atlantic and subsequent transportation to the plant's remote location. So far it took over a year to send this machinery overseas, the machinery purchased by Meyran Donnadieu y Cía entered Mexico in 1907 through Tampico customs, described by Soberón Mora [14]. Among the imported equipment was an electric alternator with a capacity of 600 kW, accompanied by 2,400 meters of piping, reflecting the scale and sophistication of the infrastructure implemented. This transaction not only highlights the role of European companies in the electrification of Mexico but also shows how transnational business networks facilitated the arrival of technical innovations in the country. Unfortunately, there is no record of the travel of the merchandise from Tampico to its final destination in the Magdalena River, in the capital of Mexico.

4.2 Geographical Context and Influence on Design

The geographical conditions of the site where the hydroelectric plant will be implemented, influenced technological choices and infrastructure design. The plant was built in a mountainous region in the southern part of Mexico City, with variable river flows. The rugged topography favored the use of turbines like Pelton, which efficiently harnessed energy from high waterfalls.

The *Magdalena River*, with its flow ranging from 215.55 to 400 liters per second [15], provided a reliable water source for hydroelectric generation. Its steep altitudinal gradient, from 3,870 to 2,570 masl⁴ [16], created natural conditions ideal for channeling and accelerating the river's flow. The location of the plant was strategically determined by these characteristics, with plants positioned on irregular slopes where water velocity was highest, maximizing hydraulic power. This adaptation to the landscape, as noted in the 1895 feasibility report by engineer José Covarrubias [17], ensured efficient electricity generation by concentrating the river's steep gradient into specific points for optimal energy conversion.

The location of this first power plant lies within the lower part of the middle section of the river, where the terrain is less irregular compared to the higher areas. The other three plants were subsequently established in the upper sections of the river, where the steeper gradients provided even greater hydraulic power.

4.3 Technology Transfer and Local Adaptation

The approach of this, the first hydroelectric plant on the *Magdalena River*, was very remarkable, because it was the starting point for the installation of three other small plants that, like this one, were linked to the interchange and technology transfer initiated by the *barcelonnettes* in the south of Mexico City.

This case exemplifies the complex dynamics of technology transfer. While the hydroelectric machinery originated in France, its successful implementation depended on its adaptation to Mexico's local conditions. The Barcelonnette entrepreneurs played a crucial role in mediating this process, leveraging their transnational networks to bridge the gap between European innovation and Mexican application.

Engineers trained in France, such as Gabriel Desrameaux applied European hydroelectric principles to the specific conditions of the Magdalena River, adapting turbine technology and hydraulic infrastructure to optimize energy generation in a challenging topography [18]. The implementation of Pelton turbines, designed for high head and low flow conditions, along with an advanced electrical transmission system, highlights how imported innovations

were reinterpreted to meet the demands of Mexico's industrial modernization.

4.4 Socioeconomic Impact

The planning of the hydroelectric plant provided a reliable energy source that supported industrial activities and improved living standards in the region. Additionally, the project generated employment opportunities, fostering local economic growth and strengthening regional infrastructure. Beyond its direct economic benefits, the plant also contributed to the social transformation of the area by attracting workers and their families, leading to the formation of new communities around industrial centers. The integration of these settlements into national economic circuits, facilitated by new transportation and communication networks, further reinforced the role of hydroelectric development as a driver of regional modernization.

4.5 Heritage and Innovation

Beyond its technical and economic significance, this case highlights the importance of recognizing hydroelectric plants as part of Mexico's industrial heritage. The integration of European technology into the Mexican landscape reflects a historical moment of innovation that continues to resonate in contemporary discussions on sustainability and heritage preservation.

Beyond its technical and economic significance, this plants, *Los Dinamos* represents an important chapter in Mexico's industrial heritage. The integration of European technology within the local landscape underscores a period of transformative innovation that shaped the country's modernization. Today, this legacy remains relevant in discussions on sustainability and heritage preservation, as these hydroelectric plants serve as tangible reminders of the adaptive ingenuity that continues to inform contemporary energy solutions.

5. Conclusions

The study of archival records provides insights into the early development of Mexico's hydroelectric infrastructure and the role of foreign technology in industrial modernization. Allows us to better understand the processes of technology transfer in the electrification of different regions. The importation of machinery was crucial, but its success depended on the ability to adapt to local conditions and the long-term vision to integrate hydropower into industrial development.

Moreover, this analysis provides a valuable insight into the processes of technological transfer, industrial modernization, and the role of transnational business networks in early 20th-century Mexico. The importation of electrical equipment from *Éclairage Électrique*, facilitated by the Barcelonnette entrepreneurs, illustrates how foreign expertise and capital contributed to the development of the

⁴ Meters above sea level (*masl*).

country's energy infrastructure. This case exemplifies how technology was not simply adopted but adapted to local geographical and economic conditions, ensuring its functionality and long-term impact.

The participation of immigrant entrepreneurs in this process underscores the importance of transnational networks in facilitating industrial progress, as they acted as cultural and economic intermediaries between Europe and Mexico.

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Energy and War: The Triano Hydroelectric Power Plant as a Strategic Infrastructure in the German Rear Lines in Italy (1939-1944)

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Abstract: This study examines the role of the Triano Hydroelectric Power Plant (Chieti, Abruzzo, Italy) in the context of World War II, focusing on its strategic significance within the German defensive lines of Gustav (1943) and Caesar (1944). It analyzes the interconnection between energy infrastructure, military logistics, and economic self-sufficiency, highlighting the impact of hydroelectric power plants on wartime operations. The research explores the technical and architectural aspects of the power plant, including its camouflage, underground structures, and defensive measures designed to minimize the risk of destruction. Furthermore, it investigates the broader economic and geopolitical context, particularly the autarkic policies of Fascist Italy and its efforts to achieve energy selfsufficiency through hydroelectric development. The findings demonstrate that the Triano Power Plant was not only a key energy hub but also an integral part of the German military defense strategy. The damage sustained during the 1944 combat operations and the subsequent post-war reconstruction underscore its significance both during the conflict and in the regional recovery efforts.

Keyword

Technical History, Hydroelectric, Gustav Line, Caesar Line, Hydroelectricity, Military logistics, World War II, Military camouflage, Warfare, Abruzzo.

1. Introduction

The liberation of Italy during World War II unfolded through a series of military operations, in which the Allied forces advanced along the peninsula, progressively overcoming the central German defensive lines, including the Gustav Line (1943) [1] and the Caesar Line (1944). These strategic barriers, built to slow down the Allied advance, were part of a broader total war context, in which industrial and energy infrastructures played a crucial role..

In this scenario, the autarkic policies of the Fascist regime, initiated in the 1930s to reduce Italy's dependence on coal imports and other resources, led to an intense expansion of hydroelectric production to support industry and wartime supply chains. This expansion contributed to the resilience of Italy's economic and industrial system during the conflict. [2] This study explores the role of hydroelectric energy within the framework of the war in Italy, with a particular focus on the strategic dynamics related to German defensive lines and the wartime camouflage of energy infrastructures. Through the analysis of concealment and protection strategies for hydroelectric plants, this research highlights the interconnection between warfare, energy policy, and territorial defense, emphasizing the delicate balance between productive needs and military vulnerability during a crucial moment in Italian history.

1.1 Theoretical Framework and Methodology

The research aims to interdisciplinarily examine the role of energy infrastructures, military strategy, and economic resilience through three key theoretical perspectives.

- a) The theory of war and infrastructure highlights the role of hydroelectric power plants as critical strategic assets, integrated into the German defensive lines, such as the Gustav Line and the Caesar Line. Their protection, camouflage, or sabotage directly influenced military tactical operations and escape strategies.
- b) Autarkic economic policies and resource mobilization provide a key framework for understanding the Fascist regime's push for hydroelectric expansion in the 1930s. This initiative aimed to reduce dependence on imported coal and ensure energy self-sufficiency to support industry and the war effort.

c) Energy security and wartime adaptation examine how Italy managed and defended its hydroelectric infrastructures under the pressures of the conflict, ensuring the continuity of energy production despite strategic bombings and the shifting frontlines. By integrating these perspectives, our study explores the relationship between energy policies, defensive strategies, and industrial continuity within the context of wartime Italy.

2. Historical and Economical context

The development of hydropower in Italy was strongly influenced by Fascist autarchy, with a gradual decline in demand for thermoelectric power [3], which encouraged its expansion to reduce dependence on imported foreign coal in favor of domestic coal. During World War II, these facilities became strategic both for industrial production and as military targets. The wartime context conditioned their use, leading to design measures for protection, concealment, and exploitation.

2.1 Historical context: defense lines in Abruzzo and Lazio for the defense of the capital city

Between 1943 and 1944, central Italy became the main theater of war between German and Allied forces advancing from the south. After the landing in Sicily and the fall of Mussolini in July 1943, the Wehrmacht, under the command of Field Marshal Albert Kesselring, reorganized its defensive strategy along the peninsula to slow the Allied advance toward Rome. The German defense was structured in a series of fortified lines, affecting the current regions of Abruzzo, Lazio, Molise and Campania considered central to the defense of the capital.

The Gustav Line, the best known and most solid of these defensive lines and fortifications, ran through central Italy from Ortona on the Adriatic to the mouth of the Garigliano on the Tyrrhenian Sea. Beyond an evocative description by Shepperd in *La campagna d'Italia (1943-1945)*, in a biography of German Field Marshal Kesselring, one senses a very careful study of the territory that enabled the Allied advance to be effectively impeded for a considerable period. [4]

Its hold was crucial for the Germans until the spring of 1944, when, after months of battles, including the devastating Cassino campaign, the Allies succeeded in breaking through the line. At the same time, Kesselring ordered the construction of new lines of resistance further north, including the Caesar Line, which represented the last major barrier before the direct defense of Rome [5]. Latium, in particular, was at the center of German resistance until the liberation of Rome on June 4-5, 1944. This context of total war also profoundly influenced the use and protection of energy and industrial infrastructure not only in a wartime context but also in a defensive line rear context. Strategic infrastructure, in fact, became wartime targets and of tactical interest to both sides.

2.2 Economic context: the hydroelectric and Mechanical industries as pillars of autarky

In the 1920s, Fascist Italy identified the hydropower sector as a strategic pillar for sustaining national industry, placing it within a broader framework of autarkic planning of the economy. Within a few years, the expansion of hydropower became a boast for the regime and an international vanguard in the country's industrial modernization in the face of growing energy demand. The exploitation of water resources was the main lever for the expansion and energy supply of strategic industries, reducing dependence on imported coal, still essential for other sectors of the war industry. This sector experienced strong expansion thanks to public and private investment with the construction of new power plants and the expansion of existing ones [6].

With the onset of World War II, hydropower and mechanical engineering became even more strategic sectors, both to support the war effort and to ensure industrial continuity amid increasing economic isolation. The expansion of the hydroelectric sector in this second phase was to be considered more costly because most of the exploitable sites had already been used [7]. For this reason, new areas and watersheds were considered and with new structural techniques. However, by 1943, with the German occupation and the Allied advance, many of these infrastructures were militarized, bombed, or sabotaged, marking a phase of crisis and forced reorganization of national industry.

3. Regional context: War, hydrography and the Aterno - Pescara basin

3.1 Hydrography and Exploitation of Water Resources in Abruzzo 1910-1943

The central Italian region has a distinctive geomorphological conformation, with a central Apennine ridge from which numerous watercourses originate. Thus, the regional hydrographic system follows an Apennine course toward the sea with short, parallel rivers that descend rapidly from the mountain ranges toward the Tyrrhenian and Adriatic coasts.

One of the most relevant elements is the peculiarity of the Aterno-Pescara catchment area of the Abruzzo region. This arrangement favored, between 1920 and 1943, an increasing exploitation of water resources for industrial and hydroelectric purposes, thanks to the availability of water and the favorable morphology: the Aterno River, in fact, has its source further north and crosses longitudinally the Apennine ridge to flow into the Pescara River, allowing it to increase its flow rate and be more exploitable from an energy point of view. Near Popoli (PE), the Aterno River merges with the Pescara River, contributing to the formation of a large drainage basin. Unlike the Aterno, the Pescara River follows a transversal course, crossing Abruzzo from west to east, until it reaches its mouth in the Adriatic Sea near the city of Pescara.

This distinctive L-shaped formation has made the Aterno-Pescara basin one of the primary water resources in the region, serving both irrigation and hydroelectric energy production.

3.2 Hydrography and the Wartime Rear-Area Context

The Gustav Line and the entire rear-area territory extending to the Caesar Line represent a quintessential example of how territorial morphology influenced the design of military defenses. Hydrography, in particular, played a crucial role in shaping advancement routes and defensive lines, with rivers and waterways serving as natural barriers that were difficult to cross and easily defensible. These elements, combined with the mountainous terrain of the Central Apennines, forced troops to converge into narrow passageways, making them vulnerable to preestablished defensive positions. Additionally, coastal areas and major rivers functioned as strategic supply routes, creating an interconnection between rear bases and key frontline positions. A meticulous study of the territory was therefore essential for the construction of the Gustav Line, demonstrating how the natural environment could be leveraged both as an obstacle to enemy advances and as a logistical support element for defensive forces.



The Allied advance near the Gustav Line between October 1943 and May 1944 [8]

3.3 The Hydroelectric Power Plants of the Pescara River

Currently, the Aterno-Pescara drainage basin hosts 21 hydroelectric power plants, which have been in operation

since the 1910s. [9] Excluding the power plants of the entire basin, this research specifically focuses on the hydroelectric power plants along the Pescara River, distributed across its four hydroelectric production drops. Particular attention is given to the last facility built, which employed special camouflage techniques. The Pescara River, running along the Caesar defensive line, served as the first rear-area barrier of the Gustav Line:

- a) Tocco da Casauria Power Plant 1° Drop of the Pescara River (1907-1910)
- b) BolognanoPower Plant 2° Drop of the Pescara River (1912)
- c) Alanno Power Plant 3° Drop of the Pescara River (1930)
- d) Triano Power Plant 4° Drop of the Pescara River (1942)

The designer of the works was engineer Ulisse Del Buono, one of the most esteemed technicians of the period, who also served as president of the Italian Electrotechnical Association between 1921 and 1923 [10]. In 1920, the association opened an Adriatic Section in Pescara, highlighting the central role that the area was gaining in the development of the electrical sector. Del Buono also designed the third and fourth hydroelectric drops of the Pescara River, shaping a comprehensive vision for the utilization of the watercourse, from its sources to just a few kilometers from its mouth.

This project was considered highly significant, with a production capacity of approximately 600 million kWh per year. It became a key element in the evolution of the region's energy system, driven by the growing energy demand from the electrochemical industry and civil sector.

Archival research reveals that all the structures were either destroyed or damaged, suffering partial or total destruction during the military operations related to the liberation of Italy in 1944 [11]. In particular, the facilities located between the Gustav Line and the Caesar Line, in the regions of Abruzzo, Lazio, Molise, and Campania, became the scene of intense conflicts, which severely compromised the functionality of minor reservoirs, dams, power plants, and pipelines.

The reconstruction of these infrastructures, documented through footage from the Enel Archive, was carried out through continuous efforts, allowing for the restoration of the power plants' operations by 1947, just three years after the end of hostilities.

By the end of June 1944, Abruzzo had lost 600 million kWh per year and a power capacity of 130,000 horsepower due to the destruction of the hydroelectric drops along the Pescara River.



The Destruction of the Power Plants Along the Pescara River- 1944 [12]

4. Analysis of the Triano Power Plant and Techniques of Protection and Camouflage

4.1 Design, Design Evolution, and Inauguration

The Triano Hydroelectric Power Plant, located in Chieti Scalo, in the San Martino area along the Pescara River, is a run-of-river facility that began operation in 1942. The plant was originally owned by SME (Società Meridionale Elettricità), and historical records indicate that TERNI provided supplies for the construction of the 4th hydroelectric drop of the Pescara River and the Triano power plant. This documentation, dated 1937, places the construction of the plant within a transitional period for Italian industry. By the 1930s, Italy had already embarked on a general rearmament and implemented autarkic economic policies. However, it was only after May 22, 1939, with the signing of the Pact of Steel between Fascist Italy and Nazi Germany, that the industrial sector experienced further acceleration towards war mobilization.

Around 1930, the third power plant on the Pescara River (third hydroelectric drop) began operation, with its energy being fully utilized by SME in the Naples area for

industrial, civil, and railway traction purposes. As a result, the third hydroelectric drop was allocated to the industrial sector of the Campania region. Later, in 1942, SME activated the fourth power plant on the Pescara River, whose energy was intended to supply the large industrial district of Chieti, particularly CELDIT Cellulosa d'Italia, whose industrial production soon came to a halt due to railway sabotage. The location of this cellulose industrial plant was also chosen due to the presence of the Triano power plant. which was only a few kilometers away. Regarding the war industry, as early as 1931-1932, the Fascist regime had developed a modernization and expansion plan with SME for the first and second hydroelectric drops of the Pescara River. The objective was to power military production facilities - including mustard gas, arsine, choking agents, and nitroglycerin - either already installed or in the process of being set up in Bussi by the Montecatini company [13]. n December 1942, the SME company submitted plans to the Pescara Civil Engineering Office for a 150 kW power line, extending 10 km to the transformation substation of the Società Unione Servizi Elettrici di Pescara.

Thus, the Triano hydroelectric power plant was designed to serve the industrial sectors of Abruzzo, the Pescara-Chieti urban area, and the Adriatic coastal belt.

The following are the phases:

- 1) In 1932, SME consolidated its energy strategy in Abruzzo, initiating, in collaboration with the government, a plan for the extraregional use of the fourth hydroelectric plant.
- 2) Between 1935 and 1936, the final design of the power plant was defined, intended to support the industrial hub of Bari.
- 3) Located near the CELDIT plant, the new power plant was designed to generate approximately 150 million kWh per year. In accordance with the established timeline, in the summer of 1942, SME officially inaugurated the fourth Pescara power plant, located in Triano, a district of San Martino, marking a significant step forward in the energy and industrial development of the region and completing the grand project for the exploitation of the Pescara river.

4.2 Structural characteristics

The derivation of the fourth hydroelectric drop extends for 16 km through an underground tunnel, continuing into an elevated channel upstream of the hydroelectric power plant, before flowing into dissipators and re-entering a tunnel until it reaches the downstream section near the power station road.

The Triano power plant, built during the wartime period, is a run-of-river facility with turbines housed in an underground cavern. The site is located just a few kilometers from the mouth of the Pescara.

Near the alternators, there is now a semi-underground open-air facility, with separated sections within a tunnel, a design solution adopted for strategic camouflage purposes. This feature is documented in archival footage. All connection cables between the alternators and the exterior are housed in underground tunnels, while access to the turbine hall, located approximately 25 meters below the alternator level, is provided via an elevator. The connection between the turbines and the three alternators is achieved through a tubular shaft. After use, the water is channeled back into a tunnel, discharged into a canal, and then released into the river.

To ensure the camouflage of the facility, a pine forest was planted on the alternator level and along the cable tunnels, serving as a strategic measure to reduce the visibility of the power plant from aerial reconnaissance and enemy patrols. Additionally, the layout of the underground tunnels was designed with security and concealment criteria, addressing the wartime requirements of the period. In summary:

a) **Underground structure**: The turbines are located 25 meters deep relative to the alternator level. The underground structure provided effective protection against aerial attacks, while also reducing visibility for territorial reconnaissance by Allied forces.

b) **Gallery Cable and Camouflage:** The tunnel structure is divided into separate underground sections to ensure the protection of primary cables and reduce direct exposure. The first section, closest to the facility, consists of a buried arched tunnel, designed to provide maximum security and insulation. Subsequently, the tunnel continues into a second section, configured as a partially buried and open channel, allowing for a controlled transition of the cables to the exterior.

c) **Operational Security**: Dedicated tunnels for personnel movement and primary cable burial ensure operational continuity and protection from external attacks. A dedicated escape tunnel is preceded by a reinforced autonomous shelter area, equipped with sanitary facilities, a bunk, and a kitchen, capable of accommodating on-duty personnel. The escape route, approximately 30 meters long, extends through a tunnel leading to open countryside.

d) **Displacement**: The facility is still dislocated today, making it difficult to fully understand its layout, including canalization, intake waters, and the electrical park. It is highly likely that the post-war reconstruction did not alter the original plant design.

4) **Camouflage**: Environmental and strategic, through the presence of an artificial pine forest and Mediterranean vegetation to reduce aerial visibility, the use of surface camouflage to conceal the electrical park, and a dislocated design planned to integrate with the territory and avoid detection by aerial reconnaissance.

5. Consideration and conclusions

In 1944, the landscape between Chieti and Pescara, downstream, was sparsely populated, with few scattered

houses and limited infrastructure. Among these, there was the railway line, interrupted in 1943, and the Cellulosa d'Italia (CELDIT) factory, one of the few industrial hubs in the area. In this context, the need to complete the hydroelectric exploitation of the Pescara River took on a strategic significance, not only from an energy perspective but also within a period marked by political and economic instability, as well as specific wartime needs.

The hydroelectric power plant, located along the Pescara River, was tasked with ensuring the supply of electricity in a semi-flat area, just a few kilometers from the coast. Its location was considered crucial for the eastern defensive line, in an area strategic for both military infrastructure and the industrial system.

It is known that Triano is the only power plant among the four hydroelectric drops to have a structure clearly oriented towards wartime protection, ensuring operational continuity during the war. During the two days of bombing that hit the hydroelectric infrastructures in the area, both the power plants and the dams were put out of service, but there are no precise data regarding the extent of the damage.

A landscape analysis is necessary to integrate these camouflage, protection, and concealment techniques, which help to give meaning to the structural choices of the plant..

As previously mentioned, the four hydroelectric drops of the Pescara River, along with the related reservoirs, dams, and pipelines, suffered damage during the Allied advance. Despite this, it took three years to fully restore the hydroelectric system, and we do not know for certain whether the original designs were completely restored or if they underwent significant modifications. However, it is likely that the Triano power plant maintained much of its original structures, as it still retains the camouflage and underground solutions designed for wartime protection.

In a particularly significant note, Engineer Masturzo cites over 400 million lire in damages to the infrastructures, but this figure does not allow us to fully understand the exact extent of the damages sustained by each plant or how much was actually recovered. [14]

The Triano Hydroelectric Power Plant was blown up during a transition period between the retreat of German forces and the advance of Allied troops. A historical document, found in a report by Angelo Meloni, describes the bombings day by day, and on June 4, 1944, it reports:

June 1944

Thursday, 1st – Bombing and air strafing on the roads in the outskirts.

Tuesday, 6th – The German ammunition depots in the Chieti area were blown up, along with the **power plant** and two sawmills in Chieti Scalo. The movement of the retreating German columns toward the north intensifies.

Wednesday, 7th – The Germans blew up bridges and roads around the city and the Chieti aqueduct.

Thursday, 8th – 4:00 PM: The German commander of the area, the Prefect, and the Republican Federal Secretary, along with the Republican military command, leave the city permanently. 11:00 PM: The Germans blew up the last remaining bridges and withdrew the rear guard units from the Province of Chieti.

Friday, 9th – 7:00 PM: A patrol of the Corpo Italiano di Liberazione enters Chieti, after overpowering a small group of saboteurs who were delayed in the city.

Saturday, 10th – Units from the Italian Nembo Division, the San Marco Battalion, and Indian troops enter Chieti. Anglo-American officers assume control of the city. A large demonstration takes place in front of the Episcopal Palace, with the Archbishop and the General Commander of the Nembo Division present. [15]

A few days earlier, the CELDIT industrial complex was also bombed, and exceptional historical photographs are available. The use of the term "saltare" (to blow up) leads us to believe that mines were likely used to sabotage the plant during the retreat towards the defensive lines beyond the Caesar Line, and that the hasty succession of events did not completely destroy the the facilities.

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Industrial Health Heritage: The Mountain Sanatorium Village in Sondalo, Italy

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Abstract. This paper presents the progress of thesis research within the framework of the Erasmus Mundus Joint Master in Techniques, Heritage, Territories of Industry (EMJM TPTI). While the thesis is based on a comparative study of the two largest mountain sanatoriums in the Americas (the 'Santa María', in Córdoba, Argentina) and Europe (the Sanatorium Village in Sondalo, Italy), this paper focuses exclusively on the latter.

By proposing the concept of 'industrial health heritage' as a new category within industrial heritage, this research underscores the historical and technological significance of the sanatorium, deeply linked to industrialisation in its origins and design. Therefore, it explores its key industrial health features —civil engineering works, integrated design, and service infrastructure— that demonstrate its relevance as an industrial heritage site.

At a more advanced stage of the research, the study will examine the mechanisms necessary to justify its recognition as part of industrial heritage and assess how this recognition could contribute to its preservation and adaptative reuse, offering a sustainable future for this partially abandoned site.

Keywords

Industralisation, industrial heritage, industrial health heritage, mountain sanatorium village, historical healthcare infrastructure, adaptive reuse, sustainable patrimonialisation.

1. Introduction

1.1 Presentation of the Topic and the Relevance of its Selection

The agreed definition of industrial heritage stated on The Nizhny Tagil Charter [1] includes the most representative examples which characterize this type of heritage, as well as those sites related to industry in which social activities are developed, such as housing, religious cult or education. However, it is important to note that the field of health —the essential human activity that supports all these activities mentioned— is not represented in the definition. This activity can be represented through public works infrastructures that constituted a systemic and organizational structure designed to provide a key public service that was crucial for the proper functioning of society and its economy.

In that sense, mountain sanatorium villages exemplify how medicine, industry, and technique converged into a complex and self-sufficient machine à guérir [2], with the aim of healing the vast number of tuberculosis victims whom industrialization had dispersed worldwide. To fulfil this purpose, these sanatoriums incorporated distinctive industrial features that were vital for guaranteeing their autonomy and effectiveness in the treatment of the disease, since the contagious nature of tuberculosis required them to be located away from populated areas and in mountain environments that provided a beneficial climate for healing. Some examples of these industrial features include power stations for electrical supply; x-ray machinery and photographic laboratories; boilers; ventilation and cooling systems; washing and disinfecting machines; kitchens and industrial ovens; labs; dams and aqueducts for water supply; sewage and water purification systems; access bridges; exclusive train stops and Decauville rails inside the sanatorium; cable cars; telegraphic systems of communication, and more, all working together as a whole.

These authentic healing cities, which share several characteristics with 'company towns', open up the possibility of rethinking what we consider industrial heritage. Despite their historical importance, they have been ignored in the academic discourse on industrial heritage. Therefore, this research aims to fill this gap by introducing an original concept: the 'industrial health heritage'. This new category broadens the traditional scope of industrial heritage to include those sites related to the health industry, places that have played a crucial role in the history and evolution of hygienism, medicine, technology and health care over time, with the mountain sanatorium village typology as its most representative example. To date, no comprehensive study has examined this dimension of industrial heritage, making this approach a pioneering contribution to the field. Recognizing these places as an integral part of industrial heritage is essential for their proper valorisation and preservation.

1.2 Historical Context

Tuberculosis, also known since the 19th century as the 'white plague', is an ancient disease that has afflicted humanity for at least 9,000 years, with traces found in Egyptian mummies and prehistoric skeletal remains. Its most common and contagious form, the pulmonary phthisis, affects the lungs and is easily transmitted through the air. Considered an epidemic at various points in history, it reached its peak between the 19th and 20th centuries as a direct consequence of the Industrial Revolution, establishing itself as a global disease.

According to Cotterau, during the 19th century, the 'hygienic-dietary treatment' emerged within bourgeois society to combat tuberculosis. This treatment involved a radical transformation of the living conditions of the industrial and urban environments: exposure to sunlight and fresh mountain air, far from cities and their polluted atmosphere, complemented by a healthy diet and strict rest cures without physical activity. This treatment gradually became a variation of bourgeois rest, although its widespread application to workers remained impracticable [3, p. 194 - 195].

