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PhD Yearbook | 2025

Chair:
Prof. Andrea Bernasconi

DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

The PhD Programme in Mechanical Engineering of Politecnico di Milano offers top-level knowledge in one of the most profitable sectors in Italy and Worldwide; it is a key instrument to access leading enterprises and to achieve prominent positions in large international companies devoted to research and development, innovation and design. The primary employment market is composed of leading companies and organizations dedicated to innovation, research and technical development, high-tech SMEs and governmental departments. The research topics of our Programme fall in the category Mechanical, Aeronautical & Manufacturing Engineering of the QS World University Rankings, where Politecnico di Milano currently ranks 12th in the world.

As for career perspectives, a recent survey (run by Politecnico in 2022) showed that our PhD Candidates are 95% employed after one year, in national and international companies and academic and non-academic research institutions, engaged in innovation, research and technical development. On average, the survey showed that people earning our PhD title are paid 35% more than the corresponding employees with a master title.

Within our Programme all Doctoral Candidates follow a minimum path of three-years, which includes specific courses and lectures, held by Faculty members and foreign professors and experts: in particular, our candidates have access to a series of research seminars delivered monthly by international top-level faculty (MeccPhD Lectures) and to full courses provided by European and non-European academic experts leading to the obtainment of ECTS. They also experience in-depth research, lab activities and active cooperation with international industries, institutions and research groups. With this background, our Doctorates are able to blend the exactness of scientific knowledge with the ability to deal with management and industrial issues. In this view, their scientific profiles are suitable for prestigious positions at national and international level within universities and research institutions, large industrial and consulting companies, SMEs.
In the following pages 40 abstracts belonging to PhDs of the 34th (1), 35th (7), 36th (22), and 37th (9) doctoral cycles (defended in 2024 and 2025) are proposed. They represent a good overview of the international vocation of our PhD Programme, with a third of them having being developed by international fellows. Female presence accounts for almost 17%.
Nearly 100% of the PhDs were supported by fellowships provided by the Italian Government, Industries, and European and National projects.

RESEARCH AREAS

The PhD Programme in Mechanical Engineering covers a number of different disciplines, being devoted, in particular, to innovation and experimental activities in six major research areas, and in an additional interdisciplinary area. All doctoral thesis displayedin the following pages belong to one of these areas:
Dynamics and vibration of mechanical systems and vehicles: this research line is organized into five research areas, namely Mechatronics and Robotics, Rotodynamic, Wind Engineering, Road Vehicle Dynamics, Railway Dynamics. It features modelling of linear and non-linear dynamic systems, stability and self-excited vibrations, active control of mechanical systems, condition monitoring and diagnostics.
Measurements and experimental techniques: The Mechanical and Thermal Measurements (MTM) group has its common background in the development and qualification of new measurements techniques, as well as in the customisation and application of well-known measurement principles in innovative fields. MTM major research focus is oriented towards the design, development and metrological characterisation of measurement systems and procedures, the implementation of innovative techniques in sound/vibrations, structural health monitoring, vision, space and rehabilitation measurements.
Machine and vehicle design: this research area is involved in advanced design methods and fitness for purpose of mechanical components. Advanced design methods refer to the definition of multiaxial low and high cycle fatigue life prediction criteria, and the assessment of structural integrity of cracked elements, the prediction of fatigue life criteria of advanced materials as polymer matrix composite materials (short and long fibers), the definition of approaches to predict the influence of shot peening on fatigue strength of mechanical components. Gears, pressure vessels and helicopter components are dealt with. Optimal design and testing of vehicle systems create a synergism between the theoretical and the experimental researches on ground vehicles.
Manufacturing and production systems: this research field gives relevance to the problem of optimal transformation of raw materials into final products, addressing all issues related with the introduction, usage, and evolution of technologies and production systems during the entire product life-cycle. PhD activities, in particular, are developed within the following research fields: Manufacturing Processes (MPR), Manufacturing Systems and Quality (MSQ).

Materials: this area is focused on the study of production process and characterization of materials, for structural and functional applications. Excellent research products were obtained both on fundamental research topics (e.g. nanostructured materials, foamed alloys, chemical phenomena in liquid melts, microstructural design etc.) and on applied research (e.g. failure and damage analysis, texture analysis, high temperature behaviour, coatings for advanced applications, etc.). The research projects carried out in recent years addressed specifically the following research topics: Steelmaking and Metallurgical Processes, Advanced Materials and Applied Metallurgy.
Methods and tools for product design: two main research topics are addressed in this field: PLM-Product Lifecycle Management, which includes process modelling, engineering knowledge management, product innovation methods, systematic innovation principles and methods, topology optimization systems, and data/process interoperability, and Virtual Prototyping, which includes virtual prototyping for functional and ergonomics product validation, haptic interfaces and interaction, reverse engineering and physics- based modelling and simulation, emotional engineering.

LABORATORIES

One of the key elements of our Doctoral Programme is represented by our laboratories; we feature some of the most unique, active and innovative set-ups in Europe: 3D Vision, Additive Manufacturing for 3D printing, Advanced Manufacturing Laboratory, Cable Dynamics, Laboratory for measurements for biomedical applications (LAMBDA), Characterization of Materials, DBA (Dynamic Bench for Railway Axles), Vehicle Dynamics, Laboratory for testing of mechanical components on real components or structures, La.S.T. – Laboratory for safety of transport systems, Material Testing and Analysis, Mechatronics, Measuring devices and calibration, Power Electronics and Electric Drives, Process Metallurgy and Simulation, Reverse Engineering, Robotics, SIP (Structural Integrity and Prognostics), Virtual Prototyping and Human Modelling Laboratory, Wind Tunnel, Water Jet.

INTERNATIONALIZATION

We foster internationalization by strongly recommending and supporting candidates' mobility abroad, for short-term study and research periods up to 18 months. Our Institution is member of Idea League (www.idealeague.org), Alliance4Tech (www.alliance4tech.eu) and ENHANCE (https://enhanceuniversity.eu/), three strategic partnerships with leading European Technical Universities. We also promote, draft and activate European and extra-European Joint Degrees, Double PhDs and Joint Doctoral Thesis (Cotutelle); our Department is actively involved in EU-based and governmental third-level education agreements such as Horizon 2020, Erasmus Mundus and China Scholarship Council.
We have ongoing agreements with MIT (Progetto Rocca), Delft University of Technology (Double PhD), RWTH Aachen (Double PhD), University of Zagreb (Double PhD), Northwestern University (Double PhD).

We also have ongoing collaborations within a wider international network, that includes some of the highest-level and best-known universities all over the world, such as the, École Polytechnique Fédérale de Lausanne (CH), Norwegian University of Science and Technology (NTNU), Chalmers University of Technology (SE), Technische Universität Berlin (DE), Warsaw University of Technology (PL), Politècnica de València (ES), Xi'an Jiao Tong University (CN), Tongji University (CN).

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DRIVER-AWARE TORQUE VECTORING CONTROL DEPLOYMENT TO ELECTRIC VEHICLES

Michele Asperti - Supervisor: Edoardo Sabbioni

Co-Supervisor: Michele Vignati

The automotive industry is currently undergoing a major paradigm shift, driven by the convergence of environmental, regulatory, and technological factors. A key trend is the transition from Internal Combustion Engine (ICE) vehicles to Electric Vehicles (EVs), spurred by the global push to reduce greenhouse gas emissions and improve air quality. A major challenge in high-performance EVs is achieving precise vehicle control, particularly in handling and stability. This has spurred significant research into active lateral dynamics control systems, with torque vectoring emerging as a crucial technology. Indeed, by distributing torque to individual wheels, torque vectoring enhances cornering response, stability, and safety. It actively counteracts understeer and oversteer, enabling more precise handling, following the approach schematized in Figure 1.

The overarching goal of this PhD research is to provide a comprehensive set of methodologies allowing the effective deployment of torque vectoring control techniques to vehicles equipped with four independently driven motors. Thus, the research is not only focusing on the design of new torque vectoring control logics, since a significant part of the work is dedicated to the study of the interaction between the human driver and the vehicle lateral dynamics active control logics. In fact, this is fundamental for the acceptance of the proposed innovative control techniques by customers, allowing for the vehicles market success.

Specifically, this research seeks to advance the current state-of-the-art in the active vehicle lateral dynamics control through the following contributions:

- *Design of an integral terminal sliding mode controller allowing for a faster reaching of the sliding surface* - The slow reaching rate of the sliding surface typical of sliding mode torque vectoring controllers results in a controller performance far from the desired one, especially during fast transients. Consequently, the research work has focused on the design of an integral terminal sliding mode controller for contemporary controlling vehicle yaw rate and sideslip angle through the combination of torque vectoring with active rear steering. The innovation of the proposed controller lies in the sliding surface definition, accounting for the combination of a proportional term with two integral terminal terms, which guarantee high convergence rates towards the sliding surface even in presence of small tracking errors;
- *Design of a torque vectoring controller in combination with suspensions tuning for improving energy efficiency while ensuring effective cornering* - When dealing with the design of a vehicle, there is usually a tradeoff between vehicle efficiency and handling performance aspects. Nonetheless, this conflict in requirements can be relaxed with a detailed design of a torque vectoring controller in combination with a specific tuning of suspension angles. This allows to automatically privilege vehicle handling or energy efficiency aspects based on the actual vehicle state. In fact, through a rather neutral setting of suspension angles and a properly designed torque vectoring controller, good handling can be achieved at vehicle cornering limits, while also guaranteeing good energy efficiency under normal driving conditions.
- *Design of an electric power steering control for compensating the steering torque feedback corruption due to torque vectoring* - The adoption of torque vectoring at the front axle of a vehicle is generating the corruption of the steering wheel feedback due to the imbalance in longitudinal tire forces at left and right sides of the vehicle. This could be detrimental for vehicle handling as drivers receive significant information about the actual vehicle dynamics from the steering wheel interface. Consequently, it is fundamental to restore the usual steering torque feedback when adopting front axle torque vectoring to guarantee a proper driver acceptance of the active vehicle lateral dynamics control. For this scope, a comprehensive torque steer theory has been developed, and its output has been adopted for the design of an electric power steering control logic for annihilating the steering feedback corruption due to the imbalance in front tires longitudinal forces.
- *Subjective-objective assessment of torque vectoring controllers* - The driver is the entity in charge of controlling the vehicle when on the road, thus it is of paramount importance to consider the human driver sensations for achieving a proper vehicle handling. This should be taken into consideration also when deploying active vehicle controls like torque vectoring, which could be even more effective if accounting for their implications on both driver burden and satisfaction. Therefore, a comprehensive assessment of torque vectoring control logics has been performed, through the setup in Figure 2, accounting for both drivers' subjective evaluations and measurable objective parameters. This has established a framework which widens the knowledge of human perception about torque vectoring control, while also enabling an effective driver-aware deployment of active vehicle lateral dynamics control to road vehicles.

By achieving these objectives, this research not only contributes to overcoming current limitations in the design of torque vectoring controllers but also sets the stage for a more effective deployment of this kind of active vehicle lateral dynamics control in production vehicles.

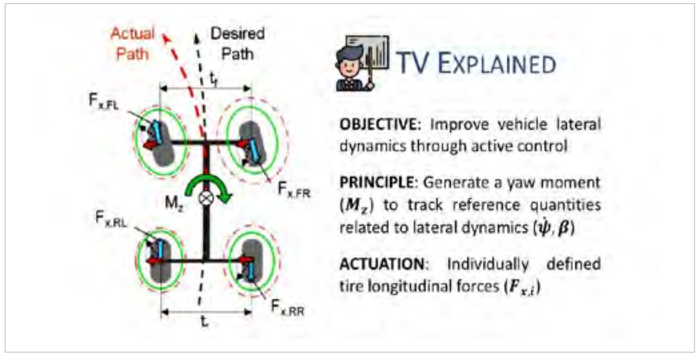

Fig. 1 - Torque Vectoring (TV) control overview.