Although national health statistics confirmed that tuberculosis was a disease of the working class far more than a disease of the bourgeoisie, states found themselves facing a contradiction. Together with the enterprises, they wanted to maximize labour efficiency by increasing the duration and intensity of work to boost production in response to market pressures; while the working class opposed the intensification of labour and demanded a reduction in working hours [3, p. 196]. The success of the business model was directly proportional to the worsening and spread of the disease among workers in their productive years, a situation that led to the state control systems to become the main promoters of the fight against tuberculosis. Unfortunately, this ended up prioritizing their own interests over the wellbeing of workers.

The rest therapy, fundamental to treatment process, was incompatible with the dominant social relations, since diagnosing the disease as a problem of 'work-related exhaustion' meant recognising the negative effects of labour on health. This would have reinforced the workers' demand for the legitimacy of rest as a preventive or therapeutic measure, something that production systems were unwilling to accept. Consequently, official diagnoses took another direction: tuberculosis began to be attributed to the lack of hygiene in housing, factories, and in the urban environment [3, p. 197], thus hiding the most important cause. These conditions, combined with mass migrations to cities, unhealthiness, overcrowding, pollution, and poverty, make

up what we now recognize as the classic consequences of the Industrial Revolution. Thus, the responsibility for the disease was largely transferred onto the workers themselves due to their precarious living conditions, further reinforcing the link between tuberculosis and poverty.

The discovery of Mycobacterium tuberculosis by German physician and microbiologist Robert Koch in 1882 confirmed the bacterial origin of the disease, consolidating its infectious nature and transforming the medical paradigm. This finding, together with industrial progress and the growing demand for labour, led the ruling classes to implement control mechanisms over the body and the health of the population [4]. Consequently, between the late 19th and early 20th centuries, governments implemented prevention and sanitary control strategies to combat tuberculosis, with the construction of mountain sanatoriums standing out as one of the main initiatives. In these establishments, the 'hygienic-dietary treatment' found the appropriate context for its systematic and controlled implementation, becoming the main pillar in the fight against the disease. Italy was no exception to these processes, building its own mountain sanatoriums as a key part of its efforts to combat the epidemic, since tuberculosis -along with malaria— was the country's most significant public health issue.

1.3 Case Study: The Villaggio Sanatoriale di Sondalo, Italy

Sondalo, a small town in northern Italy (Province of Sondrio, Lombardy region), lies at an altitude of 940 m a.s.l. within the Alta Valtellina valley, at the foot of the Western Rhaetian Alps. Crossed by the River Adda and far from the big cities, it benefited from the purity of its air and climate. Thanks to these favourable conditions, the town gained a strong reputation as a centre for tuberculosis treatment following the establishment of three sanatoriums in the area¹. Building on this legacy, between 1932 and 1940, the Italian fascist government undertook the construction of what would become the largest sanatorium in Europe: the Villaggio Sanatoriale di Sondalo (later renamed Villaggio Sanatoriale 'Eugenio Morelli'2 and, since 1973, known as Ospedale Eugenio Morelli di Sondalo). Although the facility was completed in 1940, it did not become operational until 1946, following the conclusion of World War II.

The Villaggio Sanatoriale was part of a national plan to build a network of more than 60 sanatoriums across Italy. The project was conceived and coordinated by the Ufficio Costruzioni Sanatoriali of the INFPS (Istituto Nazionale Fascista della Previdenza Sociale), based in Rome, under the direction of engineer Raffaello Mattiangeli, with the collaboration and supervision of Professor Eugenio Morelli in the functional and clinical aspects. The construction work was entrusted to the Daniele Castiglioni company from

¹ The sanatoriums of *Pineta di Sortenna* (1903) —the first Italian sanatorium— designed by architect Giuseppe Ramponi, along with *Abetina* (1927) and *Vallesana* (1929), both designed by engineer Filippo Orsatti.

² In honour of the Valtellinese phthisiologist Eugenio Morelli, who in 1928 assumed the direction of Italy's first Chair of Phthisiology and promoted the creation of the *Villaggio Sanatoriale di Sondalo*.

Milan, while the construction manager was engineer Tullio Petech, appointed by the INFPS. Although the author of the architectural design of the project remains uncertain, it has been hypothesised that it may have been the Roman architect and engineer Mario Loreti, a professor of Design at the Faculty of Architecture in Rome [5, p. 28].

The *Villaggio Sanatoriale* was, for its time and location, one of the largest public works at the national and international level, in which 1,400 workers and technicians worked on their construction, staffed by 1,500 employees and with a capacity of 2,500 beds for the patients, bringing the total number of beds to about 4,000 [6] (Fig. 1).



Fig. 1. Aerial view of the Villaggio Sanatoriale di Sondalo, old postcard, 1950s, Foto Vera.

2. Conceptual Framework

2.1 Problem Statement

The growing demand for labour in the midst of industrial progress and the scientific advancements in medicine converged in two key moments: in 1921, with the invention of the prophylactic BCG vaccine (Bacillus Calmette-Guérin) by the Pasteur Institute in France; and in 1943 with the creation of the antibiotic streptomycin by scientist Albert Schatz in the USA. The vaccine was not sufficient to achieve mass prevention due to the immunological particularities of the disease, but it is still administered today to prevent severe forms of tuberculosis in children. Streptomycin, on the other hand, became the most effective curative treatment and was adopted worldwide from the 50s onwards [3, p. 193]. This forced the sanatoriums to reinvent themselves to treat other pathologies and thus remain in operation, but those which did not achieve it went into abandonment. The result was a deep change in the economic and social network of communities that were born around the mountain sanatoriums, which went into a deep depression due to the sudden end of their source of employment.

In the late 70s, as tuberculosis was brought under control in Italy, four of the complex's eight inpatient pavilions of the *Villagio Sanatoriale di Sondalo* were closed and later abandoned. The surgical pavilion, an emblematic example of purely rationalist architecture (Fig. 2), now functions as a regional hospital, while the remaining four cure pavilions and the service facilities buildings are only partially operational.

The owner of the former sanatorium, the *Azienda Socio-Sanitaria Territoriale Valtellina e Alto Lario*, has undertaken maintenance work to prevent the rapid deterioration of the pavilions. These efforts include installing external storm drains, closing all the lower openings to prevent vandals from entering, and keeping the surrounding vegetation under control (Fig. 3).

Additionally, in 2015, it established the *Museo dei* Sanatori di Sondalo in the former reception office —where tuberculosis patients once arrived for their admission to the sanatorium—, making it the first site museum in Europe dedicated to the history of sanatorium-based treatment for tuberculosis. The museum preserves and exhibits the tangible heritage of the former sanatorium, linked to the industrial advances of medicine (medical instruments) and valuable documents such as architectonical plans and photos (Fig. 4).

Despite these positive aspects, they remain as fragmented initiatives that fail to consider the sanatorium complex as a cohesive entity. Its complexity, the vastness of its scale, its location far away from urbanized areas, not to mention the forgetting policies which it has gone through as a result of tuberculosis being stigmatized, put its cultural and surrounding natural heritage at risk, making it necessary to implement urgent actions to help ensure its proper conservation and reuse.

In that sense, its recognition as 'industrial health heritage', together with a refunctionalisation plan, could lay the foundation for a sustainable patrimonialisation process with a territorial approach —a contemporary thought promoted in the The Nizhny Tagil Charter (section 5.V [1]), further reinforced by the Agenda 2030 for Sustainable Development (goal 11, target 11.4 [7]) and the Journées Européennes du Patrimoine 2022 - Patrimoine Durable [8]—, allowing its preservation while ensuring its reintegration with the territory.



Fig. 2. View of the main facade of the Surgical Pavilion, old postcard, 1950s, Foto Vera.



Fig. 3. Current state and preventive works in the inpatient pavilion VI, 2024, Francisco I. Griotto.



Fig. 4. Overview of the *Museo dei Sanatori* and its collection, 2024, Francisco I. Griotto.

2.2 State of Research

As already discussed, the *Villaggio Sanatoriale di Sondalo* is set within an orphaned and unique landscape, structured by abandoned pavilions of high heritage value. However, it suffers from the absence of public policies capable of granting the complex a new use. As a result, the site is deteriorating, subjected to vandalism, and even used as a setting for urbex explorations. Yet, it holds an immense potential for reuse, demonstrating that, through a sustainable patrimonialisation strategy with a territorial approach, the site could be preserved, repurposed, and valued as a meaningful asset for contemporary society.

This contemporary thought, included in Journees Europeennes du Patrimoine 2022 - Patrimoine Durable [8], states that the built and natural heritage could also contribute to achieve a more sustainable future, as when already existing buildings are intervened instead of building new ones (by recycling) by means of techniques, skills and traditional materials and, at the same time, showing its impact on the preservation of local identities and promoting a further appraisal towards natural heritage. In this sense, a paper called Valoriser le patrimoine climatique: la reconversion des sanatoriums de cure antituberculeuse [9] written by French architect Philippe Grandvoinnet, turns out to be relevant as it shows us the qualities and current challenges which are confronted by European mountain sanatorium villages. It also provides some approach methodologies at the moment of designing a project to reconvert by means of real cases of rehabilitation. As a result, this reveals the relevance of adopting a strategic approach taking into consideration the natural heritage which surrounds them (and which was its origin), specifically from the point of view of the climatic heritage, understood as a kick-off for the local development, a new source of attraction which articulates a built heritage and an environmental quality. This sets forth the need to value healing heritage on the basis of a territorial project based on the three cornerstones of sustainable development (environment, economic and social), to which a fourth can be added: the culture.

However, considering a reconversion project which helps to preserve a heritage site as important as the Villaggio Sanatoriale di Sondalo, entails a deep reflection on the renewed uses it could host. French architect Eugène Violletle-Duc said that 'the best way to preserve a building is to find a use for it'. However, setting in motion a renewed use that does not stand the load capacity of the heritage site could end up by destroying it instead of preserving it. According to Emilie Pascal and Julien Kostrzewa, authors of the article Patrimoine de la santé: vers une méthode de reconversion pour des sites historiques d'envergure urbaine [10], a new use would be necessary to preserve the 'spirit of the place' and keep a temporal continuity with its history. This article turns out to be relevant as it shows the current trends in France, some methodological aspects when designing reconversion over health heritage and possible urban strategies which help to bring back to urban life all these sites which were created to be self-sufficient. Along that same line of the problem of refurbishment, Anne Pétillot and Georges Fessy mention in their book Patrimoine hospitalier [11] these same questions: what should be done with a quality heritage which no longer complies with its end? Should it be reconverted for public use? Should it be launched again to the market? Should it be demolished? This book is a relevant reference as it positions healing institutions heritage as a source of current renewed interest thanks to its quality and history, and its strong symbolic meaning which makes us go one step further of the nostalgic remembrance to demonstrate that it already is a privileged participant in the modern world.

On the other hand, since the concept of 'industrial health heritage' is a novel category that has not yet been the subject of prior studies, this research aims to define and justify its relevance through representative examples beyond the case of the Villaggio Sanatoriale di Sondalo. One such example, which opens the door to future research in this field, is the old wastewater treatment plant in Prague: built with the purpose of minimizing the risk of waterborne diseases, it incorporated pioneering technical innovations of its time to achieve the highest possible level of water decontamination. Other remarkable examples are the 'Baths and Washhouses for the Labouring Classes' of Manchester, England, built in the 19th century to improve the physical and moral condition of the urban-industrial population [12]; and the rotating solariums designed by the French physician Jean Saidman and developed by the Aix-les-Bains Solarium jointstock company, which consisted of innovative mechanical structures designed for the treatment of tuberculosis by heliotherapy (Fig. 5). In this regard, all these examples share similarities with the sanatorium, as they were originally

designed to improve health and combat disease through *avant-garde* infrastructure and technology.



Fig. 5. On the left, the rotating solarium of Aix-les-Bains, closeup of an old postcard, circa 1940, Aix-les-Bains Municipal Archives. On the right, patent plans for a revolving solarium, 1929, Saidmann Archive.

2.3 Research Question

In what way can the *Villaggio Sanatoriale di Sondalo* in Italy be considered part of industrial heritage, and how could their recognition contribute to initiate a sustainable patrimonialisation process?

3. Objectives & Hypothesis

General Objective: To identify the necessary mechanisms to justify the inclusion of the *Villaggio Sanatoriale di Sondalo* in Italy as part of industrial heritage, and to analyse how its recognition as such could contribute to initiate a sustainable patrimonialisation process.

Specific Objectives:

- To analyse how industrialisation processes influenced the construction of mountain sanatoriums in Italy between the 19th and 20th centuries.
- To define and justify the concept of 'industrial health heritage' by identifying pioneering infrastructures related to disease prevention and treatment.
- To identify the industrial features (architectural, technological, and urban elements) that characterise the *Villaggio Sanatoriale di Sondalo* as a representative case of 'industrial health heritage'.
- To compare refunctionalisation and conservation strategies implemented in similar former sanatoriums, identifying best practices that could serve as a model for the sustainable reuse of the *Villaggio Sanatoriale di Sondalo*.
- To investigate the availability and viability of legal instruments in Italy and Europe for classifying the sanatorium under a heritage category (e.g. national/provincial monument, cultural interest site, ERIH anchor point, or UNESCO World Heritage Site), and to evaluate the impact of such possible recognition.
- To propose guidelines for the sustainable patrimonialisation of the sanatorium, ensuring its integration within the territory and its functionality for contemporary society.

Hypothesis:

- **H. No. 1:** The *Villaggio Sanatoriale di Sondalo* can be considered part of industrial heritage, specifically within the category of 'industrial health heritage', due to their close connection with industrialisation processes, both in their origins and in their architectural, technological, and urban configuration.
- **H. No. 2:** Recognising it under the 'industrial health heritage' category would not only contribute to their preservation and valorisation but could also promote sustainable reuse strategies, ensuring their integration with the territory and their functionality for contemporary society.

4. Methodological Approach

This research follows a mixed-method approach, combining historical-documentary analysis with case studies and legal instruments research.

The study will begin with historical analysis of industrialisation processes that influenced the construction of mountain sanatoriums in Italy, using direct and indirect documentary sources. It will then apply comparative and conceptual analysis to define the category of 'industrial health heritage' through representative examples and the identification of key industrial features of the sanatorium (presented in section No. 5 below).

A case study approach will examine conservation and refunctionalisation strategies in similar institutions, identifying best practices. Additionally, a legal analysis will evaluate the viability of heritage recognition of the sanatorium at national and international levels (ERIH, UNESCO).

Finally, the research will propose guidelines for sustainable patrimonialisation, with the aim of integrating the abandoned sanatorium facilities into society through an adaptive reuse, while promoting the recognition of the 'industrial health heritage' in the cultural heritage policies.

5. Industrial Features of the *Villaggio Sanatoriale di Sondalo*

The industrial features that define the sanatorium as a true case of 'industrial health heritage' can be grouped into three technical categories: civil engineering works, integrated design, and service infrastructure.

5.1 Civil Engineering Works

Road Engineering

The construction of the sanatorium required monumental civil engineering works to adapt the steep mountain terrain into a functional site. As Castiglione notes [13], the project involved the excavation and stabilization of the mountainside to provide access across the complex through a 6.2 km network of sinuous roads, supported by viaducts and monumental retaining walls of concrete and stone with closed arcades, ensuring structural stability while allowing for circulation (Fig. 6). Also, a tunnel was excavated through the mountain at the entrance of the sanatorium to facilitate access.

To overcome the mountain's steep slope, this road system was laid out in a zigzag pattern, reducing the slope by extending the length of the path and making it flatter. The interstitial spaces created by this layout provided stable horizontal planes for the construction of the pavilions, overcoming the constraints of the rugged topography. These spaces were also utilised to develop gardens and a vast terraced park, directly referencing a traditional method used in this mountainous region of Valtellina: terraced viticulture with dry-stone walls, also known as 'heroic viticulture'.



Fig. 6. On the left, construction of the fourth viaduct leading to the third pavilion, 1934, private photographic archive Giani-Castiglioni. On the right, walls containing the terraces, 1940, Archivio Storico Ospedale Morelli.

Water Distribution System

The available water resources in the area surrounding the sanatorium proved insufficient to meet its needs. After a search, the appropriate water source was identified in the locality of Le Gande, in the Rezzalo Valley, approximately 6 km in a straight line from the sanatorium, crossing the mighty Adda River.

It was then decided to build an aqueduct, designed and supervised by engineer Saverio Quadrio, in a record time of one year. This aqueduct was a fundamental work for the life of the sanatorium and a remarkable feat of engineering. From the intake point, the water was conducted to a collection chamber at 1,650 m a.s.l. (Fig. 7), before beginning a 7,802 m journey to the sanatorium's reservoir at 1,207 m a.s.l. through a seamless steel pipeline with a diameter of 200 mm, buried at a depth of 150 cm, and with a flow rate of 50 L/s, of which 15 were allocated to the municipality of Sondalo [14, p. 273].

The route had to avoid the natural obstacles of the mountainous terrain, cross a stream, traverse a state road, and pass under the Adda River. At this point, the lowest along the path, the aqueduct had descended 750 m and then had to rise another 457 m to reach the sanatorium's reservoir, located at the highest point. To achieve this, a 70 m-long tunnel was built in concrete and covered with dry

stone, descending at a 45° angle beneath the riverbank [15, p. 678 - 679]. This solution allowed the natural landscape to remain undisturbed, as would not have been the case if an elevated aqueduct had been constructed (Fig. 7-8).

The final section of the aqueduct led to two large reserve tanks with a capacity of 1,800 m³ [16, p. 310], which, according to Del Curto [14, p. 273], ensured an autonomy of two days when the sanatorium was at full occupancy. Furthermore, this author notes that the aqueduct also supplied an irrigation system with 80 hydrants to water the sanatorium's park.



Fig. 7. On the left, collection chamber at Le Gande, 1938; on the right, construction works on the tunnel under the Adda River, Luisa Bonesio archive.



Fig. 8. Longitudinal section of the tunnel under the Adda River, Archivio Storico Ospedale Morelli [13].

5.2 Integrated Design

Passive Solar Mechanism

The veranda di cura (a covered outdoor gallery, obligatorily oriented towards the south or southwest, where patients received the 'air cure' treatment in absolute repose) is the most important and characteristic functional element of sanatoriums that defined their morphology. Generally designed in a curved or angular shape at the ends to reduce wind impact, the sanatoriums of the Modern Movement began to prioritise a rectilinear morphology that ensured unobstructed visual surveillance (necessary for the disciplining of the patients), a typological decision that was applied to the *Villaggio Sanatoriale di Sondalo*.

One of the most innovative aspects of the *Villaggio*, as in other sanatoriums built by the INFPS, was the incorporation of a mechanical and mobile system of horizontal enclosure and vertical shading —designed in close collaboration with Prof. E. Morelli— to respond in an original and practical way to the functional needs of the 'air cure' treatment.

During the winter months, when adverse weather conditions made the treatment difficult, the sliding doors of the rooms could be moved along metal rails installed on the floor and ceiling of the veranda. When opened, the doors followed a semi-curved trajectory until they aligned with the veranda's railing, thus transforming it into a glazed space protected from the weather and directly connected to the rooms. Additionally, the doors could be moved forward into the veranda until it was partitioned into modules of the same width as the rooms, which helped to mitigate the impact of lateral winds and reinforced the continuity between the room and the veranda [17] (Fig. 9).

In summer, the system also featured a vertical solar protection mechanism composed of wooden shutters that slid along metal guides flush with the façade. These shutters, acting as sunshades, made it possible to control the incidence of sunlight on the veranda, creating a shaded space that enabled the expansion of the rooms, increasing their usable surface (Fig. 10). However, the most distinctive feature of this mechanism was its ergonomic design, defined by the convex curvature of its guides, conceived to facilitate the comfortable passage of doctors and nurses during their rounds, preventing their arms from hitting against the shutters as they moved along the veranda (Fig. 11).



Fig. 9. On the left, construction detail of the sliding door system, circa 1937, private photographic archive Giani-Castiglioni.

Fig. 10. On the right, construction detail of the shutter system, circa 1937, private photographic archive Giani-Castiglioni.



Fig. 11. Patients doing the 'air cure' treatment on the veranda while being visited by the doctors and nurses, a scene that shows the perfect functionality of the space, frame from the documentary film 'Il sole splende per tutti', 1950, Archivio Storico Istituto Luce.

Heating System

During the 1930s, the heating system chosen by the INFPS for its sanatoriums and hospitals was infrared radiation through radiant slabs (called 'Crittall system', also used at the Faculty of Mechanical Engineering in Prague). This system consisted of placing steel coils within the slab formwork, through which superheated water constantly circulated —after finishing the slab— and met the technical and hygienic requirements of the time: relatively low and homogeneous average temperature, and the elimination of heating equipment that could obstruct the space.

According to Del Curto, citing Prestipino & Baroni, although the initially planned heating system for the Villaggio was by radiators, in 1938 it was decided to replace it in the rooms with a radiant heating system. Since the slabs were already built, the only available alternative was the installation of prefabricated ceiling-mounted radiant panels, fixed with screws and hooks. The panels were supplied with superheated water at 55°C with a pressure of 18 atm, coming from the complex's thermal power station [14, p. 274].

It is currently being investigated whether these radiant panels corresponded to the *Pannello Radiante Italiano*, Squassi patent, by engineer Francesco Squassi, a national product which had a lower installation cost and, unlike the 'Crittall system', was exempt from patent rights abroad [18] (Fig. 11).



Fig. 11. Section of the panello radiante italiano [17].

Innovative Materials

The use of innovative materials in the Villaggio is remarkable. The general service pavilion featured *ferrofinestra* openings and *Termolux* insulating glass, a system that had just entered the market at the time of the sanatorium's construction (Fig. 12). Developed and patented by the Italian company *Vetreria Italiana Balzaretti Modigliani* of Livorno, it consisted of two transparent glass panes enclosing an internal layer of glass wool (*vetroflex*), resulting in an opalescent glazing that filtered light and minimised heat loss [19, p. 114].

Furthermore, all facades were coated with *Intonaco Terranova*, a plaster made of lime, cement, sand, and natural pigments, providing both protection and decoration to the facades. Its granulated texture and high durability made it a common finish in institutional, industrial, and healthcare buildings, thanks to its durability, easy maintenance, and refined aesthetics (Fig. 13).



Fig. 12. View of the Termolux glazed facade of the general services pavilion, 2024, Francisco I. Griotto.



Fig. 13. On the left, a sample of Intonaco Terranova cladding on the facade of an inpatient pavilion of the sanatorium, 2024, Francisco I. Griotto.

On the right, advertising propaganda for Intonaco Terranova, 1937, 'L'architettura italiana' magazine.

5.3 Service Infrastructure

From the project's conception, the principle of functional zoning was adopted, centralising the heavier general services (thermal and electrical plant, incinerator, kitchen and laundry pavilion) in the left wing of the complex. Meanwhile, the medical services (inpatient pavilions and surgical pavilion) were strategically located throughout the complex, ensuring their full autonomy from a healthcare perspective [16, p. 305 - 306]. A detailed overview of the main features of these service systems is provided below:

General Services Pavilion

This building was the operational core of the complex, designed to centralise the essential logistical functions of all the complex. It consisted of a fully functional, rationaliststyle building with two sections. The main section, quadrangular and six storeys high (Fig. 14), was organised by function across different levels:

- 1. Ground floor: large storerooms and cellar.
- 2. First floor: central laundry equipped with washing machines, dryers, and large disinfection autoclaves (Fig. 15).
- 3. Second floor: central cloakroom, with a tailoring and ironing area.

- 4. Third floor: bakery workshop, with a flour storage area and an electric bread oven (Fig. 16).
- 5. Fourth floor: grocery storage, refrigeration units, and butchery.
- 6. Fifth floor: the large central kitchen, functioning as an authentic assembly line, divided into three main sectors responsible for preparing meals for specific groups of pavilions (Fig. 17).
- Sixth floor: staff accommodation at the rear and, at the front, a semi-covered technical area from which food and linen were distributed to each pavilion via a cableway system.

To ensure efficient logistics for staff movement and the transport of supplies and food, the pavilion was equipped with 28 small freight lifts with 200 kg capacity, a large 1000 kg elevator, a staircase core, and a four-person lift [14, p. 281]. The second section, elongated and adjacent to the main one, had seven storeys that housed the scientific and pharmaceutical laboratories; accommodations for employees, doctors, and nuns; as well as a telephone exchange managing 400 internal network lines (Fig. 18).



Fig. 14. Main section of the General Services Pavilion from the memorial square, 2024, Francisco I. Griotto.



Fig. 15. Disinfection room with autoclave machines in the background, n.d., courtesy of Giacomo Menini.



Fig. 16. View of the bakery workshop and its electric ovens, circa 1960, Laboratorio Fotografico dell'Ospedale di Sondalo.



Cucina centrale



Fig. 17. Above, floor plan of the general kitchen [16, p. 314]. Below, view of the general kitchen area running on superheated water, n.d., courtesy of Giacomo Menini.



Fig. 18. Switchboard of the telephone exchange room, frame from the documentary film 'II sole splende per tutti', 1950, Archivio Storico Istituto Luce.

Cable Car System

Continuing with the sanatorium's functional approach of separating logistical and medical functions to maximise hygiene and reduce air pollution from combustion vehicles [20, p. 189], a cable car system —'Jig-Back' type— was implemented to connect the General Services Pavilion with the nine pavilions by cargo gondolas that transported food and linen from the central kitchen and laundry (Fig. 19). Upon arrival at the terminal on each inpatient pavilion's rooftop, the goods were lowered by lifts, and the dirty linen was sent back to the laundry in the other gondola.

Designed and built by the Milan-based company Ceretti e Tanfani, the cable car system had nine steel gondolas with a capacity of 490 kg each, and lifting towers installed on the ground and on top of some pavilions (Fig. 20). It operated by means of a stationary steel cable and a continuously looping traction cable. Each terminal had a motorised drive pulley, safety switches, and an electromagnetic brake in case of power failure. Additionally, the control system was equipped with safety doors that prevented the motor from starting if they were open [15, p. 681]. However, the long journey from the General Services Pavilion to the dining areas in the inpatient pavilions caused meals to arrive either too cold or overheated. Therefore, before the sanatorium was put into full operation, small kitchens were installed in the inpatient pavilion, and the cable car system was restricted to transporting only linen and food supplies [15, p. 681] until the 1980s, when it was dismantled for safety reasons [21, p. 24], except for the machinery in the General Services Pavilion (Fig. 21).



Fig. 19. View of the cable car system in full operation from the General Services Pavilion, n.d., Funiforum.org.



Fig. 20. On the left, lifting tower on the ground, n.d., Funiforum.org.

Fig. 21. On the right, guided tour with schoolchildren on the technical terrace of the General Services Pavilion, where the machines of the system still rest, 2022, Facebook Museo dei Sanatori di Sondalo.

Backup Power Plant

According to Del Curto, citing Prestipino & Baroni, the complex's power supply was provided by the *Consorzio Idroelettrico Alta Valtellina* at a voltage of 23,000 V, which was reduced to 10,000 V and distributed by underground cables to five strategically located substations, which transformed the electricity to the service voltage needed to supply the various pavilions. But to ensure autonomy and continuity of supply, a backup power plant with two diesel engines was installed [14, p. 274] (Fig. 22), ensuring the operation of the central kitchen's electrical equipment in case of an external power supply failure [16, p. 310]. The engines had power ratings of 200 and 300 hp respectively.



Fig. 22. Architectural drawings of the backup power plant, n.d., Archivio Storico Ospedale Morelli, courtesy of Giacomo Menini.

Thermal Power Plant

The heating system of the sanatorium relied on a single thermal power plant, which heated water to 190 °C at a pressure of 12 atm [16, p. 310]. It was equipped with three boilers of 10 million Kcal/h each [22, p. 47], reaching an approximate power of 20 million Kcal/h [16, p. 310] (Fig. 23). The superheated water was then distributed through underground pipes to the various buildings, where heat exchangers redirected it to heating and sanitary installations, as well as generating steam for laundry, disinfection equipment, and other medical services [14, p. 274]. Due to the steep slopes of the terrain between the thermal power plant and the buildings, in some sections of the circuit, the operating pressure reached 30 atm, giving the system exceptional characteristics [16, p. 310].

The building is clad with Clinker bricks and, like the General Services Pavilion, has *ferro-finestra* openings and *Termolux* insulating glasses (Fig. 24).



Fig. 23. Interior views of the installations, n.d., courtesy of Giacomo Menini.



Fig. 24. Main facade of the thermal power plant, 2024, Francisco I. Griotto.

Utility Tunnels

The utilities network was planned in an integrated and *avant-garde* for its time. Perhaps due to the harsh winter climate of Sondalo or simply for the practicality of ensuring effective maintenance, the network was placed underground through arched concrete tunnels (Fig. 25).

The core of this underground infrastructure was the thermal power plant, from which primary tunnels branched into smaller secondary tunnels leading to the various buildings of the complex (Fig. 26). Accessibility for the maintenance of the utilities was ensured through access points located at every tunnel intersection.

The utility tunnels transported essential service lines, such as wastewater and greywater pipes (hidden in a technical space under the floor); pipes for garden irrigation, potable water, and hot water with thermal insulation; as well as electrical cables for high and low voltage, internal tunnel lighting, telephony, radio, and remote temperature monitoring [15, p. 680] (Fig. 27).

These underground passages, branching from the thermal power plant like veins from a heart, distributed energy and essential resources throughout the complex, ensuring its integrated operation and optimising resource distribution. Moreover, this system prevented visual pollution by eliminating the need for install distribution poles and overhead cabling, thus preserving the sanatorium's landscape quality.



Fig. 25. On the left, construction of the utility tunnel in front of the surgical pavilion, 1934, Archivio Storico Ospedale Morelli, courtesy of Giacomo Menini. On the right, a recent view of a utility tunnel from the inside, n.d., courtesy of Giacomo Menini.



Fig. 26. Planimetry of the total network of utility tunnels, n.d., Archivio Storico Ospedale Morelli, courtesy of Giacomo Menini.



Fig. 27. Technical section of the main and secondary utility tunnels, illustrating the types of utility networks they contain, n.d., Archivio Storico Ospedale Morelli, courtesy of Giacomo Menini.

Wastewater Treatment Plant

Like a city, the *Villaggio Sanatoriale* had to treat its wastewater in a hygienic and responsible way to prevent the spread of waterborne diseases. Therefore, a wastewater treatment plant was built on the outskirts of Sondalo, next to the Adda River, which was avant-garde for its time and remained in operation until only a few years ago (Fig. 28). The plant, as well as the sewer system of the sanatorium, was designed by S.I.A.F. (*Società Italiana per Acquedotti e Fognature*), based in Milan [15, p. 679] (Fig. 29).

Taking advantage of the natural 300-m slope from the sanatorium to the plant, the sewage system was connected to two main collectors that converged into a single conduit, which crossed the town of Sondalo before descending to the treatment plant [15, p. 679]. The treatment process included the following stages:

- 1. The wastewater passed through a bar screen and grit chamber.
- 2. It then entered to a preliminary sedimentation tank.
- 3. The resulting sludge was sent to a pumping station.
- 4. From there, it was transported to a sludge digester.
- 5. The sludge was then dried in an open-air drying bed.
- 6. Meanwhile, the liquid effluent from the preliminary sedimentation tank was directed to a dosing tank.
- 7. It then passed through two large enclosed and ventilated trickling filters, 11 metres in diameter, with a stone bed and rotating sprinklers.
- 8. The resulting liquid reached a final sedimentation tank.
- 9. Next, it was channelled into a disinfection tank, where it was treated with chlorine gas from a chlorinator device.
- 10. Finally, the treated water was discharged into the River Adda.

It is worth noting that the gas produced by the sludge digestion process was used to supply energy to the plant caretaker's house [20, p. 188], underlining the system's efficiency and sustainability. In addition, the plant's original documents contain extracts from technical manuals and publications of the time³, demonstrating the effort to equip the complex with the latest technology [15, p. 680].



Fig. 28. Recent photos of the plant, 2022, Giacomo Menini.



Fig. 29. General planimetry of the biological sewage treatment plant for the Sondalo Sanatorial Village, 1939, SIAF, Archivio Storico Ospedale Morelli, courtesy of Giacomo Menini.

Organic Waste Treatment

Special attention also had to be paid to the treatment of pathogenic waste generated in the sanatorium, which included infected organic material, disposable medical waste, expired blood, and anatomical pathology samples, all posing a high risk of contagion. To prevent the spread of tuberculosis and ensure hygienic conditions in the *Villaggio Sanatoriale*, this waste was disposed of in an incinerator — located behind the thermal power plant— which operated until the early 1990s.



Fig. 30. The chimney of the incinerator from the memorial square, 2024, Francisco I. Griotto.

It is notable for its tall brick chimney, which not only dominates the landscape but also emphasises the industrial character of the complex (Fig. 30-31).



Fig. 31. On the left, the incinerator under construction, n.d., courtesy of Giacomo Menini. On the right, the incinerator in operation, 1987, courtesy of Enrico Baroni.

6. Conclusions

The Villaggio Sanatoriale di Sondalo, a direct product of industrialisation, follows the logic of a true 'health factory', conceived to provide an essential public service to society through a large-scale technical and engineering infrastructure, made possible by the joint efforts of several private construction companies and the national government. These characteristics directly connect it to industrial heritage —a link that remains underexplored and undervalued— through the notion of 'industrial health heritage', an innovative concept that this research aims to define in order to recognise the sanatorium's value within the industrial legacy.

However, despite its historical and heritage significance, it lacks legal protection as heritage site, and half of the complex remains abandoned, with no public policies promoting its reuse. In this regard, it is relevant to mention that past attempts to inscribe sanatoriums on the UNESCO World Heritage List have been unsuccessful, as demonstrated by the cases of Zonnestraal Sanatorium in the Netherlands (1995) and Paimio Sanatorium in Finland (2004). This situation highlights the limited consideration given by the organisation to this type of sites within traditional heritage categories, or perhaps due to the lack of appropriate strategies in the preparation of application dossiers to effectively demonstrate their true value.

A similar situation occurs with ERIH (the European Route of Industrial Heritage), where no sanatoriums have been designated as 'anchor points', although some sanitation infrastructures —such as the Prague wastewater treatment plant— have been included. This shows that, under the

³ Manual *Modern Sewage Disposal* (Heilmann, 1938), and an article from the French journal *Le Génie Civil* (Blunk, 1938).

current assessment criteria, healthcare infrastructure is still not fully recognised as part of industrial heritage.

In this context, the proposed new category of 'industrial health heritage' could provide a stronger framework needed to strengthen the heritage value of mountain sanatoriums, thus facilitating their future inscription —both nationally and internationally—, and opening new paths for their safeguarding, valorisation and positioning on the public agenda. Particularly for the *Villaggio Sanatoriale di Sondalo*, this would allow this 'city of health' to be duly recognised for its historical, architectural, and industrial importance.

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Acquisition of key precision machining technology as a prerequisite for adopting mass production of mechanical wristwatches in Czechoslovakia in the 1950s.

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Abstract.

The present article explores the acquisition of key production technology for the manufacture of the first Czechoslovak mechanical wristwatches. The text undertakes an analysis of the significance of the acquisition of special machine tools as a remnant of the wartime production of timed fuses for anti-aircraft ammunition on Czechoslovak territory in the context of the subsequent post-war launch of the industrial production of mechanical wristwatches. The article places particular emphasis on the significance and role of the special machinery especially automatic sliding head lathes, which represent a critical machinery necessary for the successful implementation of the task of introducing the industrial production of mechanical wristwatches in Czechoslovakia.

Keywords

History of technology, history of fine mechanics, history of watch production, technology transfer; sliding head lathes; metal industry, electrical engineering and armament industry; know-how, history of innovations, centrally controlled economy, 1945-1960

1. Introduction

In the summer of 1954, the development of the prototype of the first Czechoslovak SPARTAK wristwatch was completed at the national company Chronotechna in Nové Město nad Metují. Three years later, when mass production under the PRIM brand was launched at the same plant, Czechoslovakia became only the eighth country in the world capable of producing mechanical wristwatches in an industrial manner, after the USA, the USSR, France, Great Britain, Japan, Switzerland and Germany. As an industrial product, the mechanical wristwatch is one of the most difficult benchmarks to achieve, and is undoubtedly one of the most manufacturing-intensive fine-mechanical devices ever

produced by mankind using conventional engineering processes.¹

The necessity to 'compress' the movement (calibre) of a precise and complex timekeeping mechanism into a wearable size roughly equivalent to that of a larger coin makes the mastery of modern industrial watchmaking an extremely difficult task, indicative of the technological and industrial maturity of the country. The fact that Czechoslovakia in the second half of the 1950s became a member of the elite "club" of eight countries in the world capable of producing mechanical wristwatches industrially is an undeniable triumph of Czechoslovak engineering. Usually, the historical interpretation of this feat tends to reflect its political ideological and industrial-legal dimensions less so the crucial role played by the specialised machine equipment that Czechoslovakia had at its disposal as a legacy of the Third Reich's wartime production in this technological breakthrough (the successful start of industrial production of mechanical wristwatches).²

The fact that the Czechoslovak watch industry was able to rely on the cutting-edge production technology used in the manufacture of precision-timed anti-aircraft munitions introduced here in the 1940s (the rich machinery stock of specialised machine tools for fine mechanics left on Czech territory as a relic of Nazi war production) is a crucial and little-known fact. The significance and role of this controversial "heritage" of the Third Reich in the introduction of mechanical wristwatch production in postwar Czechoslovakia is analysed in this text.

¹ ŽID, J. Náramkové hodinky Prim -výsznamný úspěch čs. Strojírenství. Jemná mechanika a optika vol 5 no 3. Praha 1960, p 77 – 85.

² State Regional Archive in Hradec Králové, Archivní oddělení Hradec Králové; Messap, Meziměstí, 1942 - 1945 (1946) (NAD 1328); ref. ozn. 1/2/1//1; ukl. j. kar 1; Korespondence s Ministerstvem průmyslu v Praze (příkaz k zastavení výroby granátových zapalovačů a k urychlenému zavedení mírové výroby hodinových strojů, žádost o zachování sídla firmy v Meziměstí, jednání o sloučení s firmou Bratři Junghansové, Velká Ves u Broumova)

2. Historical and Political Context of the Acquisition of Watchmaking Technology in Czechoslovakia

In the early post-war years, Czechoslovakia experienced a significant deficit of mechanical wristwatches. This situation was primarily the result of the exhaustion of the consumer market by World War II and the subsequent long-term interruption of import flows from the West after the country's fall to the Soviet sphere of influence. In response, the leaders of Czechoslovakia's nationalised industry made the bold decision to initiate their own industrial production of mechanical wristwatches.

This initiative was underpinned by a strong militarytechnical background, particularly in the context of the rise of the Iron Curtain, and was directly related to the military precision machining technology that had been inherited and utilised in the production of timed anti-aircraft munitions. This technology was at the disposal of Czechoslovakia in the post-war era and was further developed through the civilian initiative of mechanical watch production. The capacity of Czechoslovakia to independently produce mechanical wristwatches on an industrial scale by the mid-1950s was a testament to the confluence of historical and political factors. Paradoxically, the nation's capacity to do so was bolstered by the unfortunate political developments in Europe during both the war years and the initial post-war decade, a period in which Czechoslovakia came under Soviet influence.



Fig 1 The prototype of the first Czechoslovak wristwatch Spartak. Source: Patrik Sláma

2.1 General prerequisites for the acquisition of industrial watchmaking technology

The Czech lands, which constituted the industrial core of Austria-Hungary from the latter half of the 19th century onwards, exemplified by concentrated industrial production, advanced engineering, robust transport infrastructure, and an export-oriented economy following

the establishment of Czechoslovakia, can be regarded as a developed and well-industrialised region. This prompts the following research question: what were the barriers to the Czech territory developing the capacity for industrial production of mechanical wristwatches at an earlier date? The Czech lands demonstrated a readiness to adopt the technology for the industrial production of mechanical wristwatches; however, this was met with challenges that extended beyond the capacity of conventional engineering. Economic and commercial factors also posed obstacles, hindering the development of this industry. The open economy of the First Republic of Czechoslovakia would have been unlikely to compete with traditional Western manufacturers and importers of watchmaking goods, and thus the domestic production of mechanical wristwatches would have faced significant challenges. Indeed, the only documented attempt to introduce watchmaking (of pocket mechanical watches) on our territory ended in failure even at the preparation stage. However, from the late 19th century, watch factories began to emerge in Bohemia and Moravia, the most prominent being Gustav Becker in Broumov in eastern Bohemia and Schenkler and Kienzle in Chomutov in the north of the country. These factories were primarily focused on the production of larger timepieces.³

The distinguishing characteristics of mechanical wristwatches, as opposed to other mechanical timepieces, are not the principle of their function but rather their construction, the use of special materials, and the miniature size of their components. The most notable constructional specifics in the wristwatch is use of a Swiss lever escapement consisting of a wheel with atypically shaped teeth and an anchor equipped with ruby pallets. In addition to the incorporation of ruby in the bearings and the escapement, the utilisation of special alloys for the springs and the balance wheel is of particular significance. The movement, which is housed in a brass or steel case, typically measures no more than three centimetres in a wristwatch, thus highlighting the significant challenge of miniaturisation in manufacturing. To illustrate this point, the pins of an inertia shaft, with a diameter of a tenth of a millimetre, are machined to tolerances of thousandths of a millimetre.

The fabrication of mechanical wristwatches and pocket watches is an order of magnitude more challenging. The conditions that prevailed subsequent to the conclusion of the Second World War engendered a series of 'favourable circumstances' that paved the way for the realisation of this endeavour.⁴

In Czechoslovakia, the successful introduction of watchmaking (i.e. the production of mechanical wristwatches) did not take place until the late 1950s, when the geopolitical and economic situation of the country changed completely. The advent of watchmaking in

³ MICHAL, S. Hodinářství a hodináři v českých zemích. Praha: Libri, 2002.

⁴ MARTÍNEK, Z. Dějiny československého hodinářského průmyslu I. a II. Brno, Nové Město nad Metují: ELTON hodinářská, Technické muzeum, 2009.

Czechoslovakia was contingent on the transformation of geopolitical dynamics and the realignment of the nation's strategic priorities following the cessation of the Second World War. This shift in circumstances, marked by the Soviet rule over Czechoslovakia and its subsequent integration into the Eastern Bloc, engendered a favourable environment for the commencement of watchmaking. The imperfect competitive environment facilitated the transition from the costly prototype development phase to the technologisation of industrial watch movements. The industrial production of mechanical watches is an exacting process, requiring not only specialised machinery, but also a workforce with specific qualifications and a range of expertise beyond the general knowledge and skills of classical engineering.

2.2 The effects of the introduction of wartime munitions production in Nazioccupied Bohemia on post-war watchmaking

The key issue was the transfer of technology for the production of mechanical fusees for anti-aircraft ammunition, implemented during World War II by the Third Reich in the Sudetenland, which after the restoration of Czechoslovakia was. It can be said with some simplification that the ignition device for special antiaircraft ammunition operating on the principle of mechanical explosion at the appropriate flight altitude is de facto a small watch, in terms of design and production (production requirements), so the production of these time igniters is very close to the civilian watchmaking production of mechanical wristwatches. For the later start of watchmaking production in liberated Czechoslovakia, the transfer of this production to the Czech interior was therefore a key decisive role.

In the subsequent acquisition of technology, particularly the company Messap, which was established in the early 1940s in the East Bohemian town of Meziměstí (Halbstadt) near Broumov. played a pivotal role. This Hamburg-based company,known as Deutsche Messappparate GmbH, was a subsidiary of the German watchmaking company Gebrüder Junghans A.G. Schramberg's production programme was centred on a single product: time fuses for anti-aircraft grenades. Within its German and occupied territory branches, the company relied on forced labour, enlisting prisoners of war and political detainees, many of whom were former concentration camp inmates. A similar pattern of forced labour was observed in the operations of the Messap company in the occupied territory of Czechoslovakia, where a large-capacity production facility was established in the Sudetenland, a region annexed by the Third Reich. In June 1942, one of the factory buildings at the Schroll spinning mill in Meziměstí was vacated.5

Subsequent to this, the workshops were equipped with contemporary machinery for precision mechanical largescale production, delivered from Germany and Switzerland. The total number of machine tools and special equipment installed in the plant exceeded seven hundred, including automatic lathes, gear milling machines, various special fixtures, tools and gauges. The plant's workforce was constituted by several dozen experts transferred from the parent plant in Hamburg and the Junghans company in Schramberg during the latter half of 1942. Concurrently, 150 local workers were dispatched to Germany for training purposes. The company initiated large-scale production of timed lighters at the beginning of 1943. The initial composition of the plant's workforce primarily comprised individuals who had been forcibly recruited from occupied European countries. Notably, the cohort included 150 individuals of Czech origin.

Following the liberation of Meziměstí in May 1945. only a small number of German specialists remained. These individuals established a national administration in the factory and transferred the company to the Chronotechna concern. Gradually, Czech workers, technicians and officials from the surrounding area began to fill the vacant positions. These individuals underwent training in new professions, guided by the expertise of the former German specialists. Within the Messap production facilities, a cadre of toolmakers and automatic machine adjusters with professional expertise was established, who form the core of every watchmaking company. The most proficient of these specialists (five toolmakers and three long-turn automatic machine adjusters) subsequently relocated to the recently constructed watchmaking factory in Nové Město nad Metují . This relocation also entailed the transfer of advanced equipment, including Tornos sliding head automatic lathes machines and specialised measuring instruments, among others. Consequently, the establishment of both Messap and Chronotechna in Meziměstí can be regarded as a pivotal moment in the adoption of Czechoslovak Prim watch production.



Fig.2. Manufacturing capacity equipped with sliding head lathes-Chronotechna company. Source: State Regional Archive in Hradec Králové

⁵ Archivní oddělení Hradec Králové; Messap, Meziměstí, 1942 -1945 (1946) (NAD 1328)

3. Technological challenges of watchmaking production - the need to use special machines

The movement of a modern mechanical Swiss-type wristwatch, which was also used in the first Czechoslovak Spartak watch, is an extremely precise and complex product of precision engineering. Even in its simplest version, it consists of dozens of miniature components, the dimensions and demands for accuracy of which are at the very limit of manufacturability. All manufacturing inaccuracies and deviations from rigorous dimensional tolerances are multiplied in the watch gear train and negatively affect the accuracy and reliability of its operation. The size of individual parts makes even common manufacturing operations, such as pressing, machining, heat treatment and surface treatment, an extremely demanding task. Not only the miniaturization of the components, but also their often atypical shape necessitate the use of special machining technologies (e.g. precision automatic lathes for turning shafts and special gear-cutting milling machines for producing gear train components).

In the industrial production of mechanical wristwatches, it is necessary to use a special production park of machine tools, measuring devices and other special instruments, which in their design and function differ significantly in some respects from the usual machine park of classical mechanical engineering. Precision engineering, especially in industrial watchmaking, faces technological challenges that go to the very edge of the possibilities of production processes. The choice of materials must meet the requirement for high resistance to mechanical wear and at the same time ensure good machinability with regard to the miniature dimensions and shape complexity of the components. ⁶

3.1 Sliding head automatic lathes

Sliding head lathes are also referred to as Swiss turn or Swiss automatic lathes. These were originally developed in the 19th century in Switzerland for the machining of small high-precision components for the growing Swiss watch industry. These machines use a different type of machining suitable for watch components characterized by a high diameter-to-length ratio. It is based on fixed-head machining technology - type of machining that uses a spindle that is fixed in place. The tool then moves along the machine's axis of rotation, allowing the materials to be cut. This type of machining is generally used for precision, high-speed, and complex parts.⁷

Sliding-head machining technology is a type of machining that uses a spindle that can move along the

machine's axis of rotation. It allows for the machining of large and complex parts with a high degree of accuracy. The spindle can also be used to produce intricate and complex parts because it is able to move around the part and reach areas that would be difficult or impossible to reach with a fixed head. Machines with a sliding head (Swiss Style) have the ability to produce parts impossible on conventional milling lathes due to the design of the guide bushing. Thanks to this technology, long slender shafts with very small diameters can be produced accurately and repeatedly.

Similarly, whole wristwatch technology and the majority of the machinery used are outside the general practices of mechanical engineering. For example, rotating parts with a larger diameter to length ratio can only be produced to the required accuracy by turning on sliding head automatic lathes capable of producing a range of watch parts completely in large series and with large-scale production by multi-machine operation.



Fig.3. Poster of sllidng head lathe Tornos. Source: Jean Georges Laviolette, Manuel des fabrications micromécanique, Lausanne, Scriptar 1964.

The possession of this key technology was a pivotal factor in the initiation of serial watchmaking production. (Special machine tools, particularly of Swiss origin, were available to countries that had previously adopted the industrial production of mechanical wristwatches.) The significance of this technology, and its mastery as a prerequisite for the initiation of serial production, is illustrated by a study conducted by the French-Japanese researcher Pierre Yves Donze. He highlights the acquisition of watchmaking technology in Japan and the reverse engineering of machine tools, emphasising the crucial role of sliding head automatic lathes and milling cutters in

⁶ VAJSAR, J. Technologie Hodinkových ozubených kol. Jemná mechanika a optika vol 7, no 7. Praha 1962, p.207 -212.

⁷ VAJSAR, J. Technologie sériové výroby pastorků náramkových hodinek Jemná mechanika a optika vol 10, no 1, Praha 1965, p.21-28.

watchmaking production. Furthermore, Pierre Yves Donze demonstrates that Switzerland, as a dominant producer of sliding heads automatic lathes and precision machine tools, effectively protected its industry with export embargoes on this technology. ⁸

The presence of significant quantities of German war production relics in Czechoslovakia significantly facilitated and augmented the potential for the adoption and domestic implementation of watchmaking technology for watchmaking production.



Fig.4. X-ray picture of the first movement of Czechoslovak wristwatch. Source: Jan Švadlena

4. Conclusion

The transfer of modern industrial watchmaking technology to Czechoslovakia occurred via multiple channels. This transfer was facilitated by the country's well-established technological and industrial infrastructure, which was further bolstered by the demands of war production. This process involved the repurposing of components from wartime production of precisionmechanical military equipment, particularly time fuses for artillery anti-aircraft shells, colloquially referred to as 'flak'. Subsequent to this, the Soviet Union provided technological support, and the utilisation of reverse engineering processes, including the unauthorised construction of the design of a watch movement originally from France, enabled the acquisition of scientifically and technologically significant knowledge. The pre-existing development of precision engineering, predominantly employed in the arms industry prior to the war, and the subsequent transfer of wartime precision-mechanical equipment production to the border areas annexed by Nazi Germany during the war, collectively fostered a robust industrial and knowledge base, paving the way for the advent of modern watchmaking production. In the context of socialist Czechoslovakia, it is noteworthy that industrial watchmaking, particularly the production of mechanical wristwatches, was indisputably associated with military production.⁹

The unfortunate political and economic developments that ensued following the communist coup of 1948 resulted in a situation that would not have been feasible under the normal market conditions of the First Republic. The export-oriented economy of pre-war Czechoslovakia would have been unable to withstand competition from sophisticated suppliers in countries such as Switzerland, the United States, France or Germany. However, the accumulation of resources through post-war nationalisation, imperfect competition and political efforts was able to create conditions conducive to the successful launch of watchmaking production in Czechoslovakia. This outcome was facilitated by the technological expertise that remained in Czechoslovakia following the cessation of German wartime production. This technological prerequisite, in the form of a well-developed machinery park, facilitated the implementation of strategic decisions and incremental actions that culminated in the introduction of the prototype of the first Czechoslovak wristwatch in 1954, and subsequently led to its successful serial production three years later.

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⁸ DONZE, P,Y. The Watchmaking Enterprises and the Growth of a Special-purpose Machine Tool Industry in Japan (1890-1960). Osaka economic papers, vol 60, No 1. Osaka: Economic Society of Osaka University p.21-34.

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The ESČ Testing Laboratory as the Basis of Electrotechnical Examination in Czechoslovakia

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Abstract. This paper aims to present the establishment and functioning of the testing laboratory of the Czechoslovak Electrotechnical Union (Elektrotechnický svaz československý, ESČ) in the years 1926 - 1951. The operation of this workplace was part of the ESČ's systematic efforts to standardize electrical materials and appliances. These efforts were in the context of the ongoing electrification of Czechoslovakia, in which the ESČ was a major contributor. During the period under review, the activities of the testing laboratory succeeded in establishing a good reputation for the ESČ trademark, which guaranteed quality and safety for consumers. The fact that it continued to be used even after the demise of the ESČ and the transformation of its testing facility into the Electrotechnical Testing Institute (Elektrotechnický zkušební ústav, EZU) in the early 1950s is testimony to its value.

Keywords

History of science and technology, electrification, Czechoslovakia, ESČ, testing

1. Introduction

The beginnings of the systematic electrification of the newly established Czechoslovakia are directly connected with adopting Act No. 438/1919 Coll. [1] This law demonstrated that the Czechoslovak government was aware of the importance of electrification as a tool for promoting social and economic growth. The law itself was based on unadopted legislative proposals prepared for the territory of Moravia before the First World War by Prof. Vladimír List. [2] This eminent Czechoslovak electrical engineer and teacher was involved not only in the running of the ESČ as a professional interest association but also in the running of the Czechoslovak Normalisation Society (Československá společnost normalisační, ČSN), of which he was for many years chairman.

In addition to a quality legislative framework, the electrification process could rely on a cadre of electrical experts educated at domestic technical universities. Separate electrical engineering departments existed at the Czech Technical University in Prague, the Czech Technical University in Brno, and the Prague and Brno German Technical University. [3] Equally important was a welldeveloped domestic electrical industry, capable of supplying the market with virtually all types of electrical materials and appliances. The range of these companies was extensive, from large domestic concerns (ČKD) through subsidiaries of foreign corporations (Siemens, Philips) and innovative medium-sized domestic producers (Sousedík, Palaba) to small factories and workshops producing the most straightforward appliances. [4] The competitive struggle of the production programs of these companies created an environment in which standardization, product testing, and certification were necessary. The ESČ took on this task in the second half of the 1920s.

Regarding primary materials, the study is based on documents from the provenance of the ESČ as the founder and administrator of the test laboratory. The main press body of this association was the weekly *Elektrotechnický obzor*, published under the ESČ auspices from 1923. For the needs of low-current electrotechnology, it was joined by Slaboproudý obzor in 1935. Between 1926 and 1939, the ESČ published the Yearbook (*Ročenka ESČ*). [5]

2. Establishment of the ESČ Testing Laboratory and its development up to 1938

From the perspective of the history of science and technology, the so-called Second Industrial Revolution, which included the emergence of the electrical industry, emphasized the standardization of products and the verification of their parameters and properties. The increasing technological complexity of production and final products made testing designed products and technological processes necessary. These were to ensure that the final product would perform the functions for which it was intended and that its operation would be safe. [6] These aspects are fundamental in electrical engineering. As the systematic electrification in Czechoslovakia progressed in the 1920s, an increasing proportion of the population came into contact with various forms of electricity. These users lacked practical and theoretical knowledge of the use of

electricity. Therefore, ensuring that the products they handled were safe and as easy to use as possible was important. The legislative framework for testing in Czechoslovakia was the adopted Act on Technical Testing, Testing and Evaluation of Materials No 185/1910. [7] It remained in force throughout the period under review and was replaced only by the Act on State Testing No 30/68 Coll. [8]

The second prerequisite for starting the practical tests was the existence of the required technical parameters. The ESČ had issued just such regulations as early as 1920. From 1922, he closely cooperated with the newly founded Czechoslovak Normalisation Society (Československá společnost normalisační, ČSN), [9] with which he was, among other things, personally linked by the person of the chairman of both institutions, Prof. List. List also initiated the adoption of the so-called British type of normalisation at the expense of the German one. The latter was characteristic in that it contained not only dimensional regulations like the German standards but also so-called specific ones. This meant that the quality, type of material, and method of processing were also characterized for the product, and the standard was tied to a specific product and the whole technical field. [10] The standards were published together with the ESČ Technical Regulations (Předpisy ESČ) on the pages of Elektrotechnický obzor and also separately in print. Within the ESČ, several standardization committees functioned depending on the product type. They were composed of electrical engineers, representatives of ČSN, relevant ministries (Ministry of Public Works, Ministry of Posts and Telegraphs, Ministry of Railways), and manufacturers. Before final approval, the Standards or Regulations were submitted to the Elektrotechnický obzor for review and comment by the professional community.