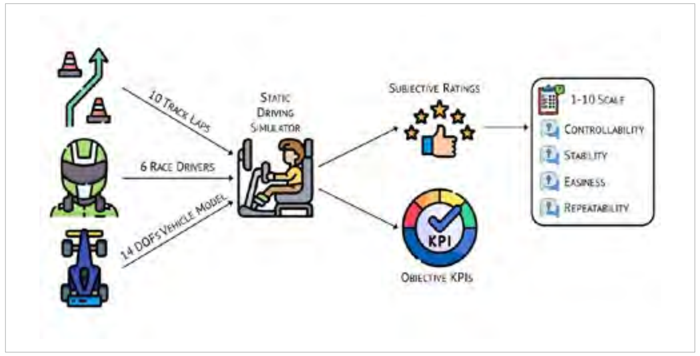

Fig. 2 - Torque vectoring control subjective-objective evaluation framework.

ROGER: ROBOTIC GARMENT EXOSUIT FOR UPPER LIMB REHABILITATION AND ASSISTANCE

Elena Bardi - Supervisors: Francesco Braghin, Emilia Ambrosini

Upper limb motor disability severely impacts people's ability to conduct activities of daily living (ADLs), negatively affecting their quality of life. Individuals with upper limb disability may require support with everyday activities through caregiver assistance or assistive devices. When considering daily assistance, soft robotic wearable devices, also referred to as exosuits, are particularly indicated thanks to their lightweight, portability, comfort, safety, low encumbrance, and low cost. However, research is preliminary and few robotic devices are currently used in home-based settings.
To promote industrialization and facilitate adoption, it is fundamental to reduce complexity and production/maintenance costs while improving the controller's robustness to prevent failures and unexpected behaviour in long-term use. Cable-driven exosuits employ force sensors to implement their control strategies which limit the range of motion of the target joint, add wiring that could reduce the ease of wearing and represent a point of failure as well as a source of higher costs. In this direction, a possible approach is to reduce the number of sensors integrated into the device and rely on more robust model-based controllers.
This work aims to design, develop, and test a simple, robust, cost-effective and portable exosuit to support the upper limb of disabled people with residual motor abilities. More in detail: 1) define the desired features and requirements and develop the suit accordingly; 2) implement a force sensor-free force controller, and evaluate the its performance and the kinematics and physiological effects of the suit; 3) evaluate the need for customizing the controller's parameters to individual users and assess their robustness in long-term use; 4) test the exosuit on end users to evaluate its efficacy in improving their ability to perform functional movements.
A questionnaire was administered to people with upper limb disability and professionals involved in the rehabilitation and assistance field to drive the design around users' needs. The exosuit ROGER was developed accordingly implementing a cable-driven actuation to support shoulder and elbow flexion (Figure 1). Shoulder gravity compensation assistance and elbow flexion assistance triggered by movements onset were selected as high-level control strategies to guarantee intuitiveness, limited calibration procedures, and sensors minimization (Figure 2). The model describing the transmission of the cable tension in the Bowden sheath was identified and inverted to be used as the low-level control strategy. The exosuit was tested on a group of non-disabled volunteers performing arm elevation movements. The control strategy achieved an accurate tracking of the desired assistive force (RMSE = 6.46 N at 50% gravity assistance, corresponding to 18%), comparable to control strategies that employ a force sensor. The suit did not affect the ability of individuals to follow a shoulder elevation trajectory while it reduced Anterior Deltoid activation (-30% when raising with 50% gravity assistance), demonstrating its ability to reduce effort when elevating the arm.
The controller was improved including modelling of the Stribeck effects. The need of personalizing the controller to account for different sheath geometries was explored by customizing its parameters for each participant with Bayesian Optimization with the goal of minimizing force tracking error. To compare the efficacy of non-customized and customized parameters, participants executed some activities with the exosuit with each set of parameters. Participants repeated the tasks on a second day using the customized parameters to evaluate their robustness over time. Although customization slightly improved force tracking performance (RMSE% from 22% to 19%), this improvement did not translate into any physiological difference (i.e., movement kinematics and muscle activation) or user perception. Moreover, performances remained stable in the second session. Thus, customization proved unessential, and periodic re-calibration unnecessary, making the sensorless approach robust enough for practical use.
Finally, six chronic post-stroke volunteers performed functional movements with and without the support of ROGER at their preferred assistance level on two different days. ROGER effectively helped the participants reach higher shoulder elevation angles (+25.6°), while also favouring elbow extension (+18.7°) in reaching movements against their abnormal flexor synergy. The shoulder support was particularly appreciated by participants with slight to moderate impairment. Nevertheless, the elbow support was generally considered unhelpful, as it was perceived to impede elbow extension.
In conclusion, this thesis demonstrates the feasibility of a model-based sensorless force controller for an upper-limb cable-driven exosuit, confirm its robustness over anthropometry and time, and validates its efficacy in delivering support to non-disabled and disabled users, underlining its potential in supporting ADLs in real-world applications. In the future, the exosuit design should be updated considering the feedback collected and a greater number of end users should be involved in testing. Preference-based optimization could be explored to customize the controller parameters and electrical stimulation could be integrated to boost the rehabilitative potential of the system.

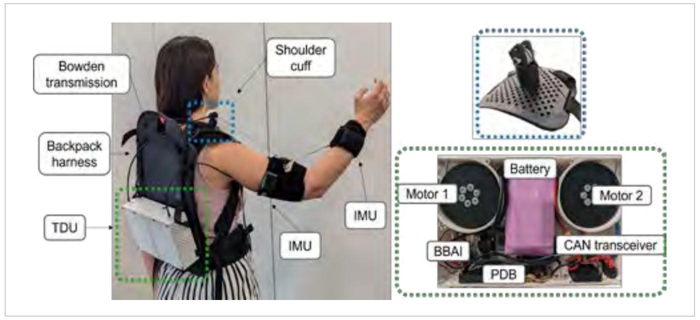

Fig. 1 - ROGER design and main components

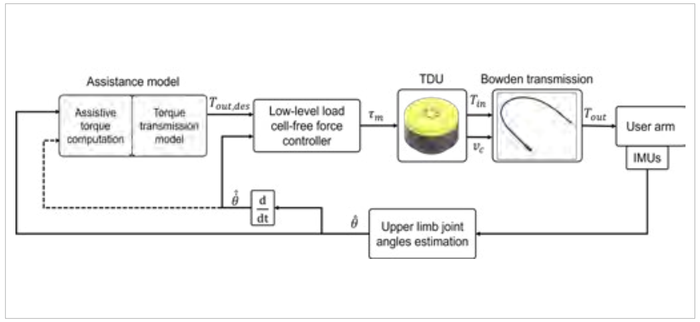

Fig. 2 - High-level control strategy

LEVERAGING ARTIFICIAL NEURAL NETWORKS FOR DESIGN AUTOMATION IN THE ENGINEERING-TO-ORDER SECTOR

Niccolò Batini - Supervisors: Gaetano Cascini, Niccolò Becattini

This PhD thesis examines the potential of artificial neural networks (ANNs) to revolutionize design automation (DA) processes in the engineering-to-order (ETO) sector, which faces significant challenges due to its need for high customization, especially in the context of the energy transition markets and complex turbomachinery systems.
The study explores whether ANNs can address the dual challenge of meeting specific customer requirements while managing short lead times and ensuring cost efficiency, with a particular focus on API 618 reciprocating compressors (RCs) in collaboration with Baker Hughes (BH). Using RCs as a case study due to their complex design requirements and their relevance in custom engineering solutions, the research tests the capabilities of ANNs to automate design processes, reduce lead times, and improve cost efficiency.
The ETO sector typically deals with bespoke products, which leads to complications in integrating engineering and production processes. This results in long lead times and increased production costs, as unique designs require more time and resource management. Customization strains inventory management and disrupts production workflows, making it difficult to maintain quality, cost-effectiveness, and flexibility. Additionally, customers expect quotes quickly, but the design and development process may take months.
To address these challenges, this research evaluates ANNs as a possible solution for automating and optimizing the design of complex systems, potentially offering a faster and more efficient alternative to traditional, computationally expensive optimization methods.
Initially, the research examined the non-routine design challenges within the ETO sector. A detailed project involving the design of a RC cylinder at BH identified gaps in the existing design process using Axiomatic Design theory. The research noted a lack of systematic approaches, which resulted in frequent design iterations and excessive information exchange, causing unacceptable delays. To address these issues, a Design Structure Matrix was developed to identify key performance parameters and define the research scope.
To test the ANN-based DA approach, the research used a database of 365 RC cylinders. The database contained performance parameters derived from previous CFD analyses, representing the design space of existing cylinders. The decision to use ANNs was supported by a literature review on machine learning techniques in DA. ANNs were chosen for their ability to create surrogate models that can make accurate predictions without the high computational costs of traditional optimization methods, especially when working with large datasets.
The study developed an integrated design process for BH RCs (cfr. Figure 1, where the colors are used to highlight the novelties with respect to the as-is process, through an IDEF0 diagram). This process involved creating a master model that incorporated knowledge-based 3D models to manage all the different cylinder configurations. ANNs were then trained using the existing dataset and integrated into the design process.
The research uses three specific case studies to assess ANNs' ability to produce accurate design solutions, even slightly beyond their training boundaries. These case studies involve:

a) Modifying an existing cylinder from the database.
b) Scaling up a cylinder already in the database.
c) Designing a new cylinder with a different gas flow path, beyond the ANN's training range.

The findings summarized in Table 1 indicate that ANNs can generate first-tentative designs with less than 1% error compared to traditional CFD analysis in some cases, with design time reductions by two orders of magnitude. In situations where ANNs had to generalize slightly beyond their training, errors remained below 2%, demonstrating a degree of flexibility in handling new configurations. However, in cases requiring substantial redesign, such as the third case study, errors increased to around 15%, underscoring the continued need for human intervention in novel design tasks.
The research also quantifies the productivity gains and cost savings from using ANNs for DA in ETO. A return-on-investment analysis showed that implementing ANNs could result in a payback period of less than one year due to significant reductions in lead times and operating costs.

The research validates the effectiveness of ANNs in automating design processes for highly customized products. However, the research also highlighted the limitations of ANNs, particularly when faced with the need for creative redesigns beyond their training range. In these cases, the error margin increased, indicating that human input remains necessary for novel design tasks. Despite these challenges, the overall time and cost savings demonstrated by the research suggest that further refinement of ANN-based methods could lead to even greater improvements in both accuracy and productivity.
The thesis concludes that ANNs can play a significant role in improving the DA process in the ETO sector, particularly for systems like RCs that require high customization. The method developed in this research could also be applied to other types of turbomachinery, further expanding its potential impact on the industry.
Ultimately, the research confirms that ANNs offer a highly effective solution for DA in the ETO sector, providing fast, accurate design solutions within their training boundaries. While there are challenges in handling entirely new configurations, the significant gains in efficiency and cost-effectiveness highlight the promise of AI-driven design methodologies for the future of the industry.

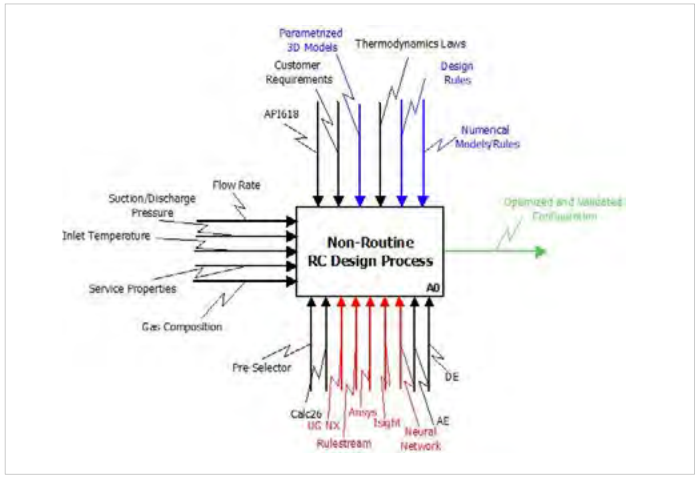

Fig. 1 - IDEF0 diagram of the integrated DA process.