The first mention of the testing of electrotechnical material is a proposal made by Prof. List in 1924 at a meeting of the Association of the Metalwork Industry. The insulated cables were to be tagged with an ESČ mark after testing. [11]



Img. 1 Older and newer emblem of the ESČ. The the latter was specified by the standard "ČSN-ESČ 100 Znak ESČ" from 1931. [12]

It has not yet been established whether these tests took place. We therefore consider 8 November 1926 to be the official beginning of electrotechnical testing in Czechoslovakia. At the board meeting of the ESČ on that day, List informed about an agreement with a domestic fuse manufacturer, [13] which would be awarded the ESČ mark after inspection of the components. It was to be stamped on each fuse as a quality guarantee, and the packages were to contain an inspection label. The checks took place in the Institute of Structural Electrical Engineering (Ústav konstruktivní elektrotechniky) laboratory of the Czech Technical University in Brno, which was equipped for testing porcelain and products made of porcelain. [14]

The testing laboratory became independent in 1928 when the ESČ purchased a building at Vocelova Street No. 3 in Prague, Vinohrady. On the ground floor, a separate workshop for evaluating electrical material was set up. [15]



Img. 2. The ESČ building in Vocelova Street. The laboratory is marked on the floor plan in the upper right part, under the sign "DÍLNA".[15]

The increasing volume of tested products led in the mid-1930s to the establishment of a second testing room in the now-non-existent building of the former hydroelectric power station in Těšnov. [16] The testing of light bulbs, the most frequently used equipment, was concentrated on these premises, which had 390 square meters available. [17] Notices of the granting of the trademark were published in *Elektrotechnický obzor*, and, from 1930, the Association published the List of Marked Products annually.

2



 Tab. 1. Number of companies and products of certain categories that were granted an ESČ trademark.[18]

The more significant increase observed between 1934 and 1935 is probably related to the change in the approach of state institutions to electrical testing. Until 1945, testing was voluntary for manufacturers; List himself opposed compulsory examinations. [19] However, the state administration gradually began to require quality and safety certification from material suppliers. The first step in this direction was the official authorization of the ESC testing laboratory. It was granted by the Ministry of Public Works on 16 June 1934 under Law No 185/1910. The scope of the tests carried out was defined as 'insulated electrical conductors, electrical installation material, small and low voltage electrical appliances and tests of protective coatings on power plant structures.' [20]

Subsequently, the Ministry of Public Works began to require that all electrical materials for the buildings it constructed be certified with an ESČ certificate. Gradually, other government agencies started to join in on a limited scale, in 1936, the Ministry of Railways and the Ministry of National Defence. [22]

3. Testing laboratory from 1938 to its demise

The political events of 1938 and 1939, associated with fragmentation and subsequent dissolution the Czechoslovakia, significantly impacted the functioning of the ESC and its Laboratory. The planned construction of its premises in Prague Krč, for which land had already been purchased, was cancelled after the Munich Agreement. As an alternative solution, the relocation of both workplaces (Vocelova, Těšnov) under one roof to the premises of the steam power plant in Holešovice was chosen. German members and companies in the ceded border territory also left the ESC. After establishing the Protectorate of Bohemia and Moravia, the validity of Czech and German standards had to be resolved. In the territory of the German Reich, the Verband Deutscher Elektrotechniker (VDE) was responsible for issuing and controlling electrotechnical regulations.

The first step was the July 1939 agreement on the mutual membership of the two organizations. [23] The ESČ

subsequently had to face pressure from the occupying authorities to invalidate its standards and regulations and replace them entirely with German ones. However, a compromise solution was reached, according to which the former Czechoslovak ESČ standards would remain in force for one year after the conclusion of peace in Europe and were then to be replaced by the VDE regulations. [24] Similar cooperation was established between the ČSN and the German Deutscher Normen ausschuss (DNA). The ČSN was formally renamed the Czech-Moravian Normalization Society (Českomoravská normalisační společnost), whose standards were to continue to apply in the territory of the Protectorate, with the proviso that the wording of German standards, if any, was to be considered when issuing new ones. [25]

The German side probably led to this compromise because of the desire not to disrupt the electrical production necessary for war purposes immediately. The ESČ regulations, still controlled by its testing laboratory, thus remained in force until the war's end. The number of tests declined during this period, which was related to the limitation of the production of domestic electrical appliances and, later, of electrotechnical material as such. This was due to a shortage of strategic raw materials (mainly non-ferrous metals).

The economic and political developments after the end of the Second World War again affected the operation of the Laboratory. The decree of the President of the Republic of October 24, 1945, nationalized, among other things, all power stations and enterprises in the electrotechnical industry with more than 500 employees. [26] In the same month, a decree on the compulsory inspection of electrical products was adopted by the Minister of Industry, Bohumil Laušman. The decree, which had been in preparation since 1938, meant that only ESC mark products could enter the Czechoslovak market. [27] This naturally meant an increase in laboratory tests. The two-year economic plan, which provided for the renewal of the energy base, brought with it further increased demands for testing. The shortage of electrical appliances on the market, caused by the wartime drawdown, factory damage, and persistent material shortages, led to manufacturers producing appliances that did not meet ESČ standards. Under these circumstances, the ESC proceeded to grant exemptions in those cases that did not directly threaten the safety of the consumer. The number of tests gradually increased and, as seen from the attached graph, by 1947, had surpassed the pre-war level.



Tab. 2 Evolution of the number of tested samples. [28]

At the same time, the ESČ significantly stepped up its standardization activities, which had also been curtailed during the war. Between 1920 and 1937, it issued 104 standards; in 1945-1951, it issued 121. [29]

Under these conditions, the technical and organizational background of the laboratory was no longer sufficient, and economic damage occurred due to the mixed economy and compulsory labeling. The solution to these constraints was severalfold. The testing laboratory has finally acquired its premises, which were sufficient in capacity. In 1947, the former Pomological Institute in Troja (Prague) was purchased at a cost of 3 042 000 Kčs, [30] and its adaptation began. Tests were conducted in this building from the end of 1948 when it was already under the new political regime. [31]

The first organizational groundbreaking was the introduction of national administration into the ESČ in February 1948. [32] This measure was intended to streamline the running of a purely private organization while ensuring a certain level of state control. As such, the testing laboratory was considered essential to the state economy, and steps were taken to abolish the ESČ monopoly in its administration. In January 1950, the Board of the ESČ agreed with the national enterprise Czechoslovak Light Metal Plants Československé závody lehkého kovoprůmyslu (Československé závody lehkého kovoprůmyslu), under which the latter took over the national administration of the Laboratory. The ESČ retained the right to award the inspection mark. The further development of the testing industry was to be managed by a newly established commission composed of representatives of the seven national enterprises and the ESČ. [33] The definitive end of the link between the ESČ and the Laboratory was brought about by the Congress of Delegates of the ESČ in March 1951. It was decided to dissolve the ESČ as a separate association at this meeting. Its members were to transfer en masse to the Revolutionary Treade unions Technicians and Improvers Club Klub techniků a zlepšovatelů ROH (Klub techniků a zlepšovatelů ROH). The standardization activities were taken over by the Research and Technical Development Centre (Ústředí výzkumu a technického rozvoje), the of periodicals and publications by several technical publishing houses. [34] With this act, the professional organization that had significantly shaped the course of the systematic electrification of Czechoslovakia and laid the foundations of the electrical testing industry ceased to exist. Its influence is evidenced, among other things, by the fact that Laboratory, already under the changed name of Elektrotechnický zkušební ústav, continued its activities and continued to use the ESČ brand, although newly spelled as Czechoslovak Electrotechnical Standard (Elektrotechnický standard československý).

4. Conclusion

During the systematic phase of electrification in Czechoslovakia after 1919, the ESČ played an irreplaceable role. In this paper, we have focused on the establishment and functioning of its testing laboratory for electrical products. However, its operation was closely related to other activities of the ESČ, primarily standardization, not only in drafting but also in publishing and controlling compliance with relevant standards and regulations. In this respect, the ESČ cooperated closely with the Czechoslovak Normalisation Society to which it was also personally linked by the figure of Professor Vladimír List.

It was List who can be credited with founding the Testing Laboratory in 1926. In spite of the modest beginnings, initially in the premises of the Czech Technical University in Brno, the test program boomed after the relocation to Prague. During the 1930s, the Testing Laboratory and, through it, the ESČ trademark were established as a symbol of the guarantee of quality, reliability, and safety of electrical products. Representatives of the domestic electrical industry used this fact to promote and sell their products. In an effort to ensure the purchase of quality goods, state institutions also began to require ESČ certification for their purchases. This led to a significant increase in the number of items tested, and the Testing Laboratory had to respond by acquiring larger premises. The establishment of the Protectorate of Bohemia and Moravia brought with it forced cooperation with the VDE. The Board of the ESČ prevented the complete abolition of the Czech technical standards that had remained in force during the war.

The period after the Second World War presented the Testing Laboratory with new challenges. The recently introduced legislative obligation to prove all manufactured electrical appliances meant a further increase in testing. Production in an environment of continuing raw material shortages and high demand led the Laboratory to start granting exemptions. Its importance to the national economy grew with the plan to rebuild and construct an industrial base in a mixed and later centrally planned economy. The politically motivated restriction and abolition of federal activities meant the demise of the ESČ as a parent organization and the transformation of the Testing Laboratory into the state-operated Electrotechnical Testing Institute, which still carries out its activities today. The ESČ thus laid the solid foundations of electrotechnical testing in Czechoslovakia and the Czech Republic, which can now boast a centuries-old tradition.

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The Landesberger Clockmaker Family and the Reconstruction of the Prague Astronomical Clock, 1787–1791

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Abstract. This paper examines the contributions and historical legacy of the Landesberger family, prominent clockmakers of the late 18th century active in the Czech lands. Beginning with Sebastian Landesberger, who notably maintained the clock on the tower of St. Vitus Cathedral in Prague and was the first in the region to adopt Clement's anchor escapement-a significant technical advancement. The study continues by exploring the achievements of his sons Ferdinand Elias, Matheus, and Elias. Ferdinand Elias is particularly recognized for constructing several important tower clocks throughout Bohemia, most famously the clock installed on Prague's Old Town Hall in 1787. At that time, Prague's iconic Astronomical Clock faced the threat of demolition. Ferdinand's initiative, coupled with the influential support of Antonin Strnad, director of Prague's Clementinum Observatory, led to essential repairs being carried out between 1787 and 1791. This paper also corrects longstanding historical inaccuracies regarding the authorship of these repairs, firmly establishing Ferdinand's key role through evidence from newly reviewed archival documents. Additionally, it explores the contributions and careers of Ferdinand's brothers, Matheus and Elias. Ongoing research includes an extensive cataloging of surviving Landesberger clocks, as well as the identification of works now presumed lost but documented in historical records.

Keywords

Sebastian Landesberger, Ferdinand Landesberger, Clockmaking, Tower clocks, Prague Astronomical Clock.

1. Sebastian Landesberger

Johannes Sebastian Landesberger was baptized on March 9, 1698, in Regensburg, as the son of the imperial chamberlain of Regensburg, Ruedolph Landesperger, and

his wife Anna Susanna.¹ He apprenticed as a clockmaker in Vienna.[1] The exact date of his arrival in Prague is unknown, but he likely came as a journeyman. The first record of his presence in Prague is a marriage entry: on July 18, 1726, he married Anna Francisca, the daughter of František Pompe, a burgher of Prague's New Town. Just a month later, on August 28, 1726, their first son, Ignatius Henricus, was born.² On December 25, 1727, another son, Johannes, was born, but he died only five days later, on December 30. In 1729, they had a son named Carolus Joannes Wenceslaus. Several more children followed: in 1732, twin daughters Maria Magdalena and Anna Polexina; in 1738, Johannes Matthias; in 1740, Franciscus Josephus; in 1741. Johannes Franciscus: in 1744. twins Johannes Josephus and Francisca; and on May 31, 1745, Ferdinand Elias. The last recorded child of Sebastian and Anna Francisca was Elias Matthias, baptized on November 2, 1750. How many children reached adulthood remains uncertain, but at least three of his sons also became clockmakers.

After the death of clockmaker Jan Václav Neumann in 1732, Sebastian Landesberger took over the maintenance of the clock on the tower of St. Vitus Cathedral on the Prague Castle. He was reportedly chosen also because he was the youngest of the candidates, was in good physical condition, and could climb the tower staircase twice a day to adjust the clock. He received an annual salary of 186 florins and 40 crowns and was given a service apartment. The cathedral clock was installed at the end of the 16th century³ at the initiative of Emperor Rudolf II, who commissioned the renowned clockmaker Hans Bechler of Magdeburg to construct it. Over time, the clock was repaired and modified. Jan Václav's father, Petr Neumann, replaced the verge escapement with a pendulum 1680 but

¹ Archiv hl.m. Prahy (dale AMP). AMP PPL IV, sig. 4962, 3.10.1716

² AMP, Sbírka matrik, sign. VO N3O3, 1717-1747, snímek 55.;

³ According to some sources, the clock was installed in 1590; other records cite the year 1593, while a commemorative plaque from 1930 lists the year as 1597.

likely retained the original crown wheel and verge mechanism. Shortly after taking office in 1733, Sebastian Landesberger carried out his first significant repair of the St. Vitus clock: he replaced the verge escapement with a recoil anchor escapement and installed a new pendulum.

In 1757, during the Prussian bombardment of Prague, the cathedral tower, together with the clock, was seriously damaged—reportedly, at least seven cannonballs hit the clockwork itself. Immediately after the end of the siege in June 1757, the clock was removed from the tower, and Landesberger repaired it in his workshop, completing the work by Easter 1758. Although the original contract entitled him to 550 florins, he requested an additional 700 florins due to the scale of the repairs and material costs. Expert clockmakers from the Old Town appraised the value of his work at 1,400 florins, but the chamber ultimately granted him 905 florins.



Figure 1: St. Vitus cathedral clock (photo: Petr Skála)

Another disaster struck the repaired clock just two years later, on June 25, 1760, when lightning struck the tower of St. Vitus and set its top ablaze. Landesberger proved himself not only as a clockmaker but also as a brave and loyal servant—he was among the first, along with Prague chimney sweeps, to help dismantle the burning tower helm, despite the strong windstorm.

Between 1769 and 1771, he participated in the reconstruction of the tower roof, which received its current shape then. He was commissioned to produce a new striking mechanism and construct the mount for the rotating weathervane bearing the symbol of the Lion at the

top of the tower. He was paid 170 florins for this work. Sebastian Londensperger served as the clock custodian until he died on February 12 1776.

He not only maintained the castle clock but also built his own. Sebastian Landesberger's oldest preserved tower clock is the clock from the tower of the Clementinum Observatory, which dates from 1736 and is now exhibited in the National Technical Museum.

His most famous clock is probably the counterclockwise one on the Prague Jewish Town Hall, which dates from 1764.



Figure 2: The clock on Prague Jewish Town Hall that runs backwards

In 1763, together with his son Matěj, he built tower clocks for the Church of St. Mary Magdalene in Karlovy Vary, as well as for the Měšice Castle and additional clocks for churches in Písek, Liberec, and Říčany and other places. He was the first clockmaker in Czech lands to use the anchor escapement, invented by the English clockmaker William Clement in 1671. This escapement became characteristic of his sons' works as well.

It is worth mentioning that Sebastian Landesberger and his son Ferdinand were also involved in the production of interior clocks, several of which are in the Museum of Prague's depository. They are also said to have made musical clocks, but unfortunately, no examples are currently known in public collections.[1]



Figure 3: Colck at Měšice Castle (photo: Petr Skála)

2. Ferdinand Landesberger

Ferdinand Elias Landesberger was born on May 31, 1745.⁴ He learned the art of clockmaking from his father, Sebastian. His earliest surviving independently signed tower clock dates from 1768 and was made for the town hall in Žatec, even though he was officially granted the title of master clockmaker only in 1775. He numbered his clocks, allowing us to estimate that he produced several dozen tower clocks during his lifetime, though only a fraction of these have survived until today.

Arguably, his most significant work was the clock made for the tower of Prague's Old Town Hall in 1787, which, unfortunately, have not survived.

At that time, the famous astronomical clock located directly below the tower clock faced destruction, as Prague city councilors intended to scrap it entirely. Thanks to the intervention of Antonín Strnad, then director of the Clementinum Observatory in Prague, the councilors were persuaded to preserve and repair this historic monument. Having recently completed the tower clock above, Ferdinand also offered to repair the astronomical clock.

⁴ AMP, Sbírka matrik, sign. V'9T N5, 1710-1755, snímek 282.;



Figure 4: Table clock by Ferdinand Landesberger (photo: Museum hlavního města Prahy)

Nevertheless, considerable confusion has persisted in historical literature regarding the identity of the clockmaker who actually performed this repair. Already during the repair, in 1788, Joseph Anton Stephan von Riegger published a chapter on the history of the Old Town Astronomical Clock in his book Statistik.[2] This chapter, likely authored by Strnad, referred to the clockmaker as Johann Landesperger. However, in his subsequent publication on the astronomical clock from 1791, Strnad mentions only the surname Landesberger, omitting the first name entirely.[3] This discrepancy raises questions about the extent of Strnad's direct involvement in the repair, as commonly attributed to him, since he apparently did not even know the clockmaker's first name. This error has persisted in historical texts until today, reinforced through repeated citations. In addition to the incorrect name "Johann," another completely fictional name, "Šimon," occasionally appears in the literature.

Today, thanks to documents preserved in the National Archives,⁵ we can definitively confirm that Ferdinand Elias Landesberger was indeed the clockmaker responsible for repairing the astronomical clock between 1787 and 1791. His own petition requesting payment for the work survives in the archives, clearly indicating that Ferdinand undertook most of the repairs, including supplying materials, at his own expense. Despite initial assurances from the Prague city council, he was ultimately only partially compensated for his work. For this important act, he deserves our historical gratitude.

⁵ Národní Archiv, NAD 1054/2 Zemský výbor Praha -1791-1873, kartib 1265, inv. č. 4249, sign. 85/9

In 1805, he carried out another minor repair of the astronomical clock, for which he was properly compensated.

In addition to the previously mentioned tower clock from Žatec, now displayed in the K. A. Polánek Regional Museum, Ferdinand's known works also include the surviving clock at Dobříš Castle, as well as other clocks mentioned in historical sources but now lost, such as those in Chlumec nad Cidlinou, Krásná Lípa, and Most.



Figure 5: Signature of Ferdinand Landsberger (written as Londensberger) from Dobříš clock (1791) (photo: Petr Skála)

He passed away on December 23, 1811. His will, in which he left all of his property to his wife Anna and their children, was read publicly at a session of the magistrate council on January 15, 1812.

3. Matheus Landesberger

Another son of Sebastian was Matheus. Naturally, he also trained under his father, receiving his apprenticeship certificate in 1777. Since there was no room in Prague for another tower clockmaker, he initially attempted to obtain permission to practice his trade in Jindřichův Hradec but was initially rejected. Eventually, he received the required permission but later relocated to Písek. Whether he independently built any clocks is unknown. However, we do know that he assisted his father in constructing the clocks in Karlovy Vary and subsequently maintained them, as he did with the clocks in Písek.[4]

4. Elias Landesberger

The last of the brothers was Elias Mathias, bp. November 2, 1750. Records show that by 1780 he was mentioned as a maker of tower clocks in České Budějovice, where he purchased a house that same year and another one in 1787. Later, he also worked in Strakonice, settling in Vodňany in 1794. He died in 1809. Apparently, Elias was financially successful, although none of his clocks have survived. His branch of the clockmaking family lasted the longest; as late as 1865, the directory of craftsmen in České Budějovice still mentions a clockmaker named Elias Landesberger, evidently a descendant.

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The importance of the Military Aviation Studies Institute for the conception and development of the Czechoslovak Army in the years 1922–1932

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Abstract. After the establishment of independent Czechoslovakia in 1918, the newly formed state faced a number of challenges, among which the issue of national defense and the modernization of the army played a key role. Given the rapid development of aviation technology during the First World War, it became essential to develop a domestic base of expertise in the field of military aviation. As a result of this effort, the Military Aviation (Aeronautical) Study Institute (Czech abbreviation VLSÚ) was founded in 1922. Within a decade, it had become an important research and technical institution of the Czechoslovak Army. The institute served as a center of scientific knowledge focused on aerodynamics, structural calculations, and the verification of aircraft designs. It conducted testing of new technologies, developed structural solutions, and facilitated cooperation between the army, technical universities, and the aviation industry. This paper focuses on the origin, functioning, and significance of the institute in the context of the years 1922 to 1932.

Keywords. *History of technology, history of aviation, Military Aviation Study Institute, Air Force, Czechoslovakia, 1922–1932*

Introduction

The inter-war period brought significant changes to Europe, not only in international politics but also in military technology. After the First World War, it became clear that the future of modern warfare would depend increasingly on the use of air power, mechanisation and automation. Aviation technology had developed rapidly during the war, and the newly established states, including Czechoslovakia, had to respond quickly to the need to build their own air forces to modern standards. In addition to building up the military itself, it became essential to create a scientific and technical base to ensure the research, development and testing of aviation technologies. It was precisely this need that led to the establishment of the Military Aviation Study Institute.

1. The Military Aviation (Aeronautical) Study Institute – Mission, Structure, and Activities

The VLSÚ was officially established on May 1, 1922, in Prague as an independent military institute¹. Initially, it was located within the premises of the aviation school in Prague's Pohořelec district, and a year later it moved to Střešovice. The institute's foundation was initiated by Captain Charles Bucháček², Doctor of Technical Sciences and head of the Aeronautical Department of the Ministry of National Defense. In 1927, a new location was found for the Institute in Prague-Letňany, near the local airport and the *Letov* manufacturing complex, where suitable—especially technical—conditions were available for its further development.

The main objective of the Institute was to provide a professional and technical base for research and testing of aviation equipment. At the same time, the Institute acted as an intermediary between the military and industry - it was responsible not only for the technical evaluation of armaments, but also for promoting innovation and cooperation with aircraft manufacturers.

Its core mission was to strengthen the defense capabilities of the republic by building a modern and efficient air force that would meet the demands of the time. The VLSÚ became a research center responsible for testing aircraft, engines, fuels, and other components essential to both military and civilian aviation.

The Institute was organised into seven specialised departments (Aerodynamics, Aircraft and Propulsion Systems, Engines, Electrical and Radio Equipment, Photo-Optics, Aeromedical and Meteorology)³, each of which focused on developing the necessary areas such as aerodynamics, aircraft and engine design, military

¹ MNO, čj. 296.293 vzduchoplavba, ze dne 25. 4. 1922

² BUCHÁČEK, Karel, Letecký studijní ústav, In Důstojnické listy, 1924, Vol. 4, Iss. 38.

³ VHA, fund VLÚS, kar. 2, inv. č. 7, Přílohy ke kronice- podklady, 1925, meteorologická sekce, 1925, p.1-2.

electronics, materials testing, aviation equipment evaluation and industrial cooperation.

The Aerodynamics Department, for example, encountered difficulties with a new wind tunnel measuring 1.8 meters in diameter that had been imported from France. It had to be rebuilt before it was fully operational. It was not until 1929 that the first tests were carried out on aircraft models and components for the Military Aircraft Factory and the *Aero* Company.



Fig. 1. Buildings of the VLSÚ / VTLÚ (Source: adapted from https://www.vzlu.cz/historie-vzlu/)



Fig. 2. Main building of the institute - entrance (contemporary photo)

The Aircraft and Propulsion Department conducted structural strength tests of airframes and addressed issues related to the strength and stiffness of the materials used. It was also responsible for issuing production and flight regulations, as well as drafting technical specifications.

In 1928, the Engine Department conducted the first full engine tests. These included the Perun II engine with 240 horsepower on an electric brake, the Lorraine-Dietrich 12E with 450 horsepower on a water brake, and later on a propeller-shielded brake. Since Czechoslovakia lacked sufficient diesel fuel resources, the institute focused on exploring various liquid hydrocarbon mixtures. As a result of research and cooperation with industry, a blend of gasoline, benzol, and ethanol was developed. Testing of different mixture compositions began with a single-cylinder Waukesha engine, continued with long-term ground tests, and was eventually extended to flight tests.

Each department had its own specific role, and together they formed a comprehensive system that enabled in-depth research into all aspects of aviation technology. The Institute's scientific work was based on close cooperation with universities and industrial companies, thus strengthening the technological base of Czechoslovak aviation. This comprehensive approach enabled systematic research into all aspects of military aviation.

The Institute cooperated with leading domestic companies such as *Avia*, *Letov* and *Škoda*. These companies provided the Institute with both prototypes and production aircraft for testing in return for access to research results. This encouraged innovation in both design and manufacturing. The Institute was also equipped with the most advanced technology available at the time.⁴ Moreover, its activities were not limited to the domestic sphere - it also established international contacts.



Fig. 3. Strength testing at VLSÚ/VTLÚ (source: *adapted from* <u>https://www.vzlu.cz/historie-vzlu/</u>)

One of the main contributions of the *Military* Aviation Study Institute (Czech abbreviation VLSÚ)⁵ was its ability to enhance the quality of Czechoslovak military aviation. Through thorough testing and analysis, the Institute provided the armed forces with verified information on the reliability and performance of various aircraft and engine types. This not only improved the quality of armaments, but also led to more efficient use of resources in the training of pilots and technical personnel.

The Institute also played an important role in the development of regulations and standards that became binding for the entire aviation sector. In addition, the VLSÚ remained open to international influences. By monitoring

⁴ SCHINDLER, J. 50 let ve službách Československého letectví, VZLÚ, 1971.

⁵ PAVLÁK, René a SVITÁK Pavel, Od vzduchoplaveckého studijního ústavu k VZLÚ. In Letectví a kosmonautika, 1997, vol. 73, No 9, p. 559.

developments abroad, it adopted new methods and technologies and adapted them to domestic conditions. In this way, the Institute acted as a bridge between the Czechoslovak technical environment and global trends in aviation, enabling new developments to be rapidly incorporated into the country's defence system.

The Institute's technical facilities were among the most advanced of their time. It was equipped with aerodynamic tunnels, engine test rigs and laboratories capable of analysing fuels, lubricants and structural materials. These resources were essential for thoroughly evaluating the reliability and performance of equipment intended for active operational use.



Fig. 4. Institute staff (source: *adapted from https://www.vzlu.cz/historie-vzlu/*)

2. Historical Significance of the Institute

One of the most important contributions of the Military Aviation Study Institute was its ability to improve the quality of Czechoslovak military aviation. Through systematic testing and analysis, the Institute was able to provide the armed forces with verified data on the reliability and performance of individual aircraft and engine types. This led not only to improved weaponry, but also to more efficient use of resources in the training of pilots and technical personnel.

The technical equipment of the VLSÚ was among the finest available in Central Europe at the time. It employed aerodynamic tunnels for aircraft model testing, engine testing stands, and laboratories dedicated to fuel, lubricant, and material analysis. This infrastructure enabled advanced experimentation, the results of which had a direct impact on the development of new aircraft technologies. The institute also focused on researching the effects of weather on aircraft operations and the development of navigation systems.

Despite its successes, the VLSÚ was disbanded in 1932 as part of a wider reorganisation of the military structure. However, its activities were not completely terminated. Many of its research tasks and functions were transferred to other institutions - in particular to the newly established Military Technical Aviation Institute (VTLÚ)⁶, which operated with four divisions. The professional and scientific potential developed within the VLSÚ was thus preserved and continued under a new organisational framework.

The Institute's technical facilities were among the most advanced of their time. It was equipped with aerodynamic tunnels, engine testing facilities and laboratories capable of analysing fuels, lubricants and structural materials. These resources were essential for thoroughly assessing the reliability and performance of technology intended for operational use.