CASE STUDY	K_s ERROR	ε ERROR	ABSORBED POWER ERROR	OPERATING TIME	LEAD TIME
a	0.1%	1%	0.3%	8 min vs 13 hrs	10 min vs 38 hrs
b	0.3%	8.7%	1.7%	8 min vs 15 hrs	10 min vs 40 hrs
c	4.7%	45%	14.8%	8 min vs 15 hrs	10 min vs 40 hrs

Tab. 1 -Summary of results.

INTEGRATING COLD-DEFORMATION AND THE SUBSEQUENT RECRYSTALLIZATION EFFECTS ON FERRITIC/FERROMAGNETIC STAINLESS STEELS AIMED FOR ELECTROMAGNETIC APPLICATIONS

Shahab Bazri - Supervisor: Carlo Mapelli

Ferritic stainless steels (FSS), which are fundamentally ferromagnetic, are vital engineering materials renowned for their magnetic, corrosion resistance, and mechanical properties. Addressing the problem involves tackling the challenges encountered in the current industrial-based research, this thesis defines optimal reduction rates of cold wire drawing and recrystallization annealing conditions for FSS, in tandem with the aforementioned multifaceted properties, pertinent to electromagnetic devices and applications. The novelty of the research lies in a comprehensive investigation into the sophisticated relationship among microstructural and textural evolution, magnetic response, mechanical properties, as well as corrosion resistance in two grades of FSS, namely EN 1.4105 and EN 1.4106 for optimization of the material selections for real-world applications. Through a combination of experimental techniques and theoretical modeling, the effects of cold drawing reduction rate (RR), annealing soaking temperature (AST), and incubation time (AIT) on the microstructure, texture, residual stresses, and consequential properties of the FSS grades are thoroughly examined. The study traces the microstructural evolution from cold-deformed elongated grains to recrystallized equiaxed grains, revealing the nucleation, growth, and orientation mechanisms during recrystallization. It would be noteworthy that the rapid nucleation is observed by increased RR, and AST, with findings corroborating well with the Johnson-Mehl-Avrami-Kolmogorov (JMAK) theory. The microstructural analysis reveals a more substantial responsiveness of grain size to the varied RR in EN 1.4105 and a slighter changing in EN 1.4106, emphasizing the complex relationship between RR and final grain size. Furthermore, cold wire drawing induces refined microstructures through recrystallization with further lower lattice misorientation, leading to improved magnetic, mechanical, and corrosion resistance properties. The corrosion behavior of the FSS grades is evaluated through potentiostatic-based corrosion analysis by immersion inside sulfuric acid electrolyte solution (SAES) and sodium chloride electrolyte solution (SCES). Surprisingly, despite exhibiting active anodic behavior in SCES without passivation formation, the FSS grades demonstrate better corrosion resistance compared to SAES, in terms of substantially-lower corrosion current densities and higher corrosion potentials. This unexpected finding features the inherent corrosion resistance mechanisms of FSS in chlorinated environments alongside the superior passivation-oriented behavior in such an acidic medium and the potential for tailored microstructural engineering to optimize corrosion resistance. All in all, this research contributes to a deeper understanding of the complex relationship among microstructures and multi-faceted properties in FSS, with implications for the design of corrosion-resistant materials for the industrial applications, mainly solenoid valves and electrovalves.

TAILORING QUENCHING AND PARTITIONING TREATMENTS FOR COMMERCIAL HIGH-STRENGTH STEELS: CHALLENGES AND OPPORTUNITIES

Marco Belfi - Supervisor: Carlo Mapelli

Co-Supervisor: Silvia Barella

This thesis explores the applicability of Quenching and Partitioning (QP) heat treatment to commercial high-strength steels, focusing on bulk materials and samples fabricated via additive manufacturing (AM). QP allows obtaining a multiphase microstructure composed of a retained austenite (RA) dispersion within a martensitic matrix, coupling highstrength and improved ductility. While QP was initially developed for tailored alloys, this work investigates its potential for commercial steel grades with non-optimized chemistries, which present challenges such as low silicon content and the consequent competing phase transformations. The goal is to introduce an improved set of properties to commercial steels that cannot be obtained through traditional treatments.
The study employed Thermo-Calc simulations to compute the critical temperatures (A1, A3, Ms) and optimize the process parameters. Experimental campaigns revealed that effective RA stabilization depends on precise control of the quenching temperature (Tq) and partitioning time (tp). Detailed microstructural analyses using X-ray diffraction (XRD), scanning electron microscopy (SEM), and electron backscattered diffraction (EBSD) revealed the presence of RA and the features of the martensitic matrix. The stability of RA was addressed using different approaches. Grades built using Binder Jetting (BJ) and Laser Powder Bed Fusion (LPBF) additive manufacturing techniques were examined. These studies highlighted challenges, such as decarburization and initial microstructural inhomogeneity, which necessitated tailoring QP treatments to achieve optimal results. The integration of AM samples demonstrated the versatility of QP in achieving microstructural control, broadening its application potential.
Mechanical tests showed that QP-treated samples have different properties compared to their traditional quenched and tempered (QT) counterparts, particularly in terms of uniform elongation, fracture toughness, yield strength and ultimate tensile strength. Despite its promise, the study identified limitations, such as carbide precipitation in low-silicon steels and the need for tighter control over phase transformations during partitioning. Compared to the literature, the present work verified the possibility of an effective QP application to commercial, low-alloy, and consequently cheaper steels, and attempted to evaluate the opportunities and criticalities observed during the research.
This thesis establishes a robust foundation for extending QP treatments to a wider range of steels, promoting their adoption in high-performance applications, such as automotive, structural components, and advanced manufacturing systems.

AUTOMATED MONITORING OF HUMAN-OPERATED MANUFACTURING PROCESSES USING COMPUTER VISION AND ARTIFICIAL INTELLIGENCE

Francesco Berardinucci - Supervisor: Marcello Urgo

The increasing demand for customization and the complexity of modern manufacturing processes highlight the critical role of human labor in industrial environments. However, the inherent variability and unpredictability of human-operated tasks pose challenges to efficiency, quality, and safety. This research aims to address these challenges by developing a novel approach for the automated monitoring of manual industrial processes. Integrating advanced human activity recognition (HAR), computer vision, and artificial intelligence (AI) techniques, the proposed methodology enables real-time monitoring, analysis, and prediction of worker activities and process dynamics. The research introduces a comprehensive framework for modeling manufacturing processes, capturing task variability, and identifying deviations from expected behavior. By leveraging pose estimation, object recognition, and statistical modeling, the system provides inference capabilities regarding the performed activities, process milestones, activity durations, and potential errors, while accounting for stoppages and idle times. A robust data acquisition pipeline utilizing multi-modal sensors ensures seamless integration with industrial environments and compliance with regulations. The study further emphasizes the importance of real-time feedback mechanisms to enhance decision-making, proactively address errors, and optimize process efficiency. The proposed approach is validated through empirical evaluations and a real-world industrial case study, demonstrating its effectiveness in improving productivity, quality, and safety. By advancing the state of process monitoring for manual industrial tasks, this research contributes to the development of smarter, more adaptive manufacturing systems.

Keywords: Human-operated Process Monitoring, Computer Vision, Artificial Intelligence

AI-BASED QUALITY INSPECTION OF METAL COMPONENTS EXPLOITING MULTI-LIGHTS IMAGE FUSION STRATEGIES

Paolo Brambilla - Supervisor: Marco Tarabini

This thesis proposes an AI-based framework for the quality inspection of metal components, specifically addressing challenges posed by reflective surfaces and heavily imbalanced datasets where defects are underrepresented. The aim is to develop acquisition and analysis strategies that maximize available information, enabling effective artificial intelligence models for defect identification in real industrial applications. From the image acquisition perspective, a method inspired by "photometric stereo" vision systems is proposed. Multiple images of the object are captured under different illumination conditions, each designed to highlight specific defects. These images are then fused into a single multidimensional dataset by stacking them along the channel dimension. This fusion allows neural networks to identify relationships between pixels across different lighting conditions at the earliest stage of analysis. For the algorithmic approach, semantic segmentation is implemented using a U-Net neural network architecture. Semantic segmentation was chosen over classification or object detection due to its ability to provide detailed information about the defects, including type, morphology, shape, and size. To address the challenges of training with a limited and heavily imbalanced dataset, two methods (Loss Functions Designed for Imbalanced Data and Class- Specific Weights) are employed and tested on two case studies: the first is the quality inspection of raw sheet metal and the second is the identification of defects in conical knurled washers. The effect of illumination setups, class weight configurations, loss functions, learning rates, and model sizes is studied using factorial Design of Experiments techniques. Results demonstrate that multi-channel lighting configurations and the application of class-specific weights significantly improve the model's ability to detect and segment defects, achieving higher Dice scores compared to single-channel approaches. The use of specialized loss functions further enhances sensitivity to underrepresented classes, confirming the effectiveness of the proposed strategies.
Keywords: Quality Inspection, Defect Detection, Vision System, Deep Learning (DL), Computer Vision (CV), Artificial Intelligence (AI), Semantic Segmentation, Convolutional Neural Network (CNN).

FORCE SENSORS AS SMART VEHICLE SUBSYSTEMS TO IMPROVE SAFETY IN INTELLIGENT TRANSPORT SYSTEMS (ITS)

Chiara Bregoli - Supervisors: Laura Maria Vergani, Carlo Alberto Biffi

Introduction. The increase in the average age of the population has led to a rise in age bone-related pathologies, such as osteoporosis, and associated bone fractures which require prosthetic treatments. More than 4 million osteoporotic fractures are recorded annually in Europe, and this number is expected to increase by 20% by 2035.
The weakening of bone tissue in elderly patients leads to a rise in acetabular fractures and a corresponding increase in total hip arthroplasty surgeries and multiple screw fixation procedures.
Consequently, there is a pressing need for prostheses that can integrate effectively also with the ageing poor quality bone. Orthopaedic prostheses should guarantee adequate osseointegration, long-term fixation, proper mechanical properties and no stress-shielding phenomena should occur.
Since the increasing number in prosthetic treatments required for elderly people, the research is spending huge efforts in the development of novel orthopaedic prostheses able to address the specific needs of the patient and able to be successfully osteointegrated in poor-quality bone tissues.
Numerous approaches have been explored to achieve this and novel technologies have contributed to these efforts. Key strategies include: i) surface treatments; ii) the development of novel materials; and iii) innovative prostheses designs.
This PhD thesis focuses on the design of innovative orthopaedic devices. This strategy considers the design as a key factor the implant success and deepen the knowledge on bone-inspired lattice structures. Additive Manufacturing (AM) technology offers the unique advantage of enabling the fabrication of these complex structures and it is able to create in inherent rough surface already demonstrated to be promising for osteointegration.
An addition issue observed with metallic orthopaedic prostheses is the higher stiffness that metallic implants exhibit in comparison with bone tissue. This discrepancy in stiffness may cause the stress-shielding phenomena. One possible strategy to address stress-shielding involves identifying materials with an elastic modulus as close as possible to that of bone; however, despite significant progress, achieving a permanent metallic biomaterial with Young's modulus comparable to that of bone remains challenging. Given these constraints, attention has shifted towards reducing the overall stiffness of the implant rather than the bulk material alone. It is demonstrated that the introduction of lattice structures into the implant decreases its overall stiffness.

Fig. 1 - Graphical abstract of the PhD thesis.

In this context, the main goal of this PhD research is the design and fabrication of advanced AMed metallic bone-like lattice structures suitable for implantable medical devices. The current research begins with a quantitative assessment of human bone, emphasising the importance of a comprehensive understanding of the biological structures hosting metallic implants.

Objectives

i) Quantitative assessment of bone structures at mesoscale: identification of novel quantitative morphometric parameters, which may differ according to physio-pathological bone state and which can be used as input for bone-inspired designs *(see paper: "Effect of trabecular architectures on the mechanical response in osteoporotic and healthy human bone, 2024").*

ii) AMed bone-like lattice structures: by starting from the quantitative data obtained from mesoscale bone structures, specific bone-inspired lattice structures are designed, AM fabricated and characterized *(see papers: "Impact of Surface Finishing on Ti6Al4V Voronoi Additively Manufactured Structures: Morphology, Dimensional Deviation, and Mechanical Behaviour, 2024"; "Mechanical response of LPBFed TI64 thickness graded Voronoi lattice structures, 2024").*

iii) Novel AMed medical devices: functional evaluation and mechanical characterization of AMed medical devices incorporating bone-inspired lattice structures *(see paper: "Additively manufactured medical bone screws: An initial study to investigate the impact of lattice-based Voronoi structure on implant primary stability, 2024").*

Results

The quantitative assessment of healthy and pathological human bone samples enables the identification of the most statistically significant parameters for characterizing bone structure. These parameters include bone density, connectivity density, trabecular spacing, and the degree of anisotropy. Additionally, connectivity density and the degree of anisotropy result to be the most reliable predictors of the mechanical response of bone (p_value < 0.05).
A comprehensive quantitative understanding of bone structure increases the utility of Voronoi tessellation in designing bone-inspired lattice structures.
Voronoi lattice-based samples are designed and fabricated by using Laser Powder Bed Fusion (LPBF) process: different struts thickness – constant and graded thickness – and different surface finishing techniques are evaluated.
An increase in constant strut thickness (from 0.5 mm to 0.9 mm) corresponds to a reduction in dimensional deviations at specific points (dimensional deviation < 0.1 mm), while a decrease in strut thickness leads to an increase in these deviations (dimensional deviation > 0.1 mm). By evaluating the surface post-processing with equal strut thickness, zirconia sandblasting proves to be the most effective technique for minimizing dimensional deviations, reducing them by approximately 50% compared to the as-built component.
The incorporation of gradient thickness designs enables the replication of the cortical-trabecular transition observed in human bone samples. The introduction of this feature into Voronoi lattice-based structures with irregular patterns significantly enhances energy absorption capacity. Furthermore, a strong linear correlation is observed between the relative Young's modulus and the relative average density, regardless of the presence of a thickness gradient.
According to the overall stiffness of the samples, the average Young's modulus in constant-thickness and functionally graded Voronoi lattice-based structures ranges from 20 MPa to 1 GPa: these values are very similar to spongy bone ones, as desired.
Finally, the incorporation of these structures into AMed medical devices, underscores their translational potential. The introduction of Voronoi lattice-based structure decrease the overall stiffness, exhibit promising results for the primary stability and it is expected to encourage the bone ingrowth thanks to the incorporated interconnected pores.
This research provides a comprehensive framework for advancing orthopaedic implant technology, bridging the gap between biological inspiration and engineering innovation. It highlights the role of AM in creating tailored solutions that address the evolving demands of an ageing population while improving patient outcomes.

A COMPACT STEERING LAUNCHER FOR THE ELECTRON CYCLOTRON HEATING SYSTEM OF DTT

Daniele Busi - Supervisor: Francesco Braghin

In the context of nuclear fusion research, the European Roadmap for Fusion Electricity has envisioned the realization of an experimental machine for studies about the power and particle exhaust problem, under plasma conditions that are relevant to future power plants. Such machine will be a Divertor Tokamak Test (DTT) located at the ENEA research center in Frascati, Italy. In order to achieve the required plasma performance, DTT will host one of the most powerful Electron Cyclotron Heating (ECH) systems in the world — with a total installed power of 32 MW — and by far the most power-dense. ECH produces localized power deposition in the plasma by means of focused, high-power microwave beams. Each of the 32 beams handled by the DTT ECH plant will deposit approximately 1 MW of heat in a plasma region of just a few cm in diameter, to fulfill various critical tasks, from bulk heating to magneto-hydrodynamic stabilization. The deposition spot can be moved in real time by means of sub-systems called launchers, which include steerable mirrors and the associated actuation mechanisms. The conceptual design phase of the DTT ECH system is currently approaching its finalization. In this context, the design of an innovative steering launcher has been carried out. While the high power density of the ECH system requires a compact launcher design, wide steering ranges and high positioning accuracy must be ensured to effectively fulfill the different tasks of the plant. In order to attain this challenging mix of characteristics, the radical design choice of an in-vessel actuation system was made, enabling considerable reduction in mechanism weight and volume compared to traditional ex-vessel systems. Among the available actuation principles, ultra-high-vacuum-compatible piezoelectric walking drives were selected. In addition to ensuring high compactness and low response times, these actuators enhance steering precision due to their micrometric stepping capability. The main drawback of walking drives is the adherence-limited driving force. This becomes particularly critical when considering the electromagnetic (EM) loads acting on the steering mirror both during normal operation and in case of disruption events. In this regard, different EM loads mitigation strategies are considered, including the innovative solution of an actively cooled, Tungsten-coated dielectric substrate for the steering mirror. Flexible elements constitute the third building block of the system. Compliant mechanisms avoid the problems of vacuum-enhanced friction, backlash and wear, while flexible pipes prevent water leakages that would result in plasma contamination and shutdown. In particular, an innovative Remote Center of Motion flexure pivot is proposed as mirror support, to cope with the stringent size limitations of the launcher assembly. In order to offset the elastic resistance introduced by flexible components and avoid any negative influence of flexures on dynamic performance, a static balancing device based on negative equivalent stiffness elements has been developed, and different strategies for integration in the assembly have been proposed. The adoption of these design solutions results in a compact, lightweight, accurate and robust steering mechanism, which constitutes a promising perspective for the feasibility of a power-dense ECH plant in DTT. After reviewing the literature, this manuscript collects and integrates detailed descriptions of the analytical, numerical and experimental design activities associated with each system component. Finally, it provides perspective about the relevance of the adopted solutions for other present and future fusion machines.

THE EFFECT OF SMALL AND LARGE-SCALE TURBULENCE ON THE AEROELASTIC RESPONSE OF BRIDGES

Filippo Calamelli – Supervisor: Daniele Rocchi

A fundamental part of atmospheric winds is turbulence, which involves random fluctuations in space and time. These fluctuations cover a range of frequencies which can be linked to spatial scales by assuming the flow as composed of a mixture of eddies with different dimensions: small vortices correspond to high frequencies, while larger vortices are associated with lower frequencies. These different scales affect wind-induced problems on bridges in various ways, interacting with the structure's dynamic behavior and the surrounding fluid dynamics. Specifically, small-scale turbulence, interfering with surface boundary layers and flow separations, alters pressure distribution around the bridge deck, impacting the resulting aerodynamic forces. Otherwise, large scales cause slow modulations in wind speed and angle of attack, leading to unsteady changes in the flow characteristics around the bridge deck, and consequently in the aerodynamic forces. These effects can be enhanced in case of extreme weather phenomena, such as storms and downbursts, which involve steep and localized changes in wind speed, direction, and angle of attack. Depending on the deck's aerodynamic properties, such fluctuations can lead to nonlinearities in the aerodynamic forces, which can strongly influence the response of bridges. This research focuses the problem, analyzing both small and large-scale turbulence effects on the aeroelastic behavior of bridges. Small-scale effects are investigated experimentally by generating a homogeneous turbulent flow impacting a deck sectional model of a bridge. To reach this purpose, a grid is designed and installed in the Politecnico di Milano wind tunnel. Subsequently, wind tunnel tests are conducted with and without a grid, by analyzing the aerodynamic and aeroelastic behavior of bluff bodies with increasingly complex geometries. Test results shown that small-scale turbulent flows can be used to fill the gap between Reynolds numbers achieved in wind tunnel tests and those characterizing atmospheric conditions, mainly impacting flow separations from curved or sharp-edge geometries as in the case of bridge decks. Large-scale effects are investigated numerically by using a nonlinear rheological model. Specifically, the method proposed by Diana et. al. for synoptic winds is updated to simulate the aeroelastic response of bridges under non-synoptic extreme phenomena. As case studies, the response of two bridges, with distinct structural and aerodynamic properties, under non-synoptic storm winds is analyzed. Results highlight that, depending on the aerodynamic characteristics of a bridge deck, low-frequency variations in wind speed and angle of attack, typical of non-synoptic phenomena, can significantly influence the aeroelastic response of the structure. Moreover, these effects would be overlooked by using standard linearized numerical approaches.

PANTOGRAPH TESTING METHODOLOGY BASED ON HYBRID SYSTEM RESPONSE CONVERGENCE

Luigi Calvanese - Supervisor: Alan Facchinetti

Pantograph-catenary coupling represents a determining obstacle for the technological improvement of high-speed railways. In fact, as the application speed increases, the dynamic and aerodynamic phenomena arising on pantograph and catenary become significant.
The mechanical interaction between the pantograph and the overhead equipment is characterised by many complexities. To study them from a dynamical point of view it is necessary to keep into account all the perturbations the system is subjected to. The level of complexity is increased by the modelling challenges given both by the pantograph and the catenary, and the very diversified working conditions they can face. Despite their reliability, full numerical simulations cannot at present substitute in-line phases of pantograph or overhead line testing.
To this scope, hybrid testing represents a strong research branch which is opening its way through the industrial world.
This thesis project proposes the adoption of the Hybrid System Response Convergence (HSRC) approach, already applied in the automotive field for the study of wheel-road interaction, to study the interaction between the pantograph and the catenary.
The increased flexibility and reliability of pantograph-catenary hybrid simulations allows making a step forward in the final objective of in line test reduction/substitution, and in the deepening of complex dynamic phenomena far from ideal conditions.
This work contains all the steps that have brought to the new methodology set up, validation and application.
The results of these studies highlight the strong reliability and potential of this innovative offline Hardware in the loop testing approach in the pantograph catenary field.
This, due to its intrinsic nature, can overcome the limitations of state-of-the-art testing and simulations systems.