In 1936, production began of the now obsolete French Bloch MB.200 bombers, powered by Walter K14 engines built under licence. The following year saw the start of licensed production of Soviet SB-2 bombers powered by Avia Hispano-Suiza 12Y engines. In 1937 the Ministry of Defence requested the Institute's participation in the design and testing of several new prototypes: the Aero A-300 bomber, the Avia B-35 fighter, the E-51 reconnaissance aircraft (produced by ČKD Praha) and the Letov Š-50 for auxiliary purposes. In the period immediately before the Second World War, the Institute concentrated mainly on aerodynamics and structural strength calculations. During this period, aircraft from the *Letov, Aero, Avia* and *Praga* factories were tested at the Institute.⁷



Fig. 5. Visit to the Institute by a French general (source: adapted from <u>https://www.vzlu.cz/historie-vzlu/</u>)

3. The Role and Impact of the Institute on Czechoslovak Aviation

From a historical perspective, the Military Aviation Research Institute can be seen as a cornerstone on which the tradition of Czechoslovak aviation research was built. Its contribution lay not only in technological development, but also in the professionalisation of the entire field. The Institute demonstrated how the integration of science, engineering and the military could significantly enhance national security. Although it existed for a relatively short

⁶/www.vuapraha.cz/wp-content/uploads/2021/12/vojenske_ustavy_-

_1918-1939.pdf

⁷ VHA, fund: VLÚS, kar.2, inv. č. 7, Přílohy ke kronice- podklady, 1931 motorové oddělení.

period, its legacy had a lasting impact on both Czechoslovak and later Czech aviation.

The VLSÚ played a key role in the development and modernisation of the Czechoslovak Air Force. It provided reliable data to support decisions on the introduction of new technologies, significantly improving the effectiveness and safety of military aviation. It also contributed to the standardisation and formulation of technical norms that defined how aviation technologies should be designed and operated.

4. Conclusion

The *Military Aviation Study Institute* was an important stage in the history of Czechoslovak aviation. Although it existed for only ten years, its contribution was substantial - not only in terms of technological progress, but also as an example of effective cooperation between the state, the military and industry. The Institute succeeded in creating an environment in which research was closely linked to the practical needs of national defence, and its legacy continued in successor institutions long after its dissolution.

The VLSÚ was a key institution in the development of Czechoslovak aviation. It contributed to the professionalisation of military research and the strengthening of ties with industry. In 1932, the institute was officially dissolved as part of a military reorganization. However, its functions did not cease-most of its expert activities were transferred to the newly established Military Aviation Technical Institute, which directly continued the mission of the VLSÚ. Both personnel and technical capacities were preserved and further developed. The institute played a crucial role in shaping the tradition of Czechoslovak aeronautical research and development.

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The Integration of Computer Science into Educational Systems in France and Czechoslovakia: A Historical Comparison (1955-1965)

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Abstract. This study compares the introduction of computer science and cybernetics into the educational systems of France and Czechoslovakia between 1955 and 1965. This period marks the first initiatives in teaching these disciplines within a context of technological and pedagogical transformations. In France, early experiments in the use of computer science and cybernetics gradually developed within major technical institutions such as École Polytechnique and Supelec, supported by academic and governmental initiatives. In Czechoslovakia, despite different political and economic constraints, the teaching of these fields expanded in polytechnic universities, particularly in Prague. This study explores the strategies implemented in both countries, focusing on curricula, teacher training, and the first applications of technology in education. Special attention is given to comparing the educational systems in terms of cybernetics and computer science, highlighting challenges, differences, and the early influence of technology on education in these two contexts.

Keywords. *History of technology, history of education, computer science, educational system, reforms, 1955-1965, Czechoslovakia, France.*

1. Introduction:

Computing and cybernetics, though still new in the mid-20th century, profoundly transformed societies and educational systems. This article compares their introduction into education in France and Czechoslovakia between 1955 and 1965, a period marked by the first academic experiments in these fields. While the United States and the United Kingdom had developed computing for military purposes during World War II, France, occupied during that time, lagged and only began modernizing in the late 1940s. Initiatives such as the work of Cofinal and the development of CNRS and Bull contributed to this progress. Czechoslovakia, despite economic and political In restrictions due to its position within the Eastern Bloc, some polytechnic universities, such as the one in Prague, gradually integrated computing into their technical and scientific education. However, political choices influenced how these technologies were adopted.

This article examines the strategies implemented in both countries, analyzing several key aspects: the development of technological infrastructure, teacher training, and the first attempts to integrate computing and cybernetics into education. It also raises several essential questions: How did major educational institutions train engineers and disseminate these new technologies? How did the first computing and cybernetics courses evolve in France and Czechoslovakia? What differences marked their integration in each country? Finally, how did educational and industrial policies, as well as political and economic contexts, influence their development?

From a methodological perspective, this study highlights the role of public policies and institutional decisions in introducing these new technologies. It demonstrates that this evolution was not uniform but resulted from complex interactions between scientific progress, economic constraints, and political choices. This approach thus provides a better understanding of how national specificities shaped initiatives in computing and cybernetics education in France and Czechoslovakia.

2. The Emergence of Computing and Cybernetics in Education:

2.1. The Case of France:

In the 1950s, France, during post-World War II reconstruction, began investing in emerging technologies, particularly computing. This period was marked by a push for technological and educational modernization, supported by government and academic initiatives. However, France faced significant technological delays compared to the United States and the United Kingdom¹, due to the isolation of French researchers during the war and the immediate priorities of reconstruction.

As early as 1947, the CNRS (National Center for Scientific Research) signed a contract with the company *Logabax* to build the *Couffignal* machine, France's first electronic digital

¹ CHAVAROCHE-SI. L'histoire de l'informatique en France. In Chavaroche-SI [en ligne]. Accessed on February

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calculator. This initiative marked the beginning of France's efforts to catch up in computing. In 1948, the creation of the SEA (Society for Electronics and Automation) by François-H. Raymond played a key role in the development of computing in France. The SEA was one of the first companies to install electronic machines in defense-related organizations and later in commercial enterprises.

In 1962, the term "informatique" (computer science) was coined by Philippe Dreyfus, director of the National Center for Electronic Computing at Bull², reflecting the emergence of a new discipline focused on the automatic processing of information. That same year, the creation of the Bull Group by French engineer *Jean Trémège* marked the beginning of the French computer industry. Bull, supported by public investment, quickly became one of Europe's leading manufacturers of computers and computing systems.



Fig. 1. Automatic calculating machine with Dr. T. Kilburn and Prof. F. C. Williams $\ensuremath{\mathbb S}\xspace{5mu}$ Sipa^3

Funding for computing in France during this period was ensured through public-private collaborations. In 1966, the French government launched the *Plan Calcul*⁴, an ambitious initiative aimed at establishing a competitive national computer industry. This plan led to the creation of the *Compagnie Internationale pour l'Informatique* (CII) and funded the acquisition of computers in universities, particularly in Grenoble, Toulouse, and Nancy, where computing centers were established through government grants and partnerships with companies like IBM and Bull.

Pioneering universities, such as Grenoble, received specific funding for equipment purchases, such as the Bull Gamma ET in 1957⁵. These investments enabled the development of computer research laboratories and the training of the first generation of specialized teacher-researchers.

The first computer science courses in France emerged in a context marked by the rise of computing technologies and the need to train engineers and scientists capable of mastering these new tools. As early as the 1950s, prestigious institutions like the *École Polytechnique* and *Supélec* played a pioneering role by integrating courses on electronic calculators and computer systems. These innovative courses combined theoretical aspects (algorithms, mathematical logic, automata theory) with practical ones (programming, machine operation, solving concrete problems)⁶.

In universities, early computer science courses were often integrated into applied mathematics and numerical computing programs. For example, in Grenoble, Jean Kuntzmann established a certificate in numerical computing as early as 1949, followed by practical work on office machines and analog calculators. In Toulouse, Emile Durand introduced numerical computing courses in 1949, which evolved into a certificate program in 1956. These courses were primarily aimed at engineering and physical science students, meeting a growing demand for computing and programming skills.

In 1958, a notable initiative took place at the Sanatorium universitaire *Jacques Arnaud* in *Bouffémont*, where programming courses were offered to convalescent students. This modest experiment marked a turning point in the integration of computing into education, demonstrating that discipline could be taught outside traditional university centers⁷.

Training teachers in computer science was crucial to ensure the dissemination of this new knowledge. In the 1950s and 1960s, computer science teachers were often mathematicians or physicists who retrained in this new field. For example, *Jean Kuntzmann* in Grenoble and Emile Durand in Toulouse, both initially specialized in applied mathematics, played key roles in the development of university-level computer science. Continuing education programs were established, often in collaboration with companies like Bull, to help professors familiarize themselves with computing concepts and tools.

From the 1960s onward, pioneering universities like Grenoble and Toulouse developed postgraduate programs in computer science, training the first generations of specialized teacher-researchers. These programs helped meet the growing demand for computing skills in both academia and industry⁸.

² ibid.

³ Source(online) :

https://www.radiofrance.fr/franceculture/podcasts/lespasseurs-de-science-l-informatique/pour-une-histoire-de-linformatique-2612903

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⁵ ibid.

⁶ EMILIEN. Comment s'est-elle développée l'informatique en France In Musée Informatique [online]. Updated on September 6, 2022. Accessed on February 28, 2025. Available at: <u>https://www.museeinformatique.fr/comment-</u> sest-elle-developpe-linformatique-en-france/.

 ⁷ Michel Grossetti, Pierre-Eric Mounier-Kuhn. Les Debuts de l'informatique dans les Universites.*Revue française de sociologie*, 1995, XXXVI - n°2, pp.295-324.
 ⁸ Ibid.

The introduction of the first computers in educational institutions had a significant impact on teaching methods. Electronic calculators modernized educational practices, particularly in scientific and technical fields. For example, students could solve complex problems more quickly, opening new avenues for academic research. Starting in 1970, computers like the Mitra 15 and T1600 were installed in 58 high schools, allowing students and teachers to familiarize themselves with this new technology.

Despite these efforts, France struggled to compete with American giants like IBM. French computers, though innovative, were often less powerful and more expensive than their American counterparts, limiting their adoption in businesses and educational institutions. For example, in Toulouse, academics had to turn to IBM to acquire an IBM 650 in 1957 due to insufficient resources to develop a local solution. In 1975, France ceded the CII to the American company Honeywell Bull, marking the end of its ambition for an independent national computer industry.

Moreover, the development of computer science in universities was often hindered by disciplinary rivalries. "Pure" mathematicians, influenced by the Bourbaki group, sometimes resisted the emergence of computer science as an academic discipline, viewing it as a lesser applied science. These tensions slowed the integration of computer science in some institutions, such as Nancy, where mathematicians long refused to hire specialists in numerical computing.

2.2. The Case of Czechoslovakia:

In the 1950s, Czechoslovakia, under communist rule, also began to take an interest in computing and cybernetics, albeit in a very different political and economic context from France. As a member of the Eastern Bloc, the country was heavily influenced by the Soviet Union, which saw these technologies as a way to strengthen the planned economy and compete with the West technologically. However, Czechoslovakia faced specific challenges, including relative isolation from Western technological advancements and a centralized economy that limited private innovation.

As early as the 1950s, Czechoslovakia began developing its own computers, often in collaboration with other Eastern Bloc countries. For example, in 1957, the first Czechoslovak computer, the SAPO (SAmočinný POčítač, or "Automatic Calculator"), was built at the Institute of Mathematics of the Czechoslovak Academy of Sciences. Designed by engineer Antonín Svoboda, the SAPO was a relay-based computer, one of the first in the world to incorporate redundancy mechanisms to improve reliability. The SAPO used three parallel arithmetic units to vote on results, a technique called triple modular redundancy, which allowed error detection and correction. Though technically innovative, the SAPO reflected the technological and material limitations of the time, including a shortage of high-quality electronic components. In 1960, a fire caused by a short circuit in the relays destroyed the SAPO, ending its use.

Funding for computing in Czechoslovakia was entirely state-controlled, as part of five-year plans aimed at modernizing the economy and industry. Unlike in France, where public-private partnerships played a key role, Czechoslovakia relied almost exclusively on public investment and cooperation between research institutes and state-owned enterprises⁹. For example, the company ZPA (Závody přesného strojírenství), specialized in electronic equipment production, was tasked with manufacturing computers for national needs.

In the 1960s, Czechoslovakia launched several ambitious projects, including the development of the MSP series (Malý Střední Počítač, or "Small Medium Computer"), which was used in universities and research centers. However, these projects were often hindered by quality and reliability issues, as well as a lack of coordination among stakeholders. For example, the production of computers like EPOS 1 (using vacuum tubes) and EPOS 2 (using transistors) was delayed by component shortages and conflicting industrial priorities, such as tractor production.

The introduction of computer science into Czechoslovak education was slower and more centralized than in France. The first computer science courses were primarily offered at technical universities, such as the Czech Technical University in Prague (ČVUT) and the Slovak Technical University in Bratislava, where engineering and applied mathematics students were trained in the basics of numerical computing and programming.

In the 1960s, specific courses on cybernetics and automation were introduced, reflecting the regime's interest in these fields. For example, at Charles University in Prague, courses on automata theory and control systems were integrated into mathematics and physics programs. However, these courses were often theoretical and lacked practical resources due to the scarcity of computers available to students. Students often had to rely on paper simulations or work with outdated machines, limiting their ability to acquire practical skills¹⁰.

Teacher training in computer science in Czechoslovakia was also centralized and state controlled. Teachers were often mathematicians or engineers who received additional training at research institutes or technical universities. For example, the Institute of Mathematics of the Czechoslovak Academy of Sciences played a key role in training the first computer science teachers by organizing seminars and workshops on new technologies.

However, the shortage of equipment and teaching resources limited the quality of this training. Teachers often had to rely on theoretical textbooks and paper simulations due to a lack of access to functional computers. This created a gap

at: <u>https://alian.info/historia-a-vyvoj-pocitacov-v-</u> ceskoslovensku-v-rokoch-1950-az-1989/

¹⁰ EFMERTOVÁ, M., GOLAN, P., MANNOVÁ, B. Česká stopa v historii výpočetní techniky. Praha 2021.

⁹ ALIAN. História a vývoj počítačov v Československu v rokoch 1950 až 1989. In Alian [online]. January 21, 2005 [accessed on February 28, 2025]. Available

between academic training and the real needs of industry, hindering innovation and the adoption of new technologies.

The introduction of computers into Czechoslovak educational institutions was much more limited than in France. Early computers, such as the SAPO and the MSP series, were primarily used in research centers and major universities, while secondary schools and smaller universities had to make do with outdated or nonexistent equipment.



Fig. 2. The first computer almost took up an entire room.¹¹

This had a significant impact on teaching methods, which remained largely theoretical and disconnected from industrial practices. For example, computer science students often learned to program on paper using theoretical algorithms rather than on actual machines. This approach limited their ability to apply their knowledge in practical contexts, slowing the adoption of computing in the Czechoslovak industry.

Czechoslovakia faced major challenges in developing computer science, including technological isolation and excessive economic centralization. Czechoslovak computers, though conceptually innovative, were often less powerful and less reliable than their Western counterparts due to shortages of high-quality components and a lack of coordination among stakeholders.

Additionally, communist ideology sometimes stifled innovation by prioritizing short-term projects and limiting academic freedom. For example, Czechoslovak researchers had little contact with their Western counterparts, limiting their access to the latest technological advancements.

3. Conclusion:

The integration of computer science and cybernetics into the educational systems of France and Czechoslovakia between 1955 and 1965 reveals both shared ambitions and distinct trajectories shaped by their respective political, economic, and cultural contexts. While both nations recognized the

transformative potential of these emerging technologies, their approaches to implementation, resource allocation, and institutional adaptation differed significantly.

In France, the post-war period was marked by a concerted effort to modernize its technological infrastructure and educational systems. Government initiatives, such as the Plan Calcul, alongside collaborations between academia and industry, facilitated the rapid development of computer science programs in prestigious institutions like École Polytechnique and Supélec. The French approach was characterized by a blend of theoretical and practical training, supported by significant investments in equipment and teacher training. However, challenges such as competition with American technological giants and internal disciplinary rivalries hindered the full realization of France's ambitions for an independent computer industry.

In contrast, Czechoslovakia's integration of computer science and cybernetics was heavily influenced by its position within the Eastern Bloc. Centralized state control and a focus on planned economic development led to innovative but often constrained technological advancements, as seen in the development of the SAPO computer. Educational initiatives were more theoretical and less resource-intensive, reflecting the limitations of a centralized economy and technological isolation from the West. Despite these challenges, Czechoslovak institutions like the Czech Technical University in Prague made significant strides in introducing cybernetics and automation into their curricula, albeit with limited practical applications due to resource shortages.

The comparison between France and Czechoslovakia highlights the profound impact of political and economic systems on the adoption and dissemination of new technologies in education. France's decentralized, collaborative approach allowed for greater flexibility and innovation, while Czechoslovakia's centralized model emphasized theoretical rigor but struggled with practical implementation. Both nations, however, laid the groundwork for the future development of computer science education, demonstrating the importance of adapting educational systems to technological advancements.

Ultimately, this historical comparison underscores the complex interplay between scientific progress, institutional frameworks, and socio-political contexts in shaping educational reforms. The experiences of France and Czechoslovakia offer valuable insights into the challenges and opportunities of integrating emerging technologies into education, lessons that remain relevant as we continue to navigate the digital transformation of the 21st century.

Acknowledgment

¹¹ Source(online) : <u>https://www.poznatsvet.cz/veda-a-</u> technika/sapo-ceskoslovensky-pocitac/

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MISSION: STOP THE SPARKS! A device for steam locomotives

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Abstract The following article focuses on the technological development of the spark arrester used to control the expulsion of the spark produced by the steam locomotive, a spark associated with numerous forest fires at the end of the 19th century and the first half of the 20th century. From the perspectives of the history of technology and the history of engineering, the objective is to contextualize the development of the "spark arrester" device, to understand the circumstances of its emergence and its impact on the circulation of technical knowledge, as well as to identify the different agents and interests involved and to have a general understanding of the effectiveness of the device.

Key words

Spark-arrestor, history of technology, steam locomotive, forest fires.

1. Introduction

The steam locomotive, since the nineteenth century, had become the undisputed protagonist of the project called "progress", of civilization and to join the free market circuit. This powerful engine that crossed diverse landscapes, leaving smoke and ash in its path, which were the product of the combustion produced in the firebox, producing the heat and material that passed to the smokebox through the boiler tubes and flues, where it intermingled with the exhaust steam and was propelled up the chimney and into the atmosphere



Fig. 1. Illustration of spark production in the firebox.

This residue sent into the atmosphere had the potential to cause fires, which implied the emergence of a spark arrester project. This device, designed for the steam locomotive, is our object of interest, which will be approached from the perspective of the *history of technology* and placed in a variety of geographical conditions as well as different economic, political and intellectual dynamics. In this same line, technological change and development should be understood as a cultural phenomenon that was crossed by diverse interests and power relations. [1]

In addition, this perspective incorporates reflections from environmental history that permits to ask new questions to issue that have already been discussed: "technology is a cultural expression, its intersection with the natural sphere creates a subfield of environmental history, just as this intersection creates a subfield of the history of technology". [2]

This research is based mainly on the debates about the spark that took place among mechanical-railway engineers, discussions that can be perceived through publications such as the Journal of Institution of the Locomotives Engineers, Anales de Ingeniería Colombiana etc. These debates took place between the time limits of the end of the 19th century and the first three decades of the following one, meaning that it starts with the peak of the steam locomotive, an industry also favored by the impact of the end of the First World War and a "peaceful" industry, up to the moment of its decadence. I would like to highlight the following contributions: Passalacqua Faire de l'histoire ferroviaire par l'environnement et aborder les enjeux environnementaux par l'histoire ferroviaire: une voie à double sens; Emile, La locomotive à vapeur et le monde rural : une relation incendiaire. Compagnies ferroviaires et riverains face au risque incendie (1837-1937); Corvol, Le Feu, à la maison, par les bois et dans les champs (1993); and, Grady, Common Law Control of Strategic Behavior: Railroad Sparks and the Farmer.

Several fires were presumably caused by sparks from combustion, but other factors have also contributed to the increased risk of forest fires, such as weather conditions, cigarette butts from travelers. [3] There were even allegations that some of the fires were provoked by the owners themselves for the purpose of collecting compensation later.

The sparks are composed of partially consumed charcoal and ash and obey many variable factors, both in the action of the shot, which is the amount of vacuum in the smoke box is called, and secondarily, the condition of the fire and the character of the fuel.

The pressure from the landowners affected, the financial impact of the

compensation payments, pushed the experts to find a technical solution that would control the spark, attracting the investment of economic capital and the circulation of engineers. Likewise, prevention and reaction strategies were promoted, as well as the adoption of laws related to the protection against forest fires.



Fig. 2. Fire-killed Douglas fir: a study of its rate of deterioration, usability, and strength, 1913.

With respect to forest fires: in Canada, there were 686 between 1912-1916 that burned 37,263 acres and 34 percent of the causes were assigned to locomotives. [4] In the United States, the Great Southern Railway, during 1912, there were 16 and in 1913 this number increased to 64. [5] In France, the Landes Forest suffered fires in 1870-1873, in the early 1890s, around 1818-1920, and especially during the 1940s, which coincided with the introduction of the locomotive in this area.

2. The spark arrester



Fig. 3. Steam train engine and men, "Jumbo" engine with spark arrester, Oregon. 1910.

The spark arrester, also called *deflector* or diaphragm, varied depending on the diversity of locomotive models. Basically, it was of wire mesh and of perforated steel plate with two or three perforated plate protrusions, the purpose of which was for the sparks to impact. break, and then be ejected extinguished. [6] Besides, the spark-arrestor acted as a device for regulating the *draft*. In other words, to prevent and control potentially incendiary sparks affected the power of the engine, which could disable the locomotive. [7]

The first steam locomotives used wood for combustion and used a chimney with its huge balloon that housed a spark arrester. Later, coal was adopted, and finally almost all the engines were converted to burn fuel oil, due to the advantages of handling and economy offered by this fuel.



Fig. 4. Spark-arrestors "capó" / Spark arrestor used in E&C.R.

There were generally two types of spark arresters: the first was the "hood" type that was installed at the top of the chimney and used wood as fuel, however, when coal became widespread, the maintenance of these chimneys that had employed this type of spark arrester became a heavy burden of expense, due to repairs and replacements were a constant necessity. The second type of spark arrester was the "front end" which fits on the head of the engine. It was a device fitted to the inside of the smokebox of a locomotive to prevent active sparks from escaping up the chimney. [8]



Fig. 5. Spark-arrestor, Young's patent, 1833.

The first patent for a spark arrester appeared in 1833 by engine builder E. A. Young, of New Castle, U.S.A. Among the different spark arrester systems were those of the house Saint Leornard, in Belgic, which had a bell designed to stop small sparks from being carried away by the gas stream inside the chimney; the Boomerang by Washington Iron Works in USA, that stood out for being very resistant and worked equally well with wood or coal; [9] the Secova were characterized by their efficiency, by their light weight and that could be easily installed and removed and was available in various sizes; the Lima R&H Diamond Stack of the Lima Locomotive & Machine Co. began to equip locomotives with this stack in 1905, it had the advantage of eliminating the possibility of obstruction and the other is that an easy and free shot is obtained when starting the fire; In the United States, the spark arrester was a rigorously used accessory. Around 1910, the standard Mechanical Master Front Spark Arrestor Device, designed by Mr. Slater, was adopted and used by all North American railroads. such the Chicago as and Northwestern In 1912. Railroad: the Caledonian Railway introduced one of the best spark arresters used in Great Britain, the purpose of which was to extinguish the spark, or at least to keep it in the smokebox long enough for it to lose most of its heat and then be expelled; In 1914, Westralian, an Australian spark arrester consisting of an outer casing replacing the ordinary chimney and containing two rotors rotating in opposite directions and interlocking with each other. [10]



Fig. 6. Spark-arrestor Lima R&H Diamond Stack, 1905.

It is ambiguous to try to define whether the spark arrester was a device that really solved the problem. First, the manufacturing real cost had to be considered, as well as the posterior cost of maintenance, the decrease in locomotive efficiency because of reduced steam and the increased fuel consumption resulted. This is why the use of spark arresters, which was a necessity and an obligation in some cases, in the face of forest fires could affect the efficiency of the engine, since any obstruction in the smokebox and in the chimney of a locomotive reduces its steam generation capacity and increases fuel consumption. [11]

According to some there were "years went by, and it became apparent that the railroads were expending an immense amount of effort and money on experiments which were duplicates of others already made, or which gave misleading or contradictory results for lack of information." Others said "I'm afraid I can say very little about them [spark arrestors], because I don't believe in any of them. I believe that the best way to minimize spark emission is by careful design of the details of the smoke box". [12]

It is possible to affirm that around the spark arrester project there are several motivations, such as, for example, at an economic level, which is the one that prevailed, the device not only meant the possibility of making money taking advantage of the world market that had gone wild towards the railway development, but also to avoid the financial decline of the railway companies that had to pay millionaire compensations due to the forest fires. On the intellectual side, there is no doubt that it motivated the creativity of engineers in different parts of the world, which at the time gave them more prestige as fundamental figures in the industrialization process. Paradoxically, railway engineers, who had dedicated many years to the steam locomotive, were relegated with the technological change.

The environmental impact of the damage caused by forest fires contributed to the beginning of a new way of thinking about the environment. The pressure from the government authorities due to the numerous fires, added to the pressure from the owners of the damaged lands and the impact on the finances of the railway companies due to the high indemnities they had to pay, promoted the development of a device that could minimize the problem.

3. Conclusions

History, as a discipline, is called upon to take sides in the great debates of today. The historian must be more inclined to interdisciplinary work and to think about questions already thought about, but from a critical new. more point of view. Environmental history and the history of technology are presented as methodologies that renovate the historical duty, that allow us to explore and ask new questions -sometimes uncomfortable- to traditional topics.

The spark arrester was a device that concentrated diverse efforts and interests, from the authorities in charge of protecting against forest fires that pressured the railway companies to find solutions, and the latter involved mechanical engineers who, thanks to their technical knowledge, tried to find practical solutions and also to standardize a spark arrester, despite the impossibility due to the great diversity of types of steam locomotives, which hindered the unification of a solution and made the problem even more complex. However, the above mentioned is also a reflection of the reality of that time, where the geographical and climatic variety, etc., prevented standardization, since the response had to be adapted to the conditions.

The speech of the benefits of the diesel locomotive and the diesel-electric locomotive by not producing spark was used to contribute to the decline of the steam locomotive and, therefore, any initiative to design or improve the spark arrester lost its raison for being. Although the spark arrester did not achieve absolute spark control, it did decrease the number of sparks expelled from the locomotive's funnel into the atmosphere.

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From Lwow and Warsaw to Prague. A talk about professors Adamiecki, Hasa, and Šlechta

Czechoslovak-Polish scientific cooperation in the years 1929-1949

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Abstract: This paper focuses on the personalities of the labour organisation movement, including engineer Emanuel Šlechta, who was appointed Secretary of the Czechoslovak Committee for the Scientific Management of Labour upon his return from the USA, where he worked closely with the Committee's chairman, Professor

1. Introduction

The scientific labour organisation movement was rooted in American Taylorism and in the early 20th century aimed to improve production and cost efficiency in industry, including the use of new innovative knowledge, technical breakthroughs and more efficient machines. When Taylor presented evidence of his theories, actions, and research in the fall of 1910, the technical literature was suddenly enriched by a new conception of scientific management. Another important exponent was Henry L. Gant, known for his diagrams and the introduction of bonuses. Frank and Lillian Gilbreth built on Taylor's ideas and further. developed them Harrington Emerson is also worth mentioning for his work on efficiency.

František Hasa, e.g. as editor in the publication of the journal "Zpravy ČSKO".