PRESERVING MATERNAL HEALTH: ENGINEERING DESIGN METHODS AND TOOLS TO ADDRESS INEQUITIES

Sara Candidori - Supervisor: Serena Graziosi

Every year, millions of women experience postpartum haemorrhage (PPH), commonly defined as a blood loss of 500 ml or more within 24 hours after birth. The World Health Organization describes PPH as the leading cause of maternal mortality, accounting for nearly one-quarter of all maternal deaths globally. Reducing the global maternal mortality ratio to less than 70 deaths per 100,000 live births is the first target of Goal 3 of the Sustainable Development Goals (SDGs) set by the United Nations in 2015. However, the latest published data show 287,000 deaths in 2020, corresponding to a ratio equal to 223. Moreover, the majority of these deaths occurred in low- and middle-income countries (LMICs) due to the lack of prevention and the low diffusion of pharmacological strategies and medical devices to manage childbirth complications.
Potential life-saving solutions for treating PPH include uterine balloon tamponade (UBT) devices. These relatively simple catheter-balloon systems are inserted into the uterus and inflated to hydrostatically tamponade the bleeding. Commercial UBT devices, however, are too expensive for LMICs. At the same time, low-cost adaptations are not safe enough to guarantee complete bleeding control. They also have several limitations, such as difficulties in use and fluid leakage.
To address the urgent need for affordable and effective interventions, the research presented in this thesis describes the development of BAMBI, a novel low-cost UBT device designed for ease of use in resource-limited settings. The research journey unfolds in three key stages: the development of a uterus phantom for device validation (Fig. 1), the design and prototyping of the BAMBI device with its mechanical characterisation (Fig. 2), and a comprehensive usability assessment in a simulated scenario involving medical and non-medical users (Fig. 3). The uterus phantom, fabricated using additive manufacturing technologies, enables accurate and reproducible test environments for UBT devices, bridging a gap in existing validation protocols. Its effectiveness in allowing the measurement of the intraluminal pressure (i.e., the pressure inside the balloon during inflation), needed for the device approval, was proved by using a commercial UBT device (Fig. 1). The BAMBI device, designed to be affordable and easy to use, represents a critical step towards equal access to life-saving PPH treatments.
By adopting a frugal engineering approach, the device was designed starting from the so-called "condom balloon tamponade" (CBT) technique, a low-cost adaptation of the UBT based on the use of a catheter, a probe cover or condom, and surgical sutures to assemble a UBT system. Having identified the connection (knots with sutures) as the critical point of the CBT solution, an innovative connector was designed to assemble the condom and the catheter reliably, as an alternative to surgical sutures. The mechanical characterisation of the BAMBI device demonstrates its comparability to already approved devices in terms of mechanical properties (Fig. 2). In addition, the usability testing campaign demonstrates that BAMBI is more effective, easier, and faster to use than the improvised CBT solution. Multiple training modalities were also compared, demonstrating them equally appropriate for both medical and non-medical users, thus, further supporting the ease of use and versatility of BAMBI (Fig. 3). Finally, a preliminary cost analysis of the designed connector confirms its affordability even for LMICs.
In addition to contributing to developing the BAMBI device, this work presents a methodological framework for developing and validating medical technologies for LMICs, aligning with the SDGs for health equity. The findings underscore the potential of bioengineering solutions in addressing global health disparities, advocating for a holistic approach that considers not only technical issues but also socio-economic determinants of health. Overall, concerning the BAMBI device, the thesis activity provides an initial non-clinical assessment of the novel device, that should be complemented by further analyses as future activities, such as biocompatibility studies, a more detailed cost analysis, and clinical trials.
Finally, the derived methods and approaches could be easily extended to other medical device development processes.
The research described in the thesis has been developed within the Polisocial BAMBI (Balloon Against Maternal BleedIng) project, funded by the Polisocial Award 2020 - Politecnico di Milano grant.
BAMBI is a multidisciplinary project involving three departments of Politecnico di Milano: the Department of Mechanical Engineering, the Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", and the Department of Design. An expert gynaecologist is also part of the research team.

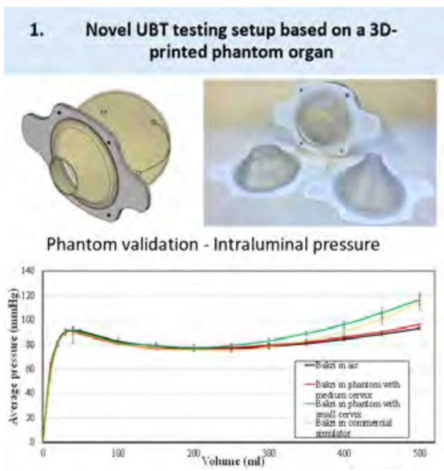

Fig. 1 -.First thesis stage: design and validation of a novel UBT testing setup. On the upper, digital model and 3D-printed prototype of the uterus phantom; on the bottom, phantom validation, based on the measurement of the intraluminal pressure with a commercial UBT device.

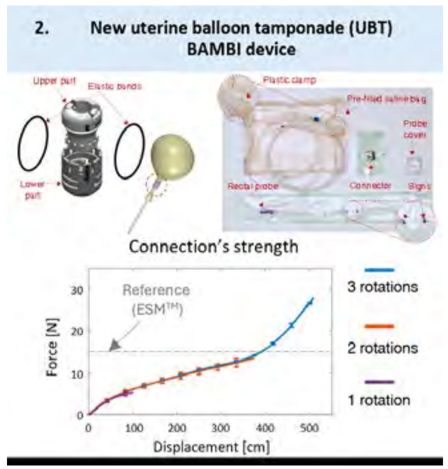

Fig. 2 -Second thesis stage: design and mechanical characterisation of BAMBI. On the upper, the novel connector and the device/kit components; on the bottom, evaluation of the connection's strength and comparison with a similar UBT device.

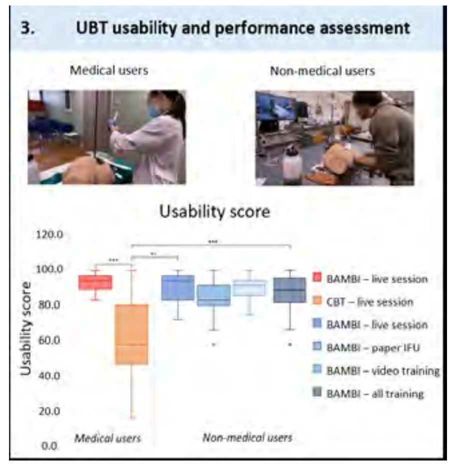

Fig. 3 - Third thesis stage: usability testing campaign. On the upper, photographs of some medical and non-medical subjects involved in the usability experimental tests; on the bottom, comparison of the user groups' usability score (different devices and training modalities were also considered).

ENVIRONMENTAL AND ECONOMIC EFFICIENCY OF PUBLIC TRANSPORT NETWORKS

Luigi Castagna - Supervisor: Pierluigi Coppola

Public Transportation (PT) plays a fundamental role in the transition towards more sustainable mobility, particularly in urban areas where high levels of congestion and pollution are prevalent. Improving PT level of service and efficiency is a priority in many urban agendas and funding programs at national and European levels. While the success of these initiatives largely depends on the availability and application of analytical and modelling tools for planning and designing actions/interventions in public transportation systems, significant gaps still persist in the application of such tools into current practices.
This thesis aims to bridge some of these gaps through the development of advanced analytical and simulation models for PT systems, pursuing three main objectives: (1) the development of a methodology for benchmarking efficiency; (2) the development of a simulation modelling framework for planning, design, and real-time operations management; (3) the validation of the proposed modelling approach through its application to a real-world case study.
In relation to the first objective, econometric analyses were conducted to assess the performance of urban rail systems based on costs and revenues, while also considering the influence of external factors (infrastructural and socio-economic) beyond the control of the firm's management. This research area, still relatively underexplored in the literature compared to other sectors such as rail and road public transport, presents significant challenges, particularly regarding the availability of economic data on operators and services, as well as the accounting of capital-related costs. To address this limitation, two distinct analyses were conducted to assess operating efficiency: the first based solely on publicly available open data, and the second including also economic data collected from transport companies.
Both methodologies follow the same analytical framework, in which the estimated "gross" efficiency (productivity) scores are regressed in a second stage against socio-economic and long-term factors beyond management control, ultimately yielding net efficiency (productivity) scores.
The first methodology applies the *stochastic frontier approach* based on production functions, using proxies for firms' resource consumption as inputs, with the number of yearly transported passengers as the output variable. The results of the second-stage regression indicate that network characteristics, population density, and the presence of complementary urban public transport systems influence metro system effectiveness. However, European metro systems generally appear well suited to the socio-economic environments in which they operate. Finally, the estimated net effectiveness results suggest that smaller transit operators tend to achieve higher net effectiveness values, indicating better performance in day-to-day management.
The second analysis incorporates operators' cost and revenue data. However, due to challenges associated with data collection, a complete analysis was feasible only for a smaller sample of European metro systems. In this analysis, net Variable Input Productivity (VIP) scores are used to assess how efficiently operators utilise their variable inputs in daily operations within the constraints of existing capital infrastructure. Input variables (soft cost input quantity index and number of employees) and output variables (passenger-km and other revenue output quantity index) are aggregated using the *Translog multilateral indexing aggregation procedure*, allowing for the estimation of gross VIP scores. Since these scores are influenced by external factors, they are not directly comparable across cities. Therefore, net VIP scores are calculated following a regression analysis.
Additionally, an integrated macroscopic and microscopic modelling architecture was developed to address objectives (2) and (3) of the thesis. This methodology advances the state of the art in railway station design and management, overcoming the limitations of disaggregated models commonly used by infrastructure managers.
In the first stage, the macroscopic model allows for the estimation of access, egress, and interchange flows based on the rail services supplied at the station and the transport modes available for reaching or departing from it. The estimated passenger flows interchanging at the station, as a function of the available access and egress modes, and the multimodal paths from origins to destinations resulting from the assignment model are used to determine the spatiotemporal distribution of passenger flows within the hub. This distribution is then used to construct the temporal Origin-Destination (OD) matrices of the hub, which are the input for the microscopic simulation model of pedestrian flows. Finally, the station's microscopic model simulates pedestrian movement within the hub and the infrastructure's responses to the estimated passenger flows. The temporal OD matrices of the hub are key components of the integrated modelling architecture, as they transform the macroscopic model outputs (passenger flows and multimodal paths) into inputs for the microscopic model.
The application of the described integrated modelling architecture to the real-world case study of *Milano Bovisa Politecnico* station validated the network-based approach, as well as the assumptions regarding the access and egress model, and those related to the microsimulation of passenger flows within the station. This application also enabled the evaluation of station performance in the as-is scenario, estimating access and egress flows, identifying the transport modes used for these movements, and assessing infrastructure performance in response to the estimated passenger flows.
The research findings provide contributions that are transferable not only to the specific areas analyzed but also to future and cross-sector studies in transportation systems. In particular, the thesis concludes with a review of the main challenges related to the implementation of real-time modelling of PT systems and the application of the *digital twin* concept to the transport sector, with a specific focus on railway stations.

ONLINE SENSOR CALIBRATION FOR AUTONOMOUS VEHICLES

Hafeez Husain Cholakkal - Supervisor: Francesco Braghin

The accuracy and alignment of LiDAR, RADAR, and camera sensors are critical for the effectiveness of perception systems in autonomous vehicles. These sensors, with their complementary operating principles and unique strengths, form the foundation of robust environmental perception, enabling precise object detection, localization, and scene understanding. However, maintaining accurate extrinsic calibration between them is a persistent challenge, especially in dynamic environments where factors such as mechanical vibrations, thermal variations, and sensor drift can progressively degrade calibration quality. Even minor misalignments can lead to sensor fusion errors, reducing perception accuracy and compromising safety.

This thesis addresses these challenges by proposing a simultaneous online extrinsic calibration framework for LiDAR, RADAR, and camera sensors. Unlike conventional calibration approaches that assume static sensor configurations and require controlled environments and calibration targets, the proposed methods enable continuous and automated calibration adjustments in real-time. To achieve this, the thesis introduces two end-to-end trainable deep learning approaches: RLCNet and RLCNet+, designed to enhance the reliability and efficiency of autonomous systems by maintaining consistent sensor alignment.

The scope of this research is specifically centered on extrinsic calibration, ensuring the accurate relative pose estimation between the three sensor modalities to facilitate precise sensor fusion. Intrinsic and temporal calibration are assumed to be accurate and remain outside the scope of this work. The proposed methodologies are extensively validated using publicly available datasets captured under real-world driving conditions, ensuring that the developed solutions are practical, scalable, and adaptable to real-world autonomous vehicle deployments.

The thesis begins with an in-depth overview of LiDAR, RADAR, and camera sensors, discussing their working principles, advantages, limitations, and their crucial roles in multi-sensor fusion architectures. A comprehensive literature review highlights a critical gap in simultaneous online calibration for all three sensors, with most existing works focusing only on pairwise calibration methods. This gap underscores the necessity of the proposed RLCNet and RLCNet+, which are specifically designed to address the performance, reliability, and real-time demands of future autonomous vehicles.

The first proposed method, RLCNet, is tailored for rotational

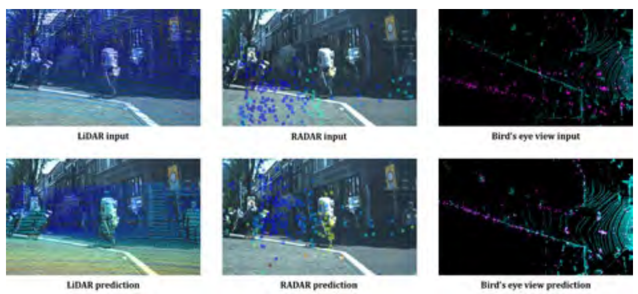

Fig. 1 -.Calibration results of RLCNet+

calibration, as rotational misalignment has a significant impact on perception accuracy. RLCNet employs a lightweight, computationally efficient architecture optimized for real-time applications, ensuring minimal latency during calibration updates. The second approach, RLCNet+, extends this capability to full six-degree-of-freedom (6-DoF) extrinsic calibration, estimating both rotational and translational parameters simultaneously. To enhance accuracy and stability, RLCNet+ incorporates a novel message-passing network that refines calibration parameters through an iterative optimization process. An illustration of calibration results of RLCNet+ is shown in Figure 1. Both networks are rigorously evaluated across multiple datasets, demonstrating high accuracy, repeatability, and robustness across different environmental conditions and miscalibration ranges.

Additionally, the thesis introduces an online calibration framework, integrating a weighted moving average and outlier detection mechanism to dynamically update calibration parameters. This framework effectively filters noisy predictions while remaining highly responsive to sensor drift, ensuring that extrinsic calibration remains stable and reliable even in prolonged operations. An ablation study investigates the impact of key design choices, highlighting the critical architectural components that contribute to the model's performance. Furthermore, benchmarking against state-of-the-art calibration methods validates the superior accuracy, efficiency, and adaptability of the proposed approaches.

Overall, this thesis makes significant contributions to autonomous vehicle research by tackling one of the fundamental challenges in multi-sensor calibration. The proposed deep learning-based frameworks, RLCNet and RLCNet+, introduce innovative optimization techniques, robust noise mitigation strategies, and real-time calibration capabilities. The findings provide a strong foundation for future advancements in automated sensor calibration, paving the way for more reliable, adaptive, and safety-critical perception systems in complex driving environments.

AN INNOVATIVE HUMAN-LIKE DRIVER MODEL

Antonio Cioffi - Supervisor: Stefano Melzi

Nowadays, the automotive industry is focused on the challenges posed by Autonomous Vehicles (AV). Among them, the toughest regards the acceptance of the proposed driving logic from the final users. To avoid a possible reject from the passengers, it is important that the driver logic resembles as much as possible the human driver behaviour. This is why many OEMs devoted resources to the understanding and modelling of the human driver.
In principle, a human driver model could be formulated by merging various manoeuvre-specific models. In practice, one of the drawbacks of this approach is that the model calibration could be a rather challenging task. This is why it would be better to formulate a comprehensive, unified model. Kolekar et al. were the first authors to create a unified framework for the modelling of the human driver. The model relies on the definition of the Driver's Risk Field (DRF), that represents the human driver's belief about the probability of an event to occur (Fig. 1).

In this thesis, an effort is made to achieve two milestones. The first is related to the development of a perception model to be integrated in the DRF. The perception model should reproduce how different drivers perceive the external environment and the other road users. The second aims at assessing the possible acceptance from car passengers of the newly proposed driver model. To do so, an experimental campaign with 31 volunteers was performed using a dynamic driving simulator. An ad-hoc experimental protocol to obtain both quantitative (EEG, ECG, SPR and an Eye-Tracker) and qualitative (surveys) answers was developed.
The reactions obtained when testing various driver model versions were compared with those obtained using a real human driver. The ECG time domain parameters seem to show reliable information on the subject emotional state: an adaptation of the passenger during driving, which led to lower Heart Rate and higher Heart Rate Variability, independently from the driver (human or modelled). Indeed, this is in agreement with the subjective measures provided by the questionnaires, which point out an increased level of trust towards AVs after completing the test, and the same level of NASA TLX cognitive load between human and human-like driver models.

Therefore, ECG-related signals could be considered the best option to chose for the investigation of the subject emotional state, even though further studies (i.e.: a larger sample of subjects, use of real world scenarios, a more sophisticated analysis, etc...) are needed to confirm the obtained results.

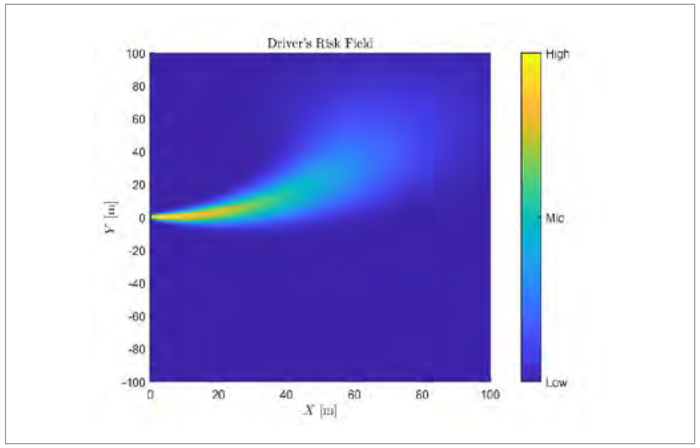

Fig. 1 - Kolekar's et al. Driver's Risk Field.

Keywords: Human Driver, Driver Model, Driver Perception, User Acceptance, Driving Simulator.

METAMATERIALS FOR UNDERWATER ACOUSTICS – A PATH TO THREE-DIMENSIONAL CLOAKING

Sebastiano Cominelli - Supervisor: Francesco Braghin

The concept of cloaking, first introduced in the early 2000s, represents a profound challenge to wave propagation control. Cloaking, which refers to the practice of directing a probing wave around an object to make it undetectable, has been the subject of research in various fields over the past two decades. However, the practical implementation of cloaking remains largely unexplored, especially in the field of underwater acoustics.

The design of an acoustic cloak can be approached using transformation acoustics (TA), inverse design or a combination of the two. The traditional method is TA, which uses coordinate transformations to define a distribution of material properties that allow a strong concealment. However, practical challenges arise in the physical implementation of these properties, particularly in achieving the required anisotropic inertia or elasticity. Conversely, inverse design allows macroscopic material properties to be optimised within the constraints of available materials, although it typically results in narrowband and directional devices.

Typically, acoustic cloaking relies on anisotropic inertial properties to manipulate sound waves. While this technique has been demonstrated in both 2D and 3D experiments, it has inherent limitations. A major drawback is the so-called *inertial catastrophe*, meaning that theoretically an infinite mass is required to achieve the perfect cloaking effect.
To overcome these challenges, the focus has shifted from inertial to pentamode (PM) cloaks. PM materials offer a promising alternative due to their ability to mimic the acoustic properties of fluids while being solid structures. Nevertheless, studies investigating PM cloaks have primarily been restricted to 2D, due to the complexities of designing and manufacturing 3D PM materials.

This thesis embarks on a journey towards the design of a 3D PM cloak and culminates in a virtual prototype that considers both macroscopic and microstructural constraints.
In the first part, we focus on inverse design methods for underwater 2D phononic crystals, where the macroscopic material properties are defined through an optimal control problem that addresses microscopic constraints. In this way, we design concealment and imaging devices that are validated through numerical simulations of their entire microstructure.
In the second part of the thesis, we leverage the principles of TA to design both inertial and PM cloaks. *In primis*, we apply TA to eigenvalue problems of open cavities and present a method for designing thin metasurfaces. Then, we develop a 3D PM acoustic cloak and explore its practical limitations, paying special attention to the microstructural design to ensure its effectiveness in real-world applications, including the complex deformations necessary for covering 3D objects.

Throughout the thesis we design various liquid-like metamaterials using model-based intuition and modern techniques such as neural networks and topology optimisation. Of particular interest is the design of a metamaterial that behaves like water in the long wavelength regime.
Significant advances in cloaking have been developed that are applicable to broader wave manipulation applications such as lenses, concentrators and waveguides.

EGO VEHICLE AND OBSTACLE STATE ESTIMATION IN DEGRADED AND LOW-RESOLUTION SENSING SCENARIOS

Pragyan Dahal - Supervisor: Francesco Braghin

Autonomous Driving Systems (ADS) have made significant strides, inching closer to real-world implementation. This technology, a hotbed of research in both academic and industrial circles, promises to transform travel, work, and leisure with applications like self-driving vehicles, robo-taxis, autonomous trucks, and more. Despite substantial progress fueled by ongoing research and investment, challenges persist at each stage of its development.

The ADS software stack comprises four key components: localization, perception, path planning, and control. This thesis focuses on the localization and perception aspects. Localization is the initial step where the vehicle determines its position in its environment. This can be achieved globally using Global Navigation Satellite Systems (GNSS) or locally with LiDAR or cameras to compute relative vehicle odometry. Two main approaches to localization are state estimation and Simultaneous Localization and Mapping (SLAM). State estimation relies on GNSS and other in-vehicle sensors for global positioning, while SLAM builds a map of the surroundings and localizes the vehicle within it. GNSS, though reliable in many situations, can falter in environments where satellite visibility is obstructed, such as urban canyons, forests, and tunnels. To counter this, additional sensors like Inertial Measurement Units (IMUs), LiDAR, and cameras are integrated to maintain localization even when GNSS fails. These sensors operate at different frequencies, causing temporal asynchronicity, complicating sensor fusion and state estimation. Additionally, sensors without a common Field of View (FoV), like multiple LiDARs facing different directions, introduce spatial miscalibration, adding noise to maps and localization accuracy. Key challenges include managing these temporal and spatial discrepancies, sensor failure, and environmental degradation.

To enhance robustness and reliability through sensor fusion, a modular algorithm is necessary, allowing easy integration of various sensors. Moreover, the algorithm must identify and disregard contributions from failed sensors in state estimation. This thesis proposes Recurrent Neural Network (RNN) based architectures for handling sensor failures and ensuring robust state estimation. Additionally, Factor Graph Optimization (FGO) based solutions address GNSS failure, temporal asynchronicity, and spatial miscalibration issues.

The perception component of ADS focuses on understanding the environment around the vehicle, including both dynamic and static objects. The initial step involves segmenting these objects into categories such as drivable roads, traffic lights, pedestrians, vehicles, and road obstructions. Dynamic objects pose significant challenges for path planning and control due to their unpredictable behavior. Detection and Tracking of Moving Objects (DATMO) aims to identify these dynamic objects and predict their future movements, providing a comprehensive representation of the vehicle's surroundings for safe path planning and control.

Challenges in perception include dealing with an unknown number of objects, imperfect detections, object occlusion, and the birth and death of objects. Sensors like LiDAR, cameras, and radar are used for object detection, with LiDAR being predominant despite its high cost. However, low-resolution LiDARs, common in current setups, pose difficulties for object detection and tracking, leading to missed detections and false positives. This thesis explores multiple algorithms for object detection and tracking using low-resolution LiDAR, complemented by radar detections through sensor fusion. It also integrates road infrastructure knowledge into the tracking framework, improving object state estimation accuracy.

This thesis aims to advance ADS localization by addressing sensor degradation and failures and conducting a comprehensive study on DATMO for low-resolution LiDAR and radar sensors. Specific goals include developing algorithms for easy integration of various sensors into the estimation framework, integrating asynchronous and miscalibrated LiDARs into a common framework for vehicle motion computation, and developing adaptive solutions to filter out contributions from failing sensors in state estimation. For DATMO, the goals are to explore alternatives to learning-based detectors for low-resolution LiDAR and track obstacles with extended state representation, perform state estimation in curvilinear road coordinates by integrating road models into the tracking framework, and develop fusion strategies for LiDAR and radar detections to improve point and extended object tracking frameworks.

The thesis makes significant contributions to both localization and perception components of ADS. It proposes a novel sensor-fault resistant deep-learning architecture for Visual Inertial Odometry (VIO) using Message Passing Neural Network (MPNN) and extends this to RobustStateNet for GNSS and in-vehicle sensor inputs. Additionally, it introduces multiple novel FGO-based localization algorithms for integrating asynchronous and miscalibrated sensors, demonstrating superiority over filtering algorithms in GNSS failure scenarios. In the domain of DATMO, the thesis proposes a hybrid measurement model for object detection using Occupancy Grid (OG) based detectors as an alternative to learning-based detectors for low-resolution LiDAR. It integrates road models into the tracking framework, enhancing object state estimation accuracy through sensor fusion and curvilinear road coordinates, validated through custom datasets.