Keywords

The scientific labour organisation,

in hand with scientific Hand management went rationalisation, which developed and pushed it further, dealing with external issues of production, such as the concentration of production for joint buying or selling, joint management, research. patents promotion. or Alternatively, it could also lead to the suspension of plants that were underperforming, whether because of inadequate facilities, location, or other factors.

After the First World War, there was a great interest in the study of the organization of work, which led to the establishment of a number of institutions and scientific centers focused on this issue. The International Labour Organisation (ILO) was founded in 1919 at Versailles as a permanent establishment of the League of Nations. The first ILO conference was held in Washington, D.C., in 1919. From December 14, 1946, it became a special organization with headquarters in Geneva. Following the International Congress of Scientific Management (PIMCO), held in Prague, 20-24 July 1924, the International Committee for Scientific Organization was established. Two years after the congress, the Czechoslovak National Committee for Scientific Organization was also founded, which took over some of the activities hitherto carried out by the Masaryk Academy of Labour of the Ministry of the Interior and the AAV of the Czech Republic.

On the basis of the Committee, there was professional interaction with Polish colleagues, both in the press and on the platform of the international congresses on labour organisation in Prague (1924), Rome (1926) and Paris (1929), Amsterdam (1932) and London (1935). The period under study begins with the arrival of engineer Emanuel Šlechta as secretary of the Czechoslovak Committee for Scientific Management of Labour (1928), when he also became editor of the journal "Zpravy ČSKO", where he worked closely with the chairman of the Czechoslovak National Committee. Professor František Hasa.

The first part of this text is devoted to the "founding" generation of this movement, i.e. the generation of engineers and university professors who began to apply the interventions of Taylorism coming from America in Central Europe. They are Professor Karel Adamiecki from the Warsaw Polytechnic and Piotr Drzewicki. On their initiative, the Labour League was founded on 26 February 1919 and existed until September 1939. On the initiative of this organization, the Institute for the Organization of Scientific Labor was



Pict. 1.1 profeosor František Hasa (source: Archive of the Czech Technical University in Prague)

founded, which promoted knowledge of psychotechnics Taylorism and and advocated economic education for society. Its publications included the publication of approximately 100 works and a series of pamphlets entitled "Will and Labour". However, this organization did not live up to the hopes placed in it and the Institute of Scientific Organization had to be dissolved for financial reasons. Adamiecki did not hide his disappointment after these setbacks. Professor Karel Adamiecki headed the Department of Principles of Industrial Organisation and Industrial Enterprises at the Faculty of Mechanical Engineering, where he gave lectures on "On the Principles of the Organisation of Work" and "Industrial Foundations".

2. Professor František Hasa

Another of the founders was Professor Ing. Dr. h.c. František Hasa, full professor of the College of Mechanical and Electrical Engineering at the Czech Technical University in Prague, chairman of the Czechoslovak National Committee for Scientific Organization. Professor František Hasa was a full professor of mechanical technology.



Pict. 1.2 profesor Karol Adamiecki (*source: Narodowe Archiwum Cifrowe*)

The Czechoslovak National Committee for (CSCO) Scientific Organization was founded on the basis of a resolution adopted at the First International Congress for Scientific Organization in Prague (PIMCO) on 24 June 1924, which was organized in cooperation with other foreign organizations by the Masaryk Academy of Labour and which gave rise to the International Committee for Scientific Organization. The preparatory work for the Comité was done by the Masaryk Academy of Labour under the leadership of Dr. Zimmler, and the structure of the Advisory Council on Economic Questions served as a model, so that the Comité was also composed of three groups, i.e., professional, workers' and employers'.

In the international field, his services to scientific organization were especially recognized by the loan of the Polish Order, by the election of the Vice-Chairman of the International Committee for Scientific Organization, and by his participation from the beginning in the organization and membership of the Administrative Committee the of Scientific International Institute for Organization in Geneva. In 1930, Professor Hasa was appointed Honorary Doctor of Technical Sciences of the Czech Technical University in Prague for his services to the development of technical sciences and his teaching activities.

The International Committee for Scientific Organization, Comité International de l'Organisation Scientifique (CIOS) evolved from the International Delegation of Permanent Scientific Congress, Management which was established at the Prague Congress in 1924. After a meeting held in Paris, and then in Prague in May of the following year, it was decided in June 1926 to transform the Permanent Delegation into the International Committee for Scientific Organization (Comité International de l'Organisation Scientifique - CIOS). The International Committee was made up of 10 national committees. The core activity of the International Committee was to prepare international congresses for scientific organisation and to promote rationalisation in general.

At the Congress in Rome (1926), Professor Adamiecki (Poland) and Professor František Hasa (Czechoslovakia) were elected vice-presidents of the CIOS. The same situation was repeated at the Paris Congress (1929). At the meeting on 20 July 1932 at the V. Hasa and Adamiecki were again elected vice-presidents. Piotr Drzewiecki was elected to the IOST.

VII. International Congress for Scientific Management in Washington in September 1938 was already marked by the proximity of World War II. Associate Professor Emanuel Šlechta attended for Czechoslovakia as a representative of the Czechoslovak government. Professor František Hasa died on 27 March 1945 in Mníšek pod Brdy at the age of 82.

3. Professor Emanuel Šlechta

The second part of the text is devoted to the Czechoslovak Minister of Technology. Emanuel Šlechta was awarded a professorship in industrial management at the Czech Technical University in 1945. In February 1948 Emanuel Šlechta was appointed Minister of Technology, on 20 December 1950 Minister of Construction Industry and from 14 September 1953 Minister of Construction Industry. In the second government of Klement Gottwald he was Minister of Technology from February 1948. He retained the post until 1950 in the government of Antonín Zápotocký and Viliam Široký in which he then became Minister of Construction (Building Industry) from 1950. He held this the subsequent position in second government of Viliam Široky until 1956 and was appointed Minister of Technology in 1948. During his tenure he made several trips to post-war Poland (1948, 1949, 1952).

4.Professor Karol Adamiecki

Karol Adamiecki (18 March 1866 Dąbrowa Górnicza - 16 May 1933, Warsaw) was a Polish engineer, management researcher, economist and professor, from 1919 associate professor at the Faculty of Mechanical and Electrical Engineering at the Warsaw Polytechnic, where he lectured in the field of rolling and forging with elements of collective labour organisation. On 16 August 1922, he was appointed an extraordinary professor and took over the chair of principles of industrial organization and industrial enterprises at the Faculty of Mechanical Engineering, which he headed until his death in 1933. From the academic year 1923/24, he lectured students in the 7th and 8th semesters at the faculties of chemistry, electrical engineering and mechanical engineering on "On the Principles of Labour Organisation" and "Industrial Foundations". František Hasa (February 4, 1863 Stínava -March 27, 1945 Mníšek pod Brdy) full professor of mechanical and electrical engineering at the Czech Technical University in Prague, chairman of the Czechoslovak National Committee for Scientific Organization. He graduated in mechanical engineering at the Czech Technical University in Prague. In 1891, he worked for the Märky, Bromovský & Schulz machine works in Prague, then joined the Fr. Ringhoffer, where he carried out a number of reconstructions of sugar Romania, factories in Hungary and Bukovina. In 1908 he was called to the chair of mechanical technology at the Czech Technical University in Prague. Similarly, here he built the institute, especially the mechanical workshops, in such a way that they would best serve practical, illustrative teaching. After 1918, he set up testing laboratories for testing tools and machine tools, as well as a research station for ductile materials.



Pict. 1.3 profesor Karol Adamiecki a Harington Emerson (source: Narodowe Archiwum Cifrowe)

The main source of information about the Polish labour organisation movement in Czechoslovakia was the magazine "Zpravy ČSKO", published by the Czechoslovak Committee for Labour Organisation. The magazine was published 10 times a year on the first of each month, except July and August. The editorial office was located in the building of the Czech Technical University in Prague, at Karlovo náměstí 14, Prague 2, publishing and administration was carried out bv "Prometheus", Prague 8, before it moved to the new building of the Bánská and Hutní společnost at Prague 2, Lazarská 7.

5. Proceedings of the Czechoslovak Committee of Labour Organisation

The debate about publishing its own journal in the Committee took place on 10 February 1928, after the visit of the Secretary General of the CIOS, Dr. Landauer, to Prague. The Comité intended to regularly inform about its activities, preferably in printed form. At the meeting on 23 March 1928 it was decided to publish the journal "Zpravy ČSKO" and its preparation was entrusted to the newly arrived Ing. Šlecht. At the committee meeting on 17 April 1928 Ing. Šlechta was elected the new Secretary of the Committee. From the very beginning of its publication, the new magazine contained news about the activities of the Polish Comité. On April 17, 1928 the new journal informed that the official delegates of the II. Polish Congress in Warsaw were appointed the President, Professor Hasa, and Dr. Jan Stocký. Professor Brdlík and Dr. Stocký promised to give papers. Subsequently, the content of one Polish paper was described in detail in an article entitled II. Congress of the Polish Committee for Scientific Organization. Section 2a, Application of Scientific Organization in Industry.

The article Lecture series on office organisation reported that the Polish for Scientific Organisation Institute organised a lecture series from 7 March to 27 March. May 1929, a series of 44 lectures on the following topics: principles of work organization (6 hours), basics of work organization in offices (6 hours), basics of work in state administration (4 hours), basics of classification of documents (2 hours), basics of standardization (2 hours), selection of administrative staff (4 hours), arrangement of office rooms (2 hours), production cost economic as an characteristic (4 hours), administration of public offices (4 hours), organization of correspondence and archives (6 hours), history of office reform (4 hours). The lecturers were Professor Karel Adamiecki, Ing. Wojciechowski, Ing. S. Twardo and others.

In April 1929, a letter arrived at the Committee's address in which M. Duivys gave further information on decimal classification, and Professor Hauswald sent information on the terminology of scientific management. On 14 May 1929 Ing. Šlechta reported on the preparations for the establishment of the terminology of the scientific procedure Reference was made to the work of M. Duyvis (Amsterdam), who was working on decimal classification. Mr. Duyvis sent information on the progress of the work connected with the publication of the code of decimal classification. Correspondence to Professor Hauswald (Lvov)

This paper was followed by a discussion on the workflow of terminology using Teyzler's technical discovery dictionary. Dr. Stocký drew attention to the French dictionary. Dr. Zimmler suggested a compilation according to Hauswald. Ing. Mansfeld recommended the dictionary of the Czech Technical Matrix. Ing. Šlechta suggests that the following procedure should be followed: that the terminology, i.e. the correct terms, should first be ascertained, given to both technicians and philologists for correction, and then passed on to the final editors of the referees, who would be elected by the committee afterwards.

In April, Professor Drzewiecki was asked to send a bibliography of Professor Adamiecki.

The first major event of the Committee, in which Šlechta was fully involved, was the preparation of the Czechoslovak participation in the IV. Czechoslovakia was represented bv Professor Hasa and Ing. Šlechta. At the beginning of the Congress, a Garden Party was held at the French Chamber of Commerce, where the Czechoslovak delegation met with colleagues from Poland, Yugoslavia and the United States. In the evening, a dinner in honour of the Czechoslovak delegation was hosted by the prominent Czech lobbyist Dr. Jan Jiří

Rückl, who was a member of the French National Committee and the liaison of the Czechoslovak National Committee in Paris, at the Lutetia Hotel.

At the Paris Congress, a number of Polish participants presented their papers in the Industry section. M. Fucholka: Systematic control equipment in coal mines, S. Tarwid: Introduction of scientific organization in the technical work of switching stations, Ing. J. Wagner:



Pict. 1.4 Warsaw Polytechnic (author's own photo)

Rationalisation of work in the workshops of the Polish State Railways, M. Bornstein: Scientific organisation in the Polish chemical industry in 1924-1928. The author of this paper reported here on the results of the work of the section for scientific organisation in the chemical wholesale industry in Poland, described the introduction of time studies in the pharmaceutical industry, the system of remuneration, wages, the use of graphic methods in industry and Gant diagrams.
A paper was published in November 1929: T. Tomaszewski: Graphic control of preparation and control of work in agriculture. On 1 September, by letter, Huta Silesia, Warsaw, asked for information about Dr Verunac's report at the Paris Congress.

This was followed by the article Production and Operation: the Coal Industry in the Czechoslovakia and Rationalisation. which said: The intensification of machine mining is one of the few competitive weapons our coal industry has against competition from, for example. Poland. Apart from the disproportionately greater social burdens on the coal business in the Czechoslovakia, the natural conditions in the Ostrava-Karviná district are much more unfavourable than in the coal mines in Poland.

In January 1930, a comprehensive biography of Professor Adamiecki with a photograph was published in Zprávy ČSKO, for which Professor Adamiecki thanked him in April with a personal letter. In 1931 the magazine reported that a psychotechnical institute for the petroleum industry had been established in Poland.

At the V International Congress in Amsterdam on 20 July 1932, Professor Hasa and Professor Adamiecki again became vice-presidents, and Ing. Drzewicki. At this congress Poland participated with only papers, 5 Czechoslovakia with 12 papers. Purely agricultural countries, such as Yugoslavia, Poland, Romania, had no papers at all in the field of agriculture.

In October 1931, in the article Rationalizing Correspondence: Harmonograms: the experiment of Professor Karl Adamiecki and long practice arrived at the construction of special tables, which we call harmonographic tables. In February 1932, Wallace Clark's article The Influence of Scheduling in Production appeared, describing: The plant is located in Poland, Pullman type passenger rail cars, freight and coal cars, streetcars, and miscellaneous equipment for railroads, such as switches, pens, etc. The plant was founded 110 years ago as a foundry and machine shop. In 1929, at the time of the beginning of the reconstruction, it employed 3,000 workers.

On 23 November 1932, a meeting of the editorial board of the ČSKO News was held, where a proposal was presented for a new cover and text design for the VIth edition, the new edition to be published with the main title Organisation. The same issue contained a large profile article on Professor Has. This was followed six months later by a lengthy article on the death of Professor Adamiecki.

In 1934, the journal Organisation published an article entitled The Use of Scientific Organisation in the Workshops of the Polish State Railways by Ing. The Ministry of Transport began to reorganise the main railway workshops in 1925. This part of the railway service was the first in which scientific organisation was applied. The Polish State Railways had inherited from the previous occupants only a few railway workshops, mostly ruined, in obsolete buildings, badly laid out and mostly incapable of being converted into modern workshops, with all the technical conveniences. In addition, the Polish railways received from the occupiers a varied rolling stock, composed of various types, in a very poor condition, caused by the World War and the war with the Bolsheviks, when it was badly damaged. In 1925 the Ministry of Transport drew up certain principles and guidelines to guide the workshops in their reorganisation. In the

same issue, an article on the reform of public administration in Poland was published. There was also an article on a paper presented at the Congress in Amsterdam by Ing. H. Paskowicz.

VI. Emanuel Šlechta represented Czechoslovakia for the first time at the International Congress in London from 15th to 18th July 1935, presenting an English paper in the Production section entitled "Reorganisation of work in locomotive workshops in Czechoslovakia". The first paper was presented in the article "The Locomotive Works of the State Railways". In place of Professor Adamiecki (who died on 12 May 1933), Piotr Drzewiecki was elected Vice-Chairman of the CIOS. Professor Hasa, who resigned as Chairman of the Czechoslovak Committee on 3 October 1933, was elected an honorary member of the Committee, and Emanuel Šlechta and Piotr Drzewiecki were appointed as new members. At the congress, Professor Limperg, President of the CIOS, in his speech appreciated the merits of the late Professor Adamiecki and his importance for the movement of scientific organization.

From September 19-24, 1938, the Congress was held in Washington, D.C. VII. International Congress for Scientific Management under the auspices of the International Committee for the Scientific Organization of Enterprises. Emanuel Šlechta attended for Czechoslovakia as a representative of the Czechoslovak government and presented a paper on continuous and intermittent work.

As the journal "Organisace" was finishing its tenth year, a short review of what the journal had done so far was published. During this time the journal had published 300 original articles in all branches of economic activity, 2,000 extracts from articles in domestic and foreign journals in so far as they dealt with questions of scientific organization, and 500 book reviews. Statistical data, however, are not the only serious measure of the quality of the work; it is necessary to analyse the content of the articles and the information that the journal has provided over the past 10 years.

6. International Awards

On 10 December 1928, the President of the Republic of Poland, Ignacy Mościcki (1867-1946), awarded the professor of the Czech Technical University in Prague, Ing. František Hasa with the Commander's Cross of the Order of Polonia Restituta.

The badge and diploma were delivered to Professor František Hasa by the Rector of the Czech Technical University in Prague, Professor Ing. František Klokner and the Dean of the College of Mechanical and Electrical Engineering, Professor Dr. František Nachtikal. On January 4, 1929, diploma "Polonia Restituta" the confirmation was sent on December 19, 1928. On Tuesday, January 8, 1929, Professor Hasa thanked the Polish Ambassador and Minister Plenipotentiary Dr. Waclaw Grzybowski for the award of the Order and asked him to convey the kind thanks of the undersigned to the President of the Republic of Poland. The Ambassador was not in Prague in December 1928, and did not return until the end of the year.

The "Polonia Restituta", a high Polish decoration, the second highest Polish civic order, established on February 4, 1921, was awarded to Professor Hasa by the Polish President Ignacy Mościcki (1867-1946), in office from 1926-1939. The proposal of the Czechoslovak Ministry of Foreign Affairs, signed by Foreign Minister Edvard Beneš, dates from 10 April 1929:

It is proposed to confer the Order of the White Lion, 4th class for civic merit, proposed by: Professor Karel Adamiecki, residing in Warszawa, Foksal 11. Reason for the proposal: Karel Adamiecki is a professor of technology in Warsaw, chairman of the Institute of Scientific Organisation and of the Polish National Committee for the Scientific Management of Work, and his work as a scientist and researcher, as well as an experienced engineer and practical Slavic patriot and a proven friend of the Czechoslovak nation, has brought and is bringing much benefit and advantage to our country for the proposed recognition. Signed this 10th day of April 1929 by the Minister of Foreign Affairs, Dr. E. Beneš.

Acusé de Réception (signature of Adamiecki).

A letter on this matter was received in Prague on 5 May 1929 by the Chancellor of the Castle, JUDr. Přemysl Šámal:

To the Chancellor of the President of the Republic in Prague,

in the Ministerial Council held on 2 May 1929, it was resolved to recommend to the President of the Republic the conferment of the Order of the White Lion for Civic Merit III. Ing. Francesco Mauro. Another letter to Šámal, this time from the President of the Masaryk Academy of Labour, Zimmler, dated 6 June 1929, sheds light on the whole situation:

Glorious Chancellor!

Forgive me for bothering you with a small request. About a year ago a proposal was made that the members of the Committee of the International Committee for the Scientific Management of Labour, whose headquarters are in Prague, namely, Senator Mauro of Italy, Professor Ing. Adamiecki of Warsaw, the French engineer Fréminville and others were awarded the "Order of the White Lion" for the merits they had gained for the Czechoslovak *Republic in organising the first congress for* the scientific management of work in Prague and the development of rationalisation technology in this country and in the world. I am involved in the proposal as far as Mr. Adamiecki is concerned, who is found to have preached the theory of rationalization before Taylor. The file, finally approved by the Ministerial Council, is, I am informed by the Foreign Office, in the office of the President. As the Congress for the Scientific Direction of Labour begins at Paris on the 19th of June this year, and the gentlemen of the Committee of Honours will be present there, it would be very desirable if the decision could be carried out by that time, so that our Messrs. (Zimmler).

6-7 June 1929 from Zimmler, Ing. Mauro, Ing. Adamiecki, Ing. Fréminville and Ing. Jusic, conferring the Order of the White Lion. Personal interest of the Chancellor to ev. satisfy Zimler.

The reply to Emil Zimmler is dated 11 June 1929:

The Chancellor Dr. Šámal has instructed me to inform you in response to your letter of 6 June that the President, by resolution of 30 May this year, has conferred the Order of the White Lion for Civic Merit on Ing. Mauro, 4th class Ing. Adamiecki and Class V Ing. Freminville and Ing. Ing. On June 6, the diplomas were sent out by our office.

On May 30, 1929, the Polish Professor Karol Adamiecki received the Order of the White Lion, IV degree. This was on the basis of the Resolution of 30 May 1929, signed by T.G.M. and Foreign Minister Edvard Beneš.

A letter dated 30 October 1929 was sent by the Office of the President of the Republic, the Ministry of Foreign Affairs enclosing a receipt signed by Ing. Karol Adamiecki, who was awarded the Order of the White Lion.

On 16 May 1933, Eng. Karel Adamiecki, professor of Warsaw technology, awarded the IV class of the Order of the White Lion (3 June 1933). Entered in the register: IV. 425. c. 334.

Conclusion

Czech-Polish cooperation was most intense in 1924-1938. At the Congress in Rome (1926), Professor Adamiecki (Poland) and Professor František Hasa (Czechoslovakia) were elected Vice-Presidents of the CIOS. The situation was the same at the Paris Congress (1929). At the meeting on 20 July 1932 at the V. Hasa and Adamiecki were again elected vicepresidents. Piotr Drzewiecki was elected to the IOST. The period of intensive mutual cooperation ended in 1933 with the death of Professor Adamiecki and the resignation of Professor Hasa as Chairman of the Czechoslovak Committee.

At the VI. International Congress in London in 1935, Professor František Hasa resigned from the position of Vice-Chairman of the CIOS and Piotr Drzewiecki was elected the new Vice-Chairman.

The new members of the International Committee were Emanuel Šlechta and Piotr Drzewiecki. VII. International Congress for Scientific Management in Washington in September 1938 was already marked by the proximity of World War II. Associate Professor Emanuel Šlechta attended for Czechoslovakia as a representative of the Czechoslovak government. Professor František Hasa died on 27 March 1945 in Mníšek pod Brdy at the age of 82.

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Dimensions of Explainability in AI Alignment

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Abstract.

Human-AI alignment is challenging due to limitations in both technical solutions and governance frameworks. Given the infeasibility of properly anticipating all potential misalignment risks, we see explainability as essential for continuous oversight, bridging the gap between AI systems, governance, and human intervention. Recognizing the multifaceted character of the problem, we argue for a structured framework for evaluating explainability methods, moving beyond narrow technical metrics, to enhance future developments in AI accountability and alignment.

1. Introduction

Ensuring alignment between AI behavior and human values remains a significant challenge in both technical and governance domains. Declarative top-down technical frameworks are widely considered infeasible due to their ambiguity and inability to address real-world complexities [1, 2]—a concern illustrated in literature dating back to Asimov [3], later extended by Bostrom [4]. However, the modern governance approaches encounter analogous difficulties in the implementation and enforcement of the complementary oversight mechanisms and AI regulations, such as the AI Act [5].

Meanwhile, contemporary technical alignment efforts continue to struggle with developing reliable, generalizable solutions for aligning AI systems. While some methods, such as symbolic learning and expert rule-based approaches, offer behavioral guarantees [6], their real-world applicability remains highly limited. Conversely, highly applicable deep learning methods, which rely on data-driven training, exhibit critical failures like reward hacking [7]—highlighting the complementary infeasibility of some safe universal value function optimization. Widespread techniques based on such optimization over user data, such as Reinforcement Learning from Human Feedback (RLHF) and its variants [8, 9, 10], thus remain unreliable. As AI systems operate in increasingly complex environments, unforeseen failure modes are inevitable. Since it is impossible to predefine and test for all risks in advance, continuous human oversight is essential. In this paper, we argue that *explainability* should serve as the foundation for such oversight, enabling ongoing assessment and intervention as new challenges emerge.

Besides ongoing misalignment issues, the development of foundational AI models remains highly centralized, controlled by a few major organizations, limiting external stakeholder influence. This opacity further exacerbates alignment concerns, as stakeholders lack insight into how these models operate. Explainability is, therefore, crucial for democratizing oversight, enabling external actors to scrutinize and challenge AI decision-making. Without such transparency, alignment efforts risk becoming monopolized, leading to governance structures that fail to reflect diverse ethical and regulatory perspectives. While initiatives like AI Safety Institutes and emerging directives represent progress, highlevel policies alone are insufficient. Effective governance requires complementary bottom-up implementation, particularly in legal contexts where AI decisions must withstand judicial scrutiny. Explainability methods are thus essential to complement top-down regulation with bottom-up accountability, ensuring AI behavior remains transparent and justifiable.

Identifying these factors, we argue for a structured, multi-faceted approach to evaluating explainability approaches in the specific context of AI alignment. While there is a broad body of technical explainability research, it prioritizes narrow metrics such as fidelity or attribution accuracy. These techniques fail to capture the broader context of alignment where explainability is not merely a technical concern but a socio-technical bridge between AI systems, governance structures, and human oversight.

2. Assessing XAI methods for Alignment

Despite the abundance of explainability (XAI) methods [11, 12, 13, 14], existing evaluation frameworks focus primarily on technical aspects [15], neglecting the explainability's role in AI alignment and governance. The 12 properties of explanations presented by Nauta et al. [16] are focused on formal requirements (e.g., correctness/faithfulness), practical issues (e.g., compactness), and user experience (e.g., coherence). User experience is (along with trust and performance) also prioritized by Kim et al. [17], Lopes et al. [18], Liao and Varshney [19]. Finally, Islam et al. [20] are proposing high-level dimensions (fidelity, interpretability, robustness, fairness, and completeness), which are, however, evaluated with a very concrete techno-centric metrics and methods.

We argue that effective oversight requires more than technical evaluations and satisfactory user experience-it demands explanations that are understandable to different stakeholders, actionable, and scalable to real-world systems. Crucially, these desiderata should be evaluated jointly to assess their potential trade-offs. Consequently, we propose the following dimensions for XAI methods that not only clarify model behavior but also support human engagement, regulatory auditing, and model corrections.

Intuitiveness to subjects The first dimension is the comprehensibility of explanations to non-expert users. This aligns with regulatory efforts, such as the "right to explanation" [21], which, while not legally binding [22], highlights the importance of intelligibility in AI decision-making. In legal and governance contexts, understandable explanations improve transparency and trust by reducing the need for expert intermediaries. We propose evaluating this criterion through empirical studies, where diverse user groups infer AI decision-making implications based on the explanations. The users' correctness is then the measure of intuitiveness.

Understandability to auditors Beyond lay users, explainability should also support expert evaluation, particularly in regulatory and safety-critical applications. Auditors, policymakers, and AI oversight bodies, such as the AI Office formed under the EU AI Act, require explanations that provide deeper insights into model behavior [23]. Unlike lay users, auditors may possess technical expertise in statistics or machine learning, allowing them to process more complex explanations. Evaluation of this dimension would involve expert assessments of explanation effectiveness in auditing scenarios, such as compliance checks or failure investigations.

Veracity A key requirement of any explanation is that it accurately represents the underlying model's behavior. Often referred to as fidelity or faithfulness [16, 24], this desideratum ensures that explanations are not misleading or oversimplified. For instance, a highly compressed symbolic explanation may be interpretable but fail to reflect the actual decision boundaries of a deep neural network. One possibility is to measure veracity as the expected proportion of inputs for which an explanation remains consistent with the model's true decision function. In local explanations, this would involve testing whether small, explanation-based input modifications yield the expected model changes.

Actionability Explainability methods must enable corrective actions to be useful in AI alignment. If an AI system produces an undesirable outcome, an auditor should be able to infer how to adjust the model. Likewise, an end-user should be advised on how to modify their input to achieve a different, desirable result. Counterfactual and contrastive explanations [25] are a prime example of actionable insights, as they specify minimal changes needed to alter an AI deci-



Relations between the dimensions of explainability.

sion. Actionability could be empirically assessed by evaluating whether users or auditors, given an explanation, can successfully adjust the model's behavior in a controlled setting.

Scalability Finally, explainability methods must be computationally feasible for modern, large-scale AI systems such as large language models [26]. The increasing complexity of these state-of-the-art models raises concerns about the practical application of interpretability techniques [27]. Scalability could be assessed by measuring the cost of generating explanations across models of varying sizes. A suitable metric would be, e.g., the expected time required to produce explanations under real-world conditions w.r.t. a given level of veracity.