Overall, the thesis advances the state of the art in autonomous driving technology by addressing key challenges in localization and perception, contributing to the realization of robust and reliable ADS.

PROSPECTIVE AND APPLICABILITY OF BIOGENIC CARBON SOURCES IN THE IRON AND STEELMAKING SECTOR

Gianluca Dall'Osto - Supervisor: Carlo Mapelli

Co-Supervisor: Silvia Barella

The iron and steelmaking industry represents one of the most challenging and difficult hard-to-abate sectors, responsible for approximately 8% of global anthropogenic emissions, 7% of the world industrial energy demand, and based for the majority of its production on the use of high-emitting furnaces that demand both fossil carbon sources and iron ore.

Accordingly, together with the technological advancements in the exploitation of hydrogen as a gaseous stream and the retrofitting of plants with carbon capture systems, the utilization of biogenic carbon sources, considered as carbon neutral, represents a major driver in the quest for effective and sustainable iron and steel production.

The objective of this research was to delineate the most optimal pathways for the integration of diverse quality-grade biogenic carbon sources into the Italian iron and steel production framework.

Building upon a technological assessment conducted between 2022 and 2050, which encompassed the sector production, emissions, energy demands, and material flows (e.g., clean iron sources and iron ore), three distinct applicability scenarios were explored:

1) The potential use of gaseous biogenic carbon sources (biomethane) as a substitute for natural gas in iron and steel production furnaces as well as direct reduction processes.
2) The potential of use solid biogenic carbon sources (e.g., biochar and hydrochar) as reductants for iron oxide-bearing residues and by-products (e.g., mill scale and Waelz slag) following their agglomeration to produce clean iron.
3) The potential use of solid biogenic carbon sources (e.g., biochar and hydrochar) in direct carbon fuel cells as a supplementary renewable energy source for iron and steel production furnaces as well as direct reduction processes.

AEROSOL JET PRINTING OF BISMUTH TELLURIDE: STUDY ON DIFFERENT SCALES

Matteo D'Angelo - Supervisor: Nora Lecis

This research programme, funded by STMicroelectronics, focuses on developing miniaturized thermoelectric generators through scalable manufacturing methods to convert waste heat into electricity, addressing the increasing demand driven by the growing microelectronics and Internet of Things markets. Within this context, the doctoral project aimed at evaluating the feasibility of fabricating thermoelectric legs with lateral dimensions and thicknesses in the tens-of-micrometer range using industrially scalable technologies. As a preliminary step, a thorough literature review was performed to determine the best fitting materials and technologies for the aim. Bismuth telluride compounds were chosen as the performance is high close to room temperature; the p-type compound $Bi_{0.5}Sb_{1.5}Te_3$ was then selected as matter of study. Ink-based deposition techniques were prioritized over sputtering, due to the technological limits of the latter in reaching the needed thicknesses. In the case, Aerosol Jet Printing was selected for its scalability, flexibility, and ability to deposit thick layers with high resolution. STMicroelectronics provided the All-in-One Materials Deposition Platform CERADROPCeraPrinterF-series, which was developed to fit supply chain of microelectronics thanks to its numerous functions and high-throughput production with interchangeable printing heads. Two approaches were used to fabricate $Bi_{0.5}Sb_{1.5}Te_3$ powders for ink preparation:

- High-energy ball milling produced large (≈ 4 µm) and irregular particles, suitable for scalable ink production but with limited ink stability and dispersible solid fraction.
- Solution-processing yielded smaller (≈ 900 nm) and more uniform hexagonal nanoplates, enabling stable inks with 40 wt% solid fraction but with lower scalability.

  The material was then studied accordingly to the following key project goals:

- *Material Characterization*: the powders fabricated by ball milling were consolidated via cold pressing and additive manufacturing (Binder Jetting), in the latter case to simulate thick film fabrication where pressure cannot be applied during the preparation of the pellets. The morphological, microstructural, and thermoelectric properties were analyzed to determine the effect of pressure during consolidation.
- *Ink Preparation*: The inks were formulated and optimized for Aerosol Jet Printing using both the typologies of particles, prioritizing high solid fractions and long-term stability.
- *Thick Film Fabrication and Optimization:* The thick films were deposited on Si/SiO_2 substrates to align with the silicon supply chain. Further, the inks prepared with the grinded particles were printed employing a custom-made system, whereas the inks dispersed with the nanoplates were used on CERADROP F-series, to compare the quality of the films using the different inks. Post-processing included conventional furnace treatments and laser irradiation to improve density. The morphological, microstructural, and thermoelectric properties were characterized to determine the quality of the deposit and the effects of post-processing. Additionally, two feasibility tests were conducted using the CERADROP system to evaluate the highest attainable line resolution and demonstrate the ability of the system to meet the requirements of the research programme.

The results revealed that ball-milled powders failed to provide sufficient density or stability, while solution-processed particles produced stable inks and adequate thickness. Between the different challenges that were faced as the films were post-processed, extensive cracking remains the most critical. Interestingly, the attained resolution resulted 25 µm, which is virtually sufficient to achieve the research programme goal.

This study demonstrates the feasibility of producing miniaturized thermoelectric legs through Aerosol Jet Printing using the industrially scalable platform CERADROP CeraPrinter F-series. It provides preliminary guidelines for process optimization, focusing on ink formulation, printing conditions, and post-processing techniques. The research highlights the potential of integrating dual printing heads to deposit p- and n-type inks simultaneously, enabling the direct fabrication of thermoelectric modules in a single process. The focus of future efforts must be the optimization of the technique to meet the stringent requirements of microelectronics manufacturing.

BEHAVIORAL MODELS TO ASSESS URBAN AIR MOBILITY SERVICES

Francesco De Fabiis - Supervisor: Pierluigi Coppola

In recent years, the Urban Air Mobility (UAM) concept has been receiving increasing attention as a new aerial mode of transport for passengers in urban areas. This popularity surge is largely attributed to advances in electric battery technology, enabling the development of new light aerial vehicles known as electric Vertical Take-Off and Landing (eVTOL) aircraft. Major vehicle manufacturers like Joby Aviation, Airbus, Volocopter, and Lilium are in competition to bring advanced eVTOL technologies to market for commercially operating UAM services. Meanwhile, national, and regional administrative and political bodies are preparing roadmaps for the sustainable adoption of UAM.

Despite several worldwide announcements of upcoming UAM service launches between 2024 and 2026, uncertainty remains about the financial sustainability of possible use cases (e.g., airport shuttles, city-taxis, or inter-city services), particularly during the initial stages when demand may not be substantial due to relatively high tariffs that are not affordable for all. Additionally, there is uncertainty about public perception of low-altitude, short-range flights for daily travel purposes. User adoption of UAM services should not therefore be taken for granted, considering the significant role of transport demand in the overall sustainability of the UAM system. Will new aerial urban services experience massive adoption, or will they remain confined to niches? Additionally, what will be the user profile that chooses them most for their travels?

In attempting to address these questions, the scientific literature on UAM demand analysis has primarily focused on UAM demand forecasting without distinguishing between different use cases. Moreover, there is still a lack of knowledge regarding the distinctive traits characterizing potential UAM users, as most studies only focus on the level of service (i.e., times and costs) and socio-economic factors affecting choices. This research aims to bridge up these gaps by comparatively analysing users' approach towards different UAM services (i.e., airport shuttles, city-taxis, or inter-city services), shedding light on individuals' latent traits influencing choices, such as personal attitudes. The goal is to provide policy recommendations for the development of a sustainable UAM ecosystem.

The methodological approach adopted in this research uses discrete choice models, traditionally used for demand behavioural studies, taking into account psychometric and statistical techniques for measuring attitudes and inferring individuals' latent factors (see Fig.1).

Furthermore, it integrates estimated models into a transport demand-supply interaction simulation tool to forecast passenger mode choices, including different UAM services, while adopting a scenario planning approach.

The application is related to the Milan metropolitan area (Italy), where a large-scale revealed and stated preference survey campaign has been conducted. Research findings indicate that users tend to value UAM for airport access/egress travels more than for other urban trips. In fact, they are willing to pay 44% - 57% more for the airport shuttle services, and 31% - 44% more for business travels compared to other purposes (Fig.2). This suggests that the most financially sustainable UAM services will likely be airport shuttle connections to and from central business districts.

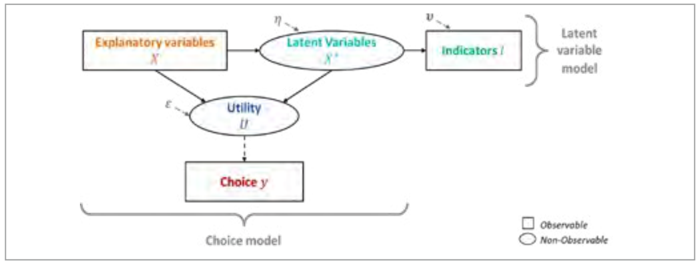

Fig. 1 - Schematic Depiction of the Hybrid Choice Modelling (HCM) Framework used in the research.

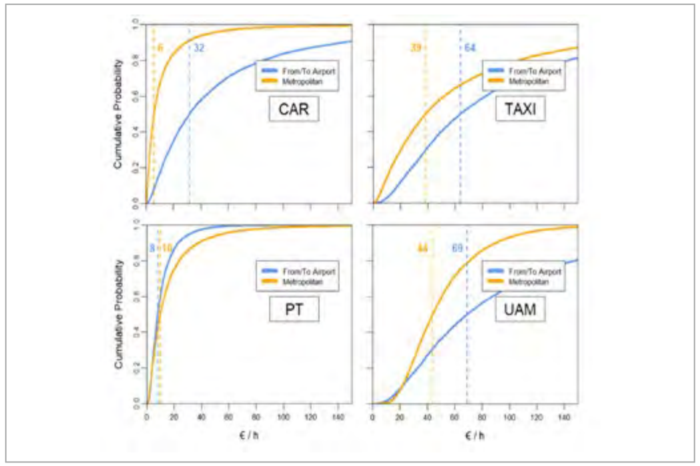

Fig. 2 - Cumulative distributions and median values (vertical dotted lines) for in-vehicle value of travel time savings, business trips.

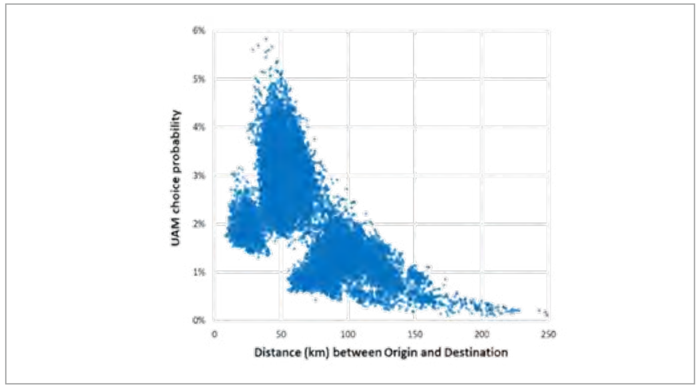

Fig. 3 - UAM choice probability, as function of OD flying distance.

Findings are confirmed by the transport demand-supply simulations related to the analysed case study (see example in Fig. 3): the probability of choosing UAM airport shuttles ranges from 2% to 5%, depending on the level of service of competing modal alternatives on the specific origin-destination pair, making them more attractive than other UAM services with a lower probability of being chosen (ranging from 1% to 3%).