Entanglement of the dimensions The proposed dimensions offer a comprehensive, albeit non-exhaustive, representation of the explainability domain; nonetheless, they are not independent of one another. Figure 1 illustrates the key relationships between the dimensions within both technical and human-centered contexts. We consider intuitiveness and understandability as primary representatives of humancentered perspective, while veracity and scalability emphasize technical aspects. Actionability serves as the connector among all elements-intuitiveness and understandability are intertwined through the empirical measurement of actionability, while scalability and veracity relate to the overall effectiveness of actionability. Additionally, several tradeoffs may exist: explanations that are sufficiently simple for lay users may lack the technical depth required by auditors; more intuitive explanations often necessitate simplification, which can compromise veracity; and more accurate explanations frequently demand additional computational resources, thereby impacting scalability.

3. Conclusion

By structuring explainability methods around the proposed dimensions, we aim to foster developments beyond narrow technical metrics towards a broader, multi-faceted explainability research for AI alignment. While the actual assessment of existing XAI methods was out of scope for this work, we laid out these dimensions to highlight the role of explainability in AI alignment-serving not just as a technical tool but as a real bridge between AI systems and humans.

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Simulation of position improvement in multi-agent system with relative measurements

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Abstract. This paper introduces a MATLAB-based simulator framework designed to evaluate position accuracy in a multi-agent system, encompassing vehicles, pedestrians, drones, and other mobile entities. The proposed system utilizes measurements of relative distances to improve the positioning accuracy of the nodes. The simulation provides insight into the characteristics and behavior of the system, serving as a tool for performance assessment under many varying conditions.

Keywords

Multi-agent system, relative measurements, swarm positioning, Kalman filter.

1. POSTER 2025 extended abstract

For outdoor localization, Global Satellite Navigation System (GNSS) signals are commonly used [1]. However, in densely urban areas, GNSS data can be significantly degraded due to signal quality variation, multi-path effect, etc. GNSS signals may also be intentionally spoofed or jammed. For these reasons, the GNSS data can be integrated using the Kalman filter (KF) [2] with the data from the Inertial Measurement Unit (IMU) to enhance the localization accuracy. The disadvantage of relying only on IMU data is that it suffers rapidly from the accumulation of errors if it is not corrected periodically by some external reference (e.g. GNSS).

For situations when GNSS signals are poor, alternative methods must be employed to correct IMU errors. These alternative methods can also be applied in multi-agent systems, where some agents have access to a reliable GNSS signal and accurate positioning, while others do not. One such approach, as considered in this paper, involves the use of relative distance measurements obtained via radio signals. Using relative measurements and data fusion, less accurate agents refine their localization by referencing more reliable ones, improving system robustness and accuracy. [3, 4, 5]

The contribution of this paper is to analyze the behavior of a system composed of multiple agents (refered as "nodes" – vehicles, persons, robots, drones, etc.), which utilize relative distance measurements to enhance the positional accuracy of each node. Obtaining precise node positioning within the swarm or system of nodes, especially in dense urban areas, is crucial for numerous fields of modern technologies and applications today.

The research presented in this paper focuses on a specific application scenario involving a given multi-agent system composed of rescue workers and their vehicles in emergency response situations. Each node, representing either a vehicle or a worker, is equipped with an IMU, GNSS receiver, and a radio communication unit. The nodes are connected in a mesh topology radio network operating at a frequency of 430 MHz, where the message update rate is 3 seconds (1 cycle) due to the low channel bandwidth. Vehicles typically remain outdoors, where they are within the coverage area of reliable GNSS signals. In contrast, rescue workers often enter buildings, where only IMU data are available.

When the system and network are built up, each node runs the pedestrian navigation and transmits every 3 seconds (one network cycle) the relative difference in position from the previous cycle, along with the 1-sigma boundary of uncertainty in position. Additionally, during each cycle, one selected node may request measurements of relative distances from up to five other surrounding nodes using radio signals at 430 MHz, and transmits the results. These messages are collected by a central computational unit, which receives all data via a network gateway. The central unit processes the data using KF to fuse the measurements and estimates the absolute position and corresponding standard deviation (std) of each node in every cycle.

For data fusion performed in the central unit, an errorstate Kalman filter is implemented. Specifically, an 8-state Kalman filter is employed, where three states represent errors in position, and five states account for errors in relative distance measurements. When a node transmits only the position difference and the corresponding std, only a simple time update of the Kalman filtering process is performed to estimate the updated position and the std. If relative measurements along with their associated standard deviations for a specific node are also available, the KF time update is followed by the calculation of innovations, defined as the difference between the predicted distances (computed between the requesting node and the referenced nodes) and the relative distance measurements obtained via radio signals. Subsequently, the Kalman filter correction update is processed, followed by a feedback compensation step to mitigate the estimated errors in both position and relative measurements.

For the evaluation of the proposed system, a MATLABbased simulation is developed. The simulator demonstrates the characteristics and behavior of the node system and serves as a tool for assessing the system's performance. Specifically, it may be used to determine the maximum permissible measurement uncertainties under which the system remains operational for the defined scenarios.

The simulation includes several configurable parameters that allow for a comprehensive evaluation of the system's performance under varying conditions. Such parameters are the std of the position of the node, the std of the relative distance measurement, and the number of cycles (time interval) between measurement updates for a given node, representing the cycle delay between specific node is selected again for requesting the relative measurements. The simulation can also be executed under various error models: (1) white noise, (2) random walk, (3) an initial offset (in position and/or relative measurements) combined with white noise, and (4) an initial offset combined with random walk. Additionally, the simulation allows for the configuration of certain nodes as static (e.g. no motion and zero std), providing further flexibility in scenario analysis.

All simulation parameters and error models can be configured within predefined ranges, allowing the simulation to systematically iterate through all considered variations. The performance of each configuration is evaluated by comparing the estimated node positions to the true positions. Assessment metrics include the root mean square error (RMSE), mean absolute error (MAE), maximum position error, and standard deviation of position estimates. These metrics provide a comprehensive evaluation of the system's accuracy and stability under different conditions.

The simulation output enables the analysis of various characteristics of the system. For instance, it allows for determination of the required radio measurement parameters to ensure that the position error remains below a specified threshold. Additionally, the simulation provides insights into the behavior of node position estimation when affected by initial offsets in position and/or radio measurements. It also enables an analysis of the influence of each source of error on overall positioning accuracy. This evaluation helps assess the system's robustness and convergence properties under different conditions. An example of the simulation output is shown in Fig. 1.

In addition, a static experiment was conducted to collect real data with actual noise characteristics. The experiment involved six static U-blox GNSS receivers randomly distributed within a 40×40 m area, recording data for approximately 30 minutes. The true distances between each receiver were measured manually. The collected data were subsequently integrated into the simulation, where the mea-



Fig. 1. Example of the position errors and its std for 120 s (40 cycles) in simulation with perfect measurements (both std = 0) with node init offset [10,-7,1] in position (up) and simulation with noise (position std = 0.2 m, relative measurements std = 2 m) with the same init offset in position (down).

sured static positions with random walk replace the node positions along with their associated stds. Similarly, manually measured distances were used in place of radio-based distance measurements, with the option of introducing additional noise into the simulation for further analysis.

The simulation utilizing real-world input data demonstrates the capability of the node system to enhance position accuracy through the fusion of relative measurements using the Kalman filter (see Fig. 2). The results highlight the effectiveness of the proposed approach in reducing positioning errors by leveraging relative node distance information, even in the presence of measurement noise.



Fig. 2. Example of effect node position improvement using corrections – node 2 corrects its original position (red) with relative distance measurements (with std = 2 m) to other randomly walking GNSS nodes with std between 1 and 2 meters (yellow).

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Neural Network-Based Estimation of Acoustic Impulse Response

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Extended abstract. The estimation of an acoustic impulse response (IR) is a crucial challenge in various fields, including room acoustics modelling, speech enhancement, forensic analysis, and spatial audio rendering. Traditional methods rely on direct measurements or system identification techniques, which require extensive data collection and complex signal processing, such as blind deconvolution. These approaches can be computationally expensive and impractical for real-time applications. Recent advancements in deep learning, particularly neural networks, provide an efficient and accurate alternative, reducing computational costs while improving precision. This study focuses on creation of a reverberated dataset based on the OpenAIR data collection and the design of a deep neural network (DNN) optimized for IR estimation, with an emphasis on minimizing computational cost while maximizing accuracy. The DNN model was developed with the following key components:

We constructed a dataset using real impulse responses recorded in diverse environments. 22 types of (IRs) from acoustically distinct spaces were sourced from York University's OpenAIR database to ensure high realism and fidelity. Additionally, we included anechoic recordings from the same database. We convolved the anechoic recordings with the IRs, creating a dataset of 2,178 samples. The dataset was split into a training set (1,524 samples), a validation set (348 samples), and a testing set (306 samples). Each sample lasts between 3 to 6 seconds, with zero-padding applied for uniformity.

The neural network is built on a convolutional neural network (CNN) framework, optimized for efficiency. Various CNN architectures were tested to achieve an optimal balance between computational performance and accuracy. Different spectrogram representations of the reverberant audio signal were explored as model inputs. The best performance was achieved using mel spectrograms. On the output side, the model directly predicts the impulse response samples.



Fig.1 Proposed IREstimator model architecture.

The training process was designed to be computationally efficient while ensuring precise IR estimation. The network was trained using supervised learning with multiple loss functions, including mean squared error (MSE), short-time Fourier transform (STFT) loss with multiple resolutions, and perceptual similarity metrics. These loss functions were chosen to enhance the model's ability to preserve both temporal and spectral characteristics of the estimated impulse responses.

To further enhance accuracy and generalization, we conducted extensive hyperparameter tuning. This included adjusting the network depth, experimenting with different pooling strategies, and implementing dropout and batch normalization techniques. These optimizations ensured robust

performance while keeping computational requirements low, making the model suitable for real-time or resource-limited applications.

A significant aspect of this study is the evaluation of IR estimation performance. Various metrics were used to compare predicted impulse responses with ground truth data, including mean squared error (MSE), spectral distance measures, perceptual similarity indexes, and the Pearson correlation coefficient. Additionally, we conducted MUSHRA listening tests to assess the perceptual quality of the predicted IRs, providing a subjective evaluation alongside objective metrics. These evaluations offered a comprehensive understanding of the model's effectiveness across different acoustic environments and highlighted its ability to produce perceptually accurate results.

Preliminary experiments show that despite its lightweight design, the proposed neural network achieves high accuracy in IR estimation. The CNN-based architecture effectively captures spatial characteristics while maintaining computational efficiency. The model demonstrates strong generalization across diverse room conditions, making it a practical and reliable solution for realworld applications.

This study underscores the potential of deep learning in IR estimation, particularly when designed with a focus on both frequency and time-domain features. By using real-world impulse responses in dataset preparation, we ensure the model's applicability to practical scenarios. Future work will focus on refining the architecture further, improving real-time processing capabilities, and exploring additional evaluation metrics to enhance performance analysis. Accurate IR estimation has broad implications, including applications in audio deconvolution for signal restoration, forensic audio analysis to differentiate environmental effects, and immersive audio experiences in virtual reality and teleconferencing.

Keywords: Impulse Response Estimation, Neural Networks, Convolutional Neural Networks, Computational Efficiency, Evaluation Metrics.

Exploring the Loss Landscape of Physics Informed Neural Networks in Room Acoustics

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Abstract.

Physics Informed Neural Networks have recently gained attention for their ability to approximate solutions of ordinary and partial differential equations. By incorporating governing equations as part of the loss, PINNs enable dataefficient training and better generalization than classical NNs. However, the vanilla PINN architecture often exhibits convergence issues. Hence, it is necessary to analyze the non-trivial loss landscape and suggest strategies that would make the problem less ill-conditioned. This paper studies this problem on a specific case of inhomogeneous Helmholtz equation – the key equation governing the room acoustics.

Keywords

room acoustics, Helmholtz equation, data-driven solution, Physics Informed Neural Networks

1. Introduction

Neural Networks (NN) are used, among other, as function approximators. They leverage the availability of big data, but they can face issues with generalization. Physics Informed Neural Networks (PINNs) have recently gained attention for their ability to approximate solutions of ordinary and partial differential equations [1]. This property appears promising for computations that are either challenging in their formulation (e.g., fluid dynamics and turbulence) or computationally demanding due to the requested domain size (e.g., room acoustics). This article focuses on the latter issue. The key point is that the PINN obtained actually faithfully mimics the physics itself, not just reproduce an apparent similarity to the observed phenomenon. The main idea of preventing a neural network from violating known physics was to include a new loss term: the residual of the governing PDE. By incorporating known physics, PINNs enable dataefficient training, which makes them a powerful tool for applications in data-scarce fields.

PINNs can be applied to solve both forward and inverse problems. Although it is still a question whether in solving forward problems (i.e., from data to equation) they can outperform conventional methods like Finite Element Method (FEM) [2], they may provide an efficient approach for solving inverse problems (i.e. obtaining equation parameters from data). The applications include estimating, e.g., boundary conditions or material properties from measurements [3].

So far, many papers focused on PDE solutions in 1D or 2D space. The study on the feasibility of extending PINNs to solve the inhomogeneous Helmholtz equation in 3D was performed in [4, 5] with implementation in DeepXDE framework [6].

This work aims to improve the convergence and provide a deeper understanding of which modifications can work better. A custom PINN framework in PyTorch was developed to replace the DeepXDE implementation, allowing for more custom features. The paper is structured as follows. First, the chosen PDE and PINN setup are presented in Sec. 2 and in Sec. 3, the loss landscape is investigated. Influence of the activation function on the loss landscape and the convergence rate is investigated in Sec. 4. Finally, the conclusions are drawn in Sec. 5.

2. Statement of the problem

Throughout this paper, we assume a 3D room-like domain $\Omega = [0, 1]^3 \text{ m}^3$ with room walls $\partial \Omega = \Gamma$ described by the sound hard boundary condition and a sound source in the center of the room. The problem is governed by the inhomogeneous Helmholtz equation with a homogeneous Neumann boundary condition

$$(\Delta + k^2)p(\omega, \boldsymbol{x}) = g(\omega, \boldsymbol{x}), \quad \boldsymbol{x} \in \Omega$$
(1)

$$\nabla p(\boldsymbol{x}) \cdot \boldsymbol{n} = 0, \quad \boldsymbol{x} \in \Gamma$$
(2)

where $\Delta = \nabla \cdot \nabla$ is the Laplacian operator, $k = \omega/c_0$ is the wavenumber, ω the angular frequency and c_0 the adiabatic sound speed, p the time-harmonic acoustic pressure, and n the normal vector.



Fig.1. Results plotted at $x \in [0, 1], y \in [0, 1], z = 0.5$, prediction with relative error 5.6 %.

The source term on the right hand side $g(\omega, \boldsymbol{x})$ is chosen as

$$g(k, x, y, z) = -2k^{2} \cos(kx) \cos(ky) \cos(kz) \\ \times \exp \frac{||x - x_{0}||_{2}^{2}}{2s^{2}} \quad (3)$$

where s is a parameter influencing the sharpness of the source term, $x_0 = (0.5, 0.5, 0.5)$ m is the source location and $||x - x_0||_2$ is the Euclidean distance from the source term.

If $s \to \infty$, the source term simplifies to

$$g(k, x, y, z) = -2k^2 \cos(kx) \cos(ky) \cos(kz)$$
(4)

and the equation than has analytical solution that reads

$$p(k, x, y, z) = \cos(kx)\cos(ky)\cos(kz).$$
 (5)

The loss function is then a weighted sum of contributions from the PDE and the Neumann boundary condition:

$$\mathcal{L} = w_{\rm PDE} \mathcal{L}_{\rm PDE} + w_{\rm NBC} \mathcal{L}_{\rm NBC} , \qquad (6)$$

where the loss terms are

$$\mathcal{L}_{\text{PDE}} = \frac{1}{N_{\text{PDE}}} \sum^{N_{\text{PDE}}} ||r_{\text{PDE}}(\boldsymbol{x})||^2, \qquad (7)$$

$$\mathcal{L}_{\text{NBC}} = \frac{1}{N_{\text{NBC}}} \sum^{N_{\text{NBC}}} ||r_{\text{NBC}}(\boldsymbol{x})||^2 , \qquad (8)$$

and

$$r_{\rm PDE} = \Delta p(\boldsymbol{x}) + k^2 p(\boldsymbol{x}) - g(\boldsymbol{x}) \quad \forall \boldsymbol{x} \in \Omega , \qquad (9)$$

$$r_{\rm NBC} = \nabla p(\boldsymbol{x}) \cdot \boldsymbol{n} \qquad \forall \boldsymbol{x} \in \Gamma, \qquad (10)$$

with N_{PDE} , N_{NBC} standing for the number of points in the domains Ω , Γ , respectively.

The chosen weight coefficients are $w_{PDE} = 1$ and $w_{NBC} = 5$. For training the PINN consisting of 3 hidden layers and 180 neurons per layer, 25 points per wavelength were used, yielding 50 points per direction and 125 000 training points in total. The chosen activation function

is sin, as used in [5], with other options being, e.g. tanh or sigmoid. ReLU, commonly used in neural networks, is not applicable here because its zero second derivative will prevent the PINN from learning. A relative error measure is computed as in [4] to evaluate the results.

The PINN trained on an analytical solution with ADAM optimizer achieves usually a relative error of 4-6 %, shortly after 1500 epochs. For an illustrative example of the results, see Fig. 1. The main obstacle to achieving lower error is the optimizer struggling to converge, as shown in Fig. 2.



Fig. 2. Convergence rate. Focus on the *y*-axis and the order of the loss changes: the oscillation amplitudes should be much smaller, at most within an order of magnitude.

3. Lost in the loss landscape

The optimizer is struggling to converge due to the nontrivial loss terms that make the loss ill-conditioned, which is a common problem of PINNs [8]. To address the illconditioning, various modifications have been introduced, such as locally adaptive activation functions with slope recovery [7] or feeding in sparse data as a regulator [9], nevertheless, these two training strategies further complicate the loss function.

However, no single strategy is known to improve performance for an arbitrary PDE [8]. To analyze which of the modifications works for PDE in focus, it is not sufficient to assess suggested improvements simply by comparing the time it took the model to converge. A more insightful approach is to investigate the convexity of the loss, e.g. by analyzing the eigenvalues of the loss Hessian [10].

Using code provided by [9], we can plot the loss landscape (LL) of our trained model and compare it to the loss landscape of a neural network (see Fig. 5), that differs only in the loss, which is a mean squared error between the ground truth and the prediction. Although the surface of the NN LL is smoother and the global minimum is wider, which means better conditioning of the NN loss than the PINN loss, the overall difference in the LLs is surprisingly not that large.



Fig. 3. Loss landscape: PINN (left) vs NN (right). Imagine a gradient-based optimizer: it is hard to impossible to find the minimum in this landscape.

4. Influence of the activation function

Jagtap et al. suggest to employ a locally adaptive activation function, because the adaptive parameter should alter the loss landscape and improve the convergence, mainly at the early stage of training [7]. The proposed activation function reads

$$\sigma(na\boldsymbol{x}) \tag{11}$$

where σ is an arbitrary activation function taking input x, $n \ge 1$ is pre-defined scaling factor, and $a \in \mathbb{R}$ is an adaptive parameter acting as a slope of the activation function.

For simplicity, it was decided to begin with the Layerwise locally adaptive activation functions (L-LAAF), where each hidden layer has its slope, adding three additional parameters to optimize. The scaling factor was set to n = 2, and all adaptive parameters were initialized as ones. The alteration of the activation function from sin to L-LAAF with sin significantly changes the loss landscape, as can be seen in Fig. 5, and prevents the optimizer from being lost in the loss landscape and stuck in local minima. This has impact an on the convergence rate (compare Fig. 2 and Fig. 4), which is improved, mainly at the early stages.

The success of this strategy (for our PDE and settings) leads one to think whether the problem is not more fundamental and whether extra parameters are really necessary. Recall why we are not using ReLU as an activation: since it is a combination of linear functions, its zero second derivative would prevent the network from learning. But if the inputs of the activations are too small and around zero, the activation function sin becomes linear, and the training runs into the same issues as it would with ReLU. And indeed, after trying to take the argument of sin two times, the training converged with similar speed as with L-LAAF (see Fig. 4) and the LL is also improved in comparison to activation by simple sin (compare Fig. 3 and Fig. 5).



Fig. 4. Convergence rate. Here the oscillations are (approximately) within an order of magnitude and their mean is decreasing.



Fig. 5. Loss landscape of PINN: LAAF (left) vs $\sin(2x)$ (right). Both landscapes are more easily traversable for the optimizer than those in Fig. 3.

5. Conclusion

This implementation for both 2D and 3D Helmholtz includes Dirichlet and Neumann boundary conditions and multiple strategies to improve the convergence rate, e.g., layer-wise locally adaptive activation functions (L-LAAF) with slope recovery and sparse data regulation. For better insight, it also provides codebase for visualization of loss landscapes.

To compare the influence of new training strategies and modifications, the loss landscape study was performed. L-LAAF is not strictly necessary, but it allows the network to change the activation slope during the training without relying on one's guess. Future work is moving from training on analytical solutions to more realistic cases with sharper excitations, employing a dataset generated by FEM as a reference. This would be the next step towards the safe use of neural networks for computations in room acoustics.

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Development of 8-frame Mach-Zehnder interferometer for laser plasma density measurements

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Abstract. This work presents the development of 8-frame Mach-Zehnder interferometer dedicated for electron density measurements of hot dense plasma produced by a terawatt iodine laser system at the PALS facility in Prague.

In these experiments, copper and tantalum targets were used for X-ray and neutron production, and boronized targets were used for aneutronic inertial nuclear fusion tests.

Keywords

Mach-Zehnder Interferometer, Density Measurements, Optical Diagnostics, Scientific Instruments

1. Introduction

Thanks to advances in generation of nanosecond, highintensity laser pulses in the range of intensities around 10^{16} W/cm², new possibilities for studying processes in plasma, which were previously inaccessible due to non-sufficient laser technologies, were opened up.

Such a process is e.g. inertial confinement fusion, which initiates a fusion reaction by focusing a high-intensity laser beam onto a small area, resulting in hot plasma generation, which is necessary for nuclear fusion.

To study the key phenomena such as instability formation, α -particle production in aneutronic fusion, and the evolution of plasma density and temperature, it is crucial to probe the plasma at multiple predefined intervals for which interferometry represents an ideal tool. This technique has been widely used in numerous experiments.[1-3]

The most common interferometer is the Mach-Zehnder type. The Mach-Zehnder interferometer, which is being developed at PALS is composed of commercially available laser-optic elements such as polarizing beam splitters and dichroic mirrors. This system is easily expandable, with the only limitation being the wavelength range λ , for which the components are manufactured.

The parameters of the Asterix IV iodine laser system at the PALS are as follows[4]

parameter	value (unit)
fundamental wavelength	$\lambda_{\rm F}$ = 1315 nm
pulse duration	$\sim 300 \text{ ps}$
output energy	up to 1 kJ
max peak power	3 TW
shot frequency	1 shot / 30 minutes

Tab. 1: Parameters of the Asterix IV laser system.

The probing beam of fundamental wavelength λ_1 used for our interferometric system is taken from the main beam after passing the third amplifier.

2. Theory of interferometry

Suppose, that we have an ideal monochromatic source of light (laser) and no aberrations are present, as in fig. 1, generating a plane light wave

$$\mathbf{E}(t) = \hat{\mathbf{E}}_0 \mathbf{e}^{i\omega t},\tag{1}$$

that is propagating in the Z-axis. Here, $\hat{\mathbf{E}}_0 = \mathbf{E}_0 e^{i\varphi}$ represents the complex amplitude, ωt is the phase of the propagating wave, and *i* is a complex unit.



Fig. 1: Setup of Mach-Zehnder interferometer. **BE** - beam expander, **BS** - beam splitter, **M** - mirror, **IP** - investigated plasma.

Consider the amplitude distribution on the CCD camera, which is placed behind the interferometer, parallel to the X-Y plane. On the CCD camera, we will obtain two waves. The first is the reference wave, which does not go through the plasma, and the second is the probing wave, which has traveled through the plasma.

On the screen, the reference wave $\mathbf{E}_1(t)$, will have accumulated some phase delay relative to the initial wave. Thus, we have

$$\mathbf{E}_{1}(t) = \hat{\mathbf{E}}_{01} \exp\left[i\omega\left(t - \frac{z_{1}}{c}\right)\right],\tag{2}$$

where $\hat{\mathbf{E}}_{01}$ is the reference wave complex amplitude, $\omega = 2\pi\nu$ is its angular frequency (where ν is the frequency), t denotes time, z_1 is the distance from the observation point (screen - source at the origin) and c is the speed of light in vacuum.

The wave $\mathbf{E}_2(t)$, which has traveled through the plasma, obtain additional delay caused by the passage through the plasma

$$\mathbf{E}_{2}(t) = \hat{\mathbf{E}}_{02} \exp\left\{i\omega\left[t - \frac{z_{2}}{c} - \frac{(N-1)\Delta z}{c}\right]\right\}.$$
 (3)

Here, $\hat{\mathbf{E}}_{02}$ is the complex amplitude of the subject wave and $(N-1)\Delta z$ is the increase of the optical path \mathcal{L} due to the fact, that the subject wave has been propagating through the plasma, which is characterized by a refractive index N.

For the sake of clarity, let $\psi_1 = \omega(t - z_1/c)$ and $\psi_2 = \omega\{t - z_2/c - [(N-1)\Delta z/c]\}$ denote the phases of the reference and subject waves. The sum of these two waves at any point in space is given as

$$\mathbf{E}_{\Sigma}(t) = \hat{\mathbf{E}}_{01} \exp(i\psi_1) + \hat{\mathbf{E}}_{02} \exp(i\psi_2) =$$

= $\hat{\mathbf{E}}_{\Sigma} \exp(i\psi_{\Sigma}),$ (4)

where $\hat{\mathbf{E}}_{\Sigma}$ is the complex amplitude of the resulting wave and ψ_{Σ} is its phase.

CCD camera acts as a quadrature detector, thus the resulting detected pattern is given as $I_{\Sigma} = \mathbf{E}_{\Sigma}(t)\mathbf{E}_{\Sigma}^{*}(t)$, with $\{\cdot\}^{*}: \mathbb{C} \to \mathbb{C}$ being the complex conjugate operator. Resulting intensity is then

$$I_{\Sigma} = \mathbf{E}_{\Sigma} \exp(i\psi_{\Sigma}) \mathbf{E}_{\Sigma}^{*} \exp(-i\psi_{\Sigma}) =$$

= $|\hat{\mathbf{E}}_{01}|^{2} + |\hat{\mathbf{E}}_{02}|^{2} +$
+ $|\hat{\mathbf{E}}_{01}||\hat{\mathbf{E}}_{02}|\{\mathbf{e}^{[i(\psi_{1}-\psi_{2})]} + \mathbf{e}^{[-i(\psi_{1}-\psi_{2})]\}}\}.$ (5)

Using Euler's identity, we obtain

$$I_{\Sigma} = |\hat{\mathbf{E}}_{01}|^2 + |\hat{\mathbf{E}}_{02}|^2 + 2|\hat{\mathbf{E}}_{01}||\hat{\mathbf{E}}_{02}|\cos(\psi_1 - \psi_2). \quad (6)$$

If we assume that the arms of the interferometer have equal lengths $z_1 = z_2$, substitute the values of ψ_1 and ψ_2 and simultaneously replace ω/c by $2\pi/\lambda$ (λ being the wavelength of the waves), we get the complete form of an interferometric equation for the Mach-Zehnder interferometer.

$$I_{\Sigma} = |\hat{\mathbf{E}}_{01}|^{2} + |\hat{\mathbf{E}}_{02}|^{2} + 2|\hat{\mathbf{E}}_{01}||\hat{\mathbf{E}}_{02}|\cos\left[\frac{2\pi(N-1)\Delta z}{\lambda}\right] = I_{1} + I_{2} + 2\sqrt{I_{1}I_{2}}\cos\left[\frac{2\pi(N-1)\Delta z}{\lambda}\right]$$
(7)

This equation determines the light intensity at any point of the interference pattern in the plane of the CCD camera as a function of the refractive index N(x, y, z) inside the studied plasma.[5-6]

Using $\Delta z \rightarrow 0$, we can express the accumulated phase shift from eq. 7 as

$$\phi(x,y) = \frac{2\pi}{\lambda} \int_{z_1}^{z_2} \left[N(x,y,z) - 1 \right] \mathrm{d}z, \tag{8}$$

where z_1 is the point, where the probing beam enters the plasma and z_2 is the point, where the probing beam lefts the plasma.

To evaluate the plasma electron density, we can use an approximation of the refractive index, using the plasma electron density

$$N \approx 1 - n_{\rm e} \lambda^2 \frac{e^2}{8\pi\varepsilon_0 c^2 m_{\rm e}},\tag{9}$$

where n_e is the plasma electron density, e is the fundamental charge, ε_0 is the vacuum permeability and m_e is the electron mass. It is important to note, that this relation only holds, if the angular frequency of the probing beam ω is higher than plasma electron angular frequency ω_e . Otherwise, the plasma would shield out the incoming light beam, making it optically refractive for the probing beam.

If we now re-arrange eq. 9, we obtain

$$N - 1 = -4.46 \times 10^{-16} \lambda^2 n_{\rm e}.$$
 (10)

Combining eq. 8 and eq. 10 gives

$$\phi(x,y) = -2\pi\lambda \cdot 4.46 \times 10^{-16} \int_{z_1}^{z_2} n_{\rm e}(x,y,z) \mathrm{d}z. \quad (11)$$

Assuming an axial symmetry of the plasma, we can transform the eq. 11 into a cylindrical coordinate system, obtaining

$$\phi(x,y) = -4\pi\lambda \cdot 4.46 \times 10^{-16} \int_0^X n_e(r,x) dz.$$
 (12)

Here, X represents the maximum path length of integration along the line of sight in Cartesian coordinates. This corresponds to the extent of the plasma in the z-direction before the transformation into cylindrical coordinates.

Using substitutions $z = \sqrt{r^2 - y^2}$ and $dz = r/\sqrt{r^2 - y^2} dr$ with r denoting the radial coordinate in the cylindrical coordinate system, measured from the central axis of the plasma column, and R representing the outer radius of the plasma, we obtain following equation

$$\phi(x,y) = -4\pi\lambda \cdot 4.46 \times 10^{-16} \int_{y}^{R} n_{\rm e}(r) \frac{r}{\sqrt{r^2 - y^2}} {\rm d}r,$$
(13)

which is knows as the Abel transform of the plasma electron density. Therefore, finding the plasma electron density is an inverse process, known as the Abel inversion transform[7-8]

$$n_{\rm e}(r,z) = \frac{1}{2\pi^2 \lambda \cdot 4.46 \times 10^{-16}} \int_r^R \frac{{\rm d}\phi(y,z)}{{\rm d}y} \frac{{\rm d}y}{\sqrt{y^2 - r^2}}. \eqno(14)$$

3. Experimental setup

Fig. 2a shows the top view of the layout of the target chamber.



(a) Target chamber layout depicted with a axial point of view. **MIB** - main interaction beam, **FAL** - focusing aspherical lens, **IP** - investigated plasma, **TH** - target holder, **PB1** - probing beam in first direction, **PB2** - probing beam in second direction. Whole probing area is highlighted with yellow color.



(b) Image of the realized target chamber layout. **DPJP** - direction of plasma jet propagation.

Fig. 2: Sketch and realization of target chamber layout.

The plasma is probed by eight beams in different times. These beams utilize second ($\lambda_2 = 657$ nm) and third ($\lambda_3 = 438$ nm) harmonics, derived from the fundamental ($\lambda_F = 1315$ nm) beam.

The main interaction beam (fig. 2a, red dashed line) is focused by an aspherical lens (aspherical lens eliminates the effects of spherical abberation, creating a better focal spot and resulting in a higher focused power), which focuses the beam into an area in the range of μ m. This creates a high intensity spot, which creates a plasma that propagates backwards with respect to the interaction laser beam. When the plasma is formed, the probing beams enter it in a perpendicular direction to the plasma propagation in the pre-defined intervals (~ 0.5 ns), controlled by digital delay generator.

The interferometric setup shown in fig. 3 has been deployed for the experiment.



Fig. 3: Interferometer layout. **M** - mirror, **BS** - beam splitter, **PC** - polarizing cube, **DM** - dichroic mirror, **CCD** - CCD camera.

Upon entering the aperture, the beam is first split into S- and P-polarized components using a 50:50 polarizing cube, which reflects 50% of the beam intensity while allowing the remaining 50% to pass through. These two beams have different polarizations but share the same wavelength.

Each polarized beam is then further separated by a long-pass dichroic mirror, which transmits the second harmonic while reflecting the third, resulting in two distinct beam colors with two polarizations.

To generate the final eight beams, the four initial beams pass through a final beam splitter, which again splits each beam with a 50:50 division ratio, directing half along the reflection path and transmitting the other half forward.[9]

This setup allows for independent control of each of the eight beams by adjusting their optical paths, enabling plasma probing at specific time intervals.

After interacting with the plasma, the beams are directed onto one of eight CCD cameras that capture the resulting interferograms.

4. Experimental results

The analysis was conducted on multiple shots with nearly identical parameters. By varying the timing of individual shots, we were able to extend the temporal coverage beyond the inherent limitation of our diagnostic system. Specifically, although the interferometer used in the experiment was an 8-frame system, we strategically adjusted the timing in different shots to obtain a more comprehensive dataset. As a result, we generated a sequence of 18 densitograms (fig. 4), covering a time span from 14.9 ns to 31.9 ns with a temporal resolution of 0.5 ns.

This approach allowed us to construct a more detailed densitograms, providing improved insight into the plasma evolution over time.



Fig. 4: An example of the plasma areal densities at different two times.

The X, Y and Z axis represent the plasma size in μ m, while the colorbar next to each plot represents the value of the areal density N_a (cm⁻²).

While the spatial axis values are in correspondence with the real plasma sizes, the colorbars currently do not represent the real values of the densities (expected values are in the range $> 10^{20}$ cm⁻³). The quantitative evaluation of the exact values of the plasma density is currently being performed.

5. Conclusions

The 8-frame Mach-Zehnder interferometer was designed and successfully implemented at the PALS facility for plasma density measurements.

A representative group of different interferograms, where same plasma parameters were presumed, was used for initial data analysis to show how the plasma evolves in time. The quantitative distribution of areal densities proved that the concept was successful and it makes it possible to study the plasma jet dynamics.

Currently, a *n*-frame generalization is proposed. The main principle will again be based on the Mach-Zehnder design.

The main beam will be a white-light beam, generated by a femtosecond laser, located at the Faculty of Nuclear Sciences and Physical Engineering, CTU. The main beam will be divided by n longpass dichroic mirrors, resulting in 2n outcoming beams. The main difference will be in usage of more dichroic mirrors than in the presented design.

This generalization will lead to a better temporal resolution, resulting in a more advanced mapping of the plasma generation and density evolution phenomena.

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Automated Battery Management System Simulation for State-of-X Estimation Algorithm Development

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Abstract. During the development of a new battery management system (BMS), the design and validation of its state estimation algorithms is a time-consuming process that demands a significant amount of computational resources. Using a model-in-a-loop (MiL) toolchain enables the user to systematically evaluate a predefined test-set, covering all feasible situations and events that could occur during the lifetime of an applied BMS. In this work, this toolchain is presented as a standalone application, which is capable to simulate a reference battery depending on an applied load profile with an emulated BMS attached. The results are than passed on to the state-of-X estimation algorithms to be tested. The results demonstrate the capability of the toolchain by testing three different state-of-charge (SOC) estimation algorithms. The toolchain is designed to be flexible and easy to use, allowing for the rapid development and testing of state-of-X estimation algorithms. The standalone application is openly available on the public GitLab Website¹.

Keywords

Battery Management System, Simulation, Testing, Model-in-the-Loop, State-of-X Estimation.

1. Introduction

Despite the significant growth in the number of applications for battery-powered systems in the past few years, the operating requirements for these storage systems are becoming increasingly challenging. The objective is to optimise the performance, energy content and lifespan of the batteries to meet user demands. Simultaneously, the safe and reliable operation of the entire system must be guaranteed at all times. In this context, lithium-ion-based storage systems have proven to be highly effective in fulfilling these criteria. However, a constant monitoring of the cell states is mandatory in order to ensure safety and application demands. This is further reinforced by the controlling of auxiliary systems such as fuses and cooling systems. The battery management system (BMS) is employed as the central control unit, serving as a central processing unit that collects measurements at runtime, estimates cell state variables using various algorithms, and managing the power flow between the application and the battery system. [1]

The estimation of states such as the state-of-charge (SOC) and state-of-health (SOH) plays a key role, as this information provides an insight into the current operating range and available power of the battery. The estimation itself is a complex task, as the battery's behaviour is influenced by various factors such as the current and historic power demand, the ambient temperature, and the battery's age [2]. Therefore, there are numerous algorithms available, using different approaches to process the given measurement data. Selecting an approach to be developed as an algorithm is a challenging task, as the algorithms must be tested under various conditions to ensure their reliability and robustness. Depending on the application, the requirements and possible implementations of such estimation algorithms varies significantly [4]. There are multiple steps in the development process, starting with the basic design to the final validation with respect to the application and specific environment. In the superordinate development process, the algorithms are first tested in a Simulation environment or model-in-a-loop (MiL) setup. This allows for the testing of the algorithms under various conditions, without the need for a physical battery system. Making these simulation toolchains as accurate as possible allows to reduce the required hardware testing and therefore the costs of the development process.

In this work, an automated simulation framework based on a Simulink model of a battery and BMS is presented. The framework is designed to be flexible and easy to use, allowing for the rapid development and testing of state-of-X estimation algorithms.

¹https://git.rwth-aachen.de/isea/bms-simulation-as-mil



Fig. 1: Block diagram of the MiL-Toolchain. [3]

2. Fundamentals

This section will give an overview of the necessary fundamentals for this work.

2.1. Battery Management System

Given an application being powered by a battery storage system, it is essential that is is controlled to fulfil the requirements of the application and ensures the safety of the users, the environment and the battery system itself. The tasks of such a BMS can be divided into five main sections: Cell Monitoring, State Estimation, Energy Management, Safety Management and the Control Unit. All of these units need to be modelled and simulated in order to achieve a realistic representation of the BMS. All of these units are interconnected for information exchange. As the described framework is optimised for development and testing of new algorithms the focus is set on the state estimation unit. [1]

2.2. Battery State Estimation

The estimation of the cell states is a crucial task in the BMS, as it provides the necessary information for the other units to operate. These states are mostly not directly measurable and need to be estimated with measured values such as the battery's voltage, current, temperature, change in dimension, etc. There are numerous approaches and algorithms available for the estimation of the cell states. At this point, a distinction must be made between online and offline estimators. Online refers to the mode of operation, as these algorithms are executed and analysed at application runtime. The tool to be discussed is time series based and therefore predestined for online estimation. The most common states to be estimated are the SOC and SOH. The SOC provides a measure of the amount of stored energy in the battery at the calculated time step. The SOH indicates the battery's health and is used to determine the battery's remaining lifespan. [2]

3. Framework Structure

The framework itself has undergone continuous development and optimisation for specific purposes by various contributors. The basic form was first presented by Jöst et al. in 2019 [3]. The framework is a model-based development environment for testing diagnostic functions and their behaviour of a BMS at runtime. The results are to be evaluated taking into account various application scenarios and battery cells with different initial parameters. The tool is designed in MATLAB Simulink devided into several subsystems similar to the structure of a true BMS with an additional application and battery reference simulation. The concept is shown in Figure 1. Variables marked with a star are distorted signals.

The application profile is characterized by a power and temperature profile. The profile data consists of four parameters: the power or current profile, a dedicated flag indicating the profile type, the temperature profile and an additional charging flag to indicate the charging state. An exemplary power profile is shown in Figure 2. This data is passed on to the reference battery modelling generating the voltage and cell temperature responses to the given power use. In addition, the reference battery states needed for proper evaluation of the diagnostic algorithms are calculated. This block is supported by the ISEA Battery Framework which is a adaptive simulation framework for electrochemical battery modellings. More information can be found in [5] or on the public GitLab website [7]. This battery model is followed by the BMS model containing a hardware emulation of the monitoring unit, a communication and supervising emulation and the diagnostic functions. The resulting state estimates are then to be compared to the reference states.

In this work, the MiL-Standalone is tested with three commonly known SOC estimation algorithms. The first algorithm is the Coulomb counting method, which is based on the integration of the current over time. The second used algorithm utilises an Extended Kalman Filter (EKF), which is a recursive algorithm that approximates the nonlinear model of battery cell by linearising in the observed time step. The third approach is based on an Unscented Kalman Filter (UKF), which does not rely on linearising, but instead applying a sample-point or sigma-point based



Fig. 2: Worldwide harmonized light vehicles Test Procedure (WLTP) power profile for 40 kWh 400 V pack.

method. The results of these tests are presented in the following section. Both Kalman Filter approaches where supplied by the Simscape Battery Toolbox and require an additional battery model based on the first order Thévenin model [6].

The framework is designed to be adaptive to several different battery models and states, scenario variations and BMS disturbances such as different amount noise added by the monitoring unit. The model has been compiled into a standalone application, runable on Docker or any Linux system applying MATLAB Runtime, which is a free-to-use command line tool. This configuration enables optimised execution of the simulations and simple scaling according to requirements and computing capacity. Due to the structure of the model and the hard compiling by MATLAB there are still limitations, such as the selection of the battery simulation mode or the minimal sampling time. These limitations are to be addressed in future work. The initial version of the MiL Standalone presented herein with three SOC estimators allows the following modification options:

- **Application Profile:** The profile and its type is fully customizable.
- **Battery Model:** The battery model can be changed to any model supported by the ISEA Battery Framework. There is a maximum size of input data.
- Scenario: The initial battery state can be customized. This includes parameters such as the initial SOC, SOH, temperature.
- **BMS Structure:** There are options to modify the hardware parameters in terms of noise, precharge or the onboard charge-controller itself.
- **Diagnostic Functions:** The Look-Up-Tables (LUT) required by the model-based diagnostic functions can be changed according to the selected cell. In addition the initial parameters set for the filters and the Ah-Counter can be modified.

4. Results

To give an impression on the capabilities of the tool, a series of tests was conducted. A test basis was defined using the Worldwide harmonized Light vehicles Test Procedure (WLTP) power profile with a Samsung 35E NCA/Si-C battery cell. The exact setting can be found in Table 1.

Parameter	Value
Battery Cell	Samsung 35E NCA/Si-C
Nominal Capacity	$3.35\mathrm{Ah}$
Actual Capacity	$3.3015\mathrm{Ah}$
Nominal Voltage	$3.65\mathrm{V}$
Max / Min OCV	$4.20{ m V}$ / $2.65{ m V}$
SOC	50%
SOH (C/R)	100 % (1/1)
Temperature	$25^{\circ}\mathrm{C}$
Power Profile	WLTP

Tab. 1: Basis test setup as reference for each test scenario.

Besides this standard simulation parameters, the current and voltage sensor are emulated by adding a white noise signal to the actual values. This noise configuration for each sensor is shown in Table 2. These values were chosen in relation to commercially available sensors and the expected noise level in a real-world application. Examples for such sensors would be the Melexis MLX91216 as a current sensor and the BQ79731-Q1 by texas instruments as a voltage sensor [8, 9].

Sensor	Mean	Variance	Offset
Current Sensor	$20\mathrm{mA}$	$400\mu A^2$	$5\mathrm{mA}$
Voltage Sensor	$2.5\mathrm{mV}$	$12.5\mu\mathrm{V}^2$	$1\mathrm{mV}$

Tab. 2: Noise configuration for the current and voltage sensor.

For validation, two additional variances of the reference cell model with changing actual capacities were created. A second test run included a variation of the initial SOC with a third covering the initial ageing state SOH of the cell. The exact parameters are shown in Table 3. The resulting error signals for each estimator subdivided according to each test category are shown in the following Figures 3 to 6.

Parameter	Ref.	Var. 1	Var. 2
Actual Capacity	$3.35\mathrm{Ah}$	$3.25\mathrm{Ah}$	$3.45\mathrm{Ah}$
SOC	50%	97.5%	12.5%
SOH	100%	90%	80%
	(1/1)	(0.9/1.5)	(0.8/2)

Tab. 3: Test scenarios for each SOC estimation algorithm.



Fig. 3: Estimated SOC signals by all estimators for the reference scenario.



Fig. 4: Error signals for Ah Counter or Coulomb Counting method.



Fig. 5: Error signals for Extended Kalman Filter method.



Fig. 6: Error signals for Unscented Kalman Filter method.

5. Conclusion

The presented MiL-Toolchain is a powerful tool for the development and testing of state-of-X estimation algorithms. The tool is designed to be flexible and easy to use, allowing for the rapid development and testing of any online estimation algorithm. The results presented show the capability of the toolchain by testing three different SOC estimation algorithms under varying scenarios.

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Ga₂O₃ Vertical Transistor Modeling and Analysis

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Abstract. Alpha-phase gallium oxide $(\alpha$ -Ga₂O₃) is a promising ultra-wide bandgap semiconductor with exceptional properties, making it ideal for high-power and high-temperature applications. This study models and analyzes vertical transistors based on α -Ga₂O₃ using Silvaco Atlas simulations. Results show stable operation at elevated temperatures, with slight increases in threshold voltage and decreases in drain current due to reduced electron mobility. Higher doping concentrations in the drift layer decrease the breakdown voltage. Calibrated DC characteristics showed a drain current of 1.97 A at a drain voltage of 30 V and a gate voltage of 11.5 V, with a threshold voltage of 6.12 V and a breakdown voltage of 86.7 V. These findings highlight the potential of α -Ga₂O₃ vertical transistors for high-power and high-temperature applications. Future work will optimize device structures and explore new fabrication techniques.

Keywords

 α -Ga₂O₃, Ultra-wide bandgap semiconductor, Highpower application, Vertical transistors, Silvaco Atlas simulations.

1. Introduction

Alpha-phase gallium oxide (α -Ga₂O₃) has garnered significant attention in the last decade as a promising ultrawide bandgap semiconductor. This is due to its exceptional material properties, including a high breakdown field of 8 MV/cm [1], and a large Baliga's figure of merit (BFOM) that surpasses GaN by over three times and 4H-SiC by ten times [2], [3]. The low intrinsic carrier concentration of α -Ga₂O₃ also allows for high-temperature operations [4]. Currently, the absence of p-type Ga₂O₃ is a major challenge because single-crystal oxide semiconductors have difficulty forming shallow acceptor states [5]. Self-trapped holes [6] also contribute to very low hole mobility and a high effective hole mass [7]. Implementing enhancement-mode (E-mode) α-Ga₂O₃ MOSFETs is particularly challenging due to the lack of p-type doping, which prevents the formation of an inversion layer. To address this, researchers have explored various approaches to fabricate E-mode α-Ga₂O₃ MOSFETs, focusing on n-channel

accumulation mode devices. One common strategy involves reducing the channel thickness to fully deplete it under zero gate bias voltage [8]. Examples of this include α -Ga₂O₃ on insulator (GOOI) field-effect transistors [9], [10], [11] and gate recess processes [12], [13], [14]. Trench gate processes are frequently used in planar device structures, but vertical single trench gate α -Ga₂O₃ MOSFETs have not been widely reported [15].

2. Device Design

The initial current aperture vertical electron transistors (CAVETs) were built using AlGaN/GaN by Ben-Yaacov et al. for radio frequency (RF) power applications, achieving dispersion-free performance [16]. The AlGaN/GaN CAVET design benefits from having a large electric field region situated under the gate and into the bulk material, which allows it to function as a highvoltage switch for power electronics [17]. For ultra-wide bandgap semiconductors, building on achievements in α-Ga₂O₃ doping with shallow donors (Si) [18] and deep acceptors (Mg, N) [19], Wong et al. created the first current aperture vertical α -Ga₂O₃ power MOSFETs that operate in both depletion-mode (D-mode) [20] and enhancementmode (E-mode) [21]. Both devices used a planar gate. Fig. 1 depicts the schematic α -Ga₂O₃ current aperture MOSFET was used for simulation calibration, where the source and drain contacts are separated by a current blocking layer (CBL) made of p-ion-implanted α-Ga₂O₃. The gate-modulated current travels vertically through a defined opening, or aperture.



Fig. 1. Schematic cross-sectional view of α-Ga₂O₃ MOSFET.

3. Simulation Setup and Calibration

In this study, device simulations were conducted using Silvaco Atlas. Material-dependent parameters and physical models relevant to α -Ga₂O₃ were incorporated into the simulation process, and calibration was performed.

3.1 Calibration

The planar gate α -Ga₂O₃ current aperture MOSFET, illustrated in Fig. 1, was employed as the reference device for simulation setup and calibration. Key structural parameters are summarized in Tab. 1.

Parameter	Value
Bandgap (eV)	5.3
Mobility (cm²/Vs)	300
Permittivity	10
n** source doping concentration	5.0 x 10 ¹⁹ cm ⁻³
CBL p-type Gaussian doping peak concentration	1.5 x 10 ¹⁸ cm ⁻³
Drift layer n-type doping concentration (N _{Drift})	1.5 x 10 ¹⁶ cm ⁻³
Substrate n-type doping concentration	3.0 x 10 ¹⁸ cm ⁻³
n** source depth	0.045 μm
Al ₂ O ₃ gate dielectric thickness	20 nm
CBL depth	0.24 μm
Drift layer depth (T _{Drift})	0.3 μm
Substrate depth	2 µm

Tab. 1. Device parameters for simulation.

The calibrated DC characteristics of the planar gate α -Ga₂O₃ MOSFET are presented in Fig. 2. Specifically, Fig. 2(a) and Fig. 2(b) illustrate the output and transfer characteristics of the device, respectively. At a drain voltage (V_D) of 30 V and a gate voltage (V_G) of 11.5 V, the drain current (I_D) reaches 1.97 A. The threshold gate voltage (V_{TH}) is determined to be 6.12 V. As shown in Fig. 2(c), current density distribution confirms that the CBL regions effectively impede current flow as designed. A simulated breakdown voltage (BV) of 86.7 V was obtained, depicted in Fig. 2(d).



Fig. 2. Calibrated (a) Output and (b) Transfer characteristics of the planar gate α-Ga₂O₃ MOSFET. c) Current density. d) Breakdown characteristics.

3.2 Shockley-Read-Hall Model

The Shockley-Read-Hall (SRH) model is fundamental analyzing the recombination of carriers in for semiconductors, particularly in those with an indirect bandgap. This model illustrates how electrons and holes can recombine through energy states localized within the bandgap, which may arise from defects or impurities in the material. Recombination primarily occurs through two mechanisms: thermal recombination, which happens when an excited electron returns to a ground state, emitting a photon or dissipating energy in some other way, and recombination via intermediate states, where interaction with localized energy states facilitates the transition of electrons and holes. In the context of simulations using Silvaco's ATLAS software, the number of states in the valence and conduction bands has been set to 3.72×10^{18} cm⁻³. This setting is crucial because the density of states determines the number of available states for recombination, directly influencing the efficiency of the semiconductor device.

3.3 Field-Dependent-Mobility Model

The FLDMOB (Field-Dependent Mobility) model is essential for understanding the mobility of charge carriers in semiconductors, particularly in conditions where the electric field varies significantly. This model is particularly relevant for devices such as MOSFETs and power devices, where high electric fields can greatly influence performance. The mobility of carriers, denoted as μ , is not constant but depends on the applied electric field E. Under high electric field conditions, mobility tends to decrease due to phenomena such as velocity saturation and increased collisions between carriers and the crystal lattice. The equation that describes this dependence is:

$$\mu(E) = \mu_0 \left[\frac{1}{1 + \left(\frac{\mu_0 E}{v_{sat}}\right)^{\beta}} \right]^{\frac{1}{\beta}}$$
(1)

In this equation, μ_0 represents the mobility at low electric field strength, while E is a characteristic electric field that determines the point at which mobility begins to decrease. The exponent β is a fitting parameter that characterizes how mobility decreases with increasing electric field and v_{sat} is the saturation velocity. In this simulation, the low electric field mobility μ_0 is set to 300 cm²/Vs, while the saturation velocity is equal to 1.91×10^7 cm/s. The exponent β , instead, is assumed to be 2. By utilizing the FLDMOB model it is possible to analyze how carrier mobility varies in response to high electric fields. This analysis is crucial for optimizing the performance of semiconductor devices allowing for more effective management of heat dissipation and improving overall operational efficiency.

4. Simulation Results

4.1 Effect of Temperature

 α -Ga₂O₃ is a pivotal semiconductor material for hightemperature electronics due to its low intrinsic carrier concentration, which sustains the modulation capability of transistors at elevated temperatures. This section investigates the temperature-dependent performance of the proposed α -Ga₂O₃ MOSFET. Fig. 3 depicts the output and transfer characteristics of the α -Ga₂O₃ MOSFET at various temperatures. As the temperature increases, the drain current decreases due to reduced electron mobility. At elevated temperatures, the increased phonon concentration results in enhanced carrier scattering, thereby reducing electron mobility. The threshold voltage, shown in Fig. 3(b), increases slightly from 6.11 V at T = 260 K to 6.17 V at T = 380 K.



Fig. 3. (a) Output and (b) Transfer characteristics of α-Ga₂O₃ MOSFET at different temperatures.

4.2 Effect of Doping Concentration of Drift Layer

The effect of the drift layer doping concentration (N_{Drift}) on the transfer characteristics of planar gate α -Ga₂O₃ MOSFETs, with a drift layer thickness (T_{Drift}) of 0.3 µm, is analyzed and depicted in Fig. 4. From the figure, it is observed that the threshold voltage increases as N_{Drift} increases from 1 x 10¹⁶ cm⁻³ to 5 x 10¹⁶ cm⁻³. However, at N_{Drift} = 1 x 10¹⁷ cm⁻³, the threshold voltage becomes smaller than even that obtained at N_{Drift} = 1 x 10¹⁶ cm⁻³, resulting in better performance compared to N_{Drift} = 5 x 10¹⁶ cm⁻³.



Fig. 4. Transfer characteristics at different NDrift.

For power devices, the doping concentration and thickness of the drift layer are critical design parameters influencing the breakdown voltage (BV). The effect of N_{Drift} on BV, illustrated in Fig. 5, shows a decrease in BV with increasing N_{Drift} , which is consistent with observations in Si, SiC [22], and GaN [23] devices.



Fig. 5. Breakdown voltage at different NDrift.

5. Conclusion

In this study, we have modeled and analyzed vertical transistors based on α-Ga₂O₃, focusing on their design, simulation, and performance under various conditions. The exceptional material properties of α-Ga₂O₃, including its high breakdown field and large Baliga's figure of merit, make it a promising candidate for high-power and hightemperature applications. Simulations conducted using Silvaco Atlas, incorporated material-dependent parameters and physical models relevant to α-Ga₂O₃ and were calibrated against a planar gate α-Ga₂O₃ current aperture MOSFET. The α-Ga₂O₃ MOSFETs demonstrated stable operation at elevated temperatures, with a slight increase in threshold voltage and a decrease in drain current due to reduced electron mobility caused by enhanced carrier scattering. The doping concentration of the drift layer significantly influences the device's performance. Higher doping concentrations lead to a decrease in breakdown voltage, consistent with trends observed in other semiconductor materials such as Si, SiC, and GaN. The use of a Gaussian p-type doping profile in the current blocking layers effectively impeded current flow, as confirmed by the current density distribution. The calibrated DC characteristics showed a drain current of 1.97 A at a drain voltage of 30 V and a gate voltage of 11.5 V, with a threshold voltage of 6.12 V and a breakdown voltage of 86.7 V. These results highlight the potential of α -Ga₂O₃ vertical transistors for high-power and high-temperature applications. Future work will focus on optimizing device structures and exploring new fabrication techniques to further enhance the performance and reliability of α-Ga₂O₃ MOSFETs.

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