Focusing on the potential passenger profile, the results indicate that UAM services primarily attract business travellers and high-income individuals traveling for leisure or other non-work-related purposes. Significant differences were observed in the intention to use these services with respect to mode choice. While individuals' latent characteristics, such as 'fear of flying,' 'propensity towards technology,' and 'perceived eVTOL safety', play a significant role in profiling the intention to use UAM services, they do not add additional explanatory power to mode choice models.

POWERTAIN DEVELOPMENT FOR A HYBRID AUTONOMOUS RAILWAY VEHICLE

Nicola Debattisti - Supervisor: Davide Tarsitano

Railway vehicles have historically represented one of the most promising transportation systems, ensuring high levels of safety and comfort through rigorous operational standards. Failures in railway infrastructure can have catastrophic consequences, including significant economic losses due to service disruptions, repair costs and potential damage to goods in transit. Safeguarding railway infrastructure against intentional threats, such as terrorism, necessitates effective protective measures. The development of an Unmanned Railway Vehicle (URV), equipped with vision systems to ensure longdistance/ perimeter vision and recognition of anomalies, aims to enhance surveillance and protection of high-speed lines. The need to keep the vehicle size and weight as smaller as possible prevented the use of the overhead contact line as power supply. Therefore, the URV powertrain has been designed with a series hybrid architecture. This approach ensured a reasonably high operational range while also aligning with the global shift towards sustainable mobility, aiming to enhance energy efficiency and reduce reliance on fossil fuels. This thesis details the development of this kind of hybrid railway vehicle. Due to the series hybrid architecture adopted, the design of the URV includes the integration of a Range Extender (thus an internal combustion engine coupled with an electric generator) to the purely electric propulsion provided by the batteries and traction motors. Among the main activities, there is the development and setup of all vehicle systems; in particular, the high voltage system which involves powertrain components, the low voltage system which supplies the control units and the pneumatic braking system. However, the core of the work lies in the software development of the URV, which mainly includes the control and management algorithms implemented in the Vehicle Control Unit (VCU), which handles all vehicle operations. A Software-in-the- Loop (SiL) test bench has been developed to safely test and debug the VCU software; this involved the synthesis of a vehicle model to simulate longitudinal dynamics and powertrain elements, allowing for realistic control scenarios and dynamic failure management testing. The experimental validation has been performed using a roller test bench, where the powertrain operating points have been evaluated and real mission profiles have been simulated. The results obtained by the test sessions confirmed the accuracy of control algorithms. However, the evaluation of the vehicle performance in low adhesion conditions will need to be carried out on a real track.

DESIGN AND MANAGEMENT OF CYBER-PHYSICAL SYSTEMS IN LOW VOLUME PRODUCTION FOR ZERO-DEFECT MANUFACTURING

Ozan Emre Demir - Supervisor: Marcello Colledani

The growing trends towards custom products in various strategic, high-added value sectors, such as automotive, electronics and healthcare poses a challenge on the on-time delivery of high quality, complex products in low volume production contexts. At the same time, the interest towards lowering the environmental footprint of manufacturing process- chains through a more conscious use of materials and resources, combined with a persistent pressure on production costs, forces the reduction of scraps and wastes due to non-conformity. In response to these needs, zero-defect and zero-waste manufacturing methods, jointly considering quality, production logistics and maintenance aspects, traditionally applied to mass production contexts, should be further enhanced to cope with high variability, small-lot or individualized, down to one-of-a-kind productions, by exploiting the opportunities offered by modern digital manufacturing technologies. This thesis addresses the critical challenge of maintaining high quality while reducing eventual defects in low volume, high-variability production scenarios, characterized by custom and complex products. The thesis proposes a novel multi-layered Cyber-Physical System framework that associates three hierarchical levels of a manufacturing system: product-level, process-level, and system-level. Cyber-Physical Systems integrate real-time data from the physical world with advanced computational models, leveraging state of the art digital technologies and models to control manufacturing systems and enable dynamic decision-making to achieve Zero-Defect Manufacturing. The study highlights key challenges in specific applications and the limitations of traditional quality control mechanisms in highly variable production environments.
The proposed methodology is then tailored for implementation in three case studies of relevance to demonstrate its potential to reduce scrap generation, improve production efficiency, and ensure zero-defect outcomes in highly customized, low volume manufacturing. In the first case study, how the product-level information can be utilized to predict the final functional behaviour by means of a product model and optimization algorithm to control downstream assembly stage is shown. The next case study is dedicated to automotive industry where the precision of a decision model and the accuracy of a quality inspection instrument can have a significant influence on manufacturing system performance. The last case study, instead, demonstrates the use of whole product-, process- and system-level information to achieve optimized production planning that reduces scrap generation. Each case study has its own novel aspect in their field of study, whose impact is reflected in obtained numerical results, showing the strength of proposed approach.

Keywords: Cyber-Physical System, Zero-Defect Manufacturing, Manufacturing System

STUDY OF A NOVEL REPURPOSING PROCESS CHAIN FOR AUTOMOTIVE SHEET METALS

Daniele Farioli - Supervisor: Matteo Strano

In a world increasingly focused on environmental impact and material scarcity, the traditional "take-use-dispose" model is no longer sustainable, especially in resource-intensive sectors like the sheet metal forming industry. This thesis proposes an alternative circular path based on repurposing sheet metals through a melt-less process: reshaping via flattening. This process has been studied specifically for end-of-life (EoL) automotive components but potentially can be extended to the entire sheet metal forming sector. Flattening can be performed with a press equipped with flat and heated dies with the objective of restoring the components' planarity, making such parts potentially re-stamped for a second life (Figure 1).
The work addresses a complex, multidimensional challenge, structured around three core pillars: economic feasibility, technical viability, and environmental sustainability.
The research begins by exploring the reverse supply chain of sheet metals, dismantling plants configuration and mapping out how circular value can be generated before the point of recycling. An analysis of the car dismantling sector in Italy was carried out, where large quantities of EoL panels are currently sent to remelting at a low value. The central idea is to intercept these parts, and to repurpose them through flattening. Since these parts arrive free of charge at the dismantler, the model becomes particularly attractive and, to test this hypothesis, a cost model was developed. Such model considers a dismantling plant able to process 50 cars/day with a high level of automation. The average cost for reshaped sheets was estimated at 9.2 €/m^2 (1.2 €/kg for steel), with roofs and hoods being the most cost-effective components. Another key result is that the cost and cycle time of repurposing are independent of the incoming material: targeting high-value alloys like aluminum or stainless steel can significantly increase profit margins. However, reshaped sheets are competitive in scenarios where few panels are sold to many clients with limited individual demand for example in urban design, small construction projects, or artistic applications.
From a technical standpoint, the thesis investigates which sheet metal geometries can be successfully reshaped and under what conditions. Early simulations and experiments revealed that geometry plays a crucial role: certain features, such as deep drawing, V-bends, and double-curvature shapes, are prone to generate defects during flattening. To support dismantlers and remanufacturers, a simplified classification system that categorizes sheet panels based on shape complexity and flattening behavior was introduced. Partitioning complex geometries or applying stretch-flattening techniques can mitigate deformation issues. The flattening process itself was experimentally and numerically characterized.
Two main geometries were analyzed: V-bent samples and Nakajima-type samples with controlled curvature. Critical parameters such as dwell force, tool temperature, and dwell time were studied through Design of Experiments (DoE). The tests involved DC04, aluminum, and AISI 304 steel, with sample thicknesses from 0.8 mm to 1.2 mm, temperatures up to 293°C, and forces up to 400 ton. Using statistical tools (ANOVA) and regression models, the research produced feasibility maps that help predict residual springback for various input conditions (Figure 2).
One major discovery is that by interposing a steel mesh between the panel and the die, it's possible to operate at room temperature, reduce required forces, and even create an aesthetically interesting surface pattern, all while saving significant energy. The mechanical integrity of reshaped panels was tested with tensile experiments and finite element simulations. Results showed that, elongation at break may decrease up to ~25%. However, the residual formability remains acceptable for non-structural applications.
The third axis of the research focuses on the environmental sustainability of reshaping. Two Life Cycle Assessments (LCA) were performed, comparing reshaped sheet panels with those obtained through primary production and conventional recycling via remelting. For mild steel reshaped from an old FIAT Panda roof, huge savings in terms of Global Warming Potential (GWP) and Cumulative Energy Demand (CED) can be obtained (Figure 3). For aluminum, a similar trend was observed.
The analysis also highlights the importance of using mechanical depainting, as chemical methods significantly raise environmental burdens. Remarkably, remelting processes involve permanent material losses, especially for aluminum, where alloys often require the addition of virgin metal to restore composition (up to 15%wt.). By avoiding the molten state altogether, flattening offers a cleaner closed-loop solution.
In conclusion this thesis demonstrates that repurposing EoL sheet metals via flattening is feasible in different aspects. The approach shifts the paradigm from recycling to reshaping, unlocking a new value stream for dismantlers, remanufacturers, and designers. It provides a roadmap for implementation, from plant layout design and material selection to process control and market targeting. With the right combination of equipment, volume, and client base, repurposed panels can become a profitable and sustainable product, aligned with EU Green Deal objectives.
In essence, this work shows that waste is not a burden, but a resource waiting for its second life.

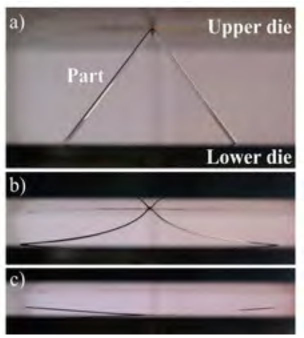

Fig. 1 - a) onset of reshaping via flattening with planar dies, b) unbending, c) springforward effect and partial recovery of planarity.

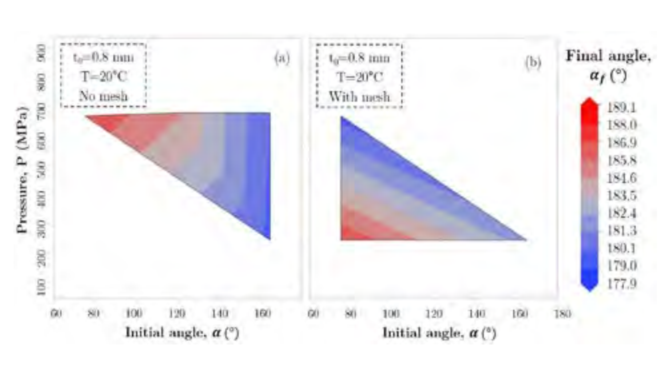

Fig. 2 - Technological process map for predicting springback post-flattening in mild-steel V-bends.

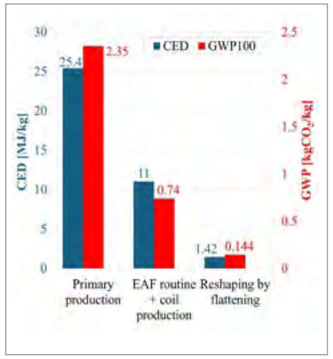

Fig. 3 - Environmental impacts comparison for producing, recycling and reshaping steel sheets.

SPATIAL BEAM SHAPING IN LASER POWDER BED FUSION FOR ENHANCING THE PROCESSABILITY OF E-MOBILITY ALLOYS

Francesco Galbusera - Supervisor: Ali Gokhan Demir

Electrification is shaping our future through the utilization of electric machines and sustainable mobility solutions. On the one hand, traditional manufacturing approaches have expressed their maximum potential in the fabrication of electrical machines. On the other hand, Additive Manufacturing technologies, such as Laser Powder Bed Fusion (LPBF), can redefine the construction principles of next-generation electric machines with complex topologically optimized geometries. Nonetheless, the LPBF process suffers from various limitations such as the scarce flexibility of the spatial beam profile. Beam shaping techniques emerge as an opportunity as they allow to tailor the beam to the specific application.
Accordingly, this dissertation delves into the application of a dynamic beam shaping technique to LPBF. First, a multi-core laser source with dynamic beam shaping capabilities was integrated into a LPBF system. Then, the novel laser beams emitted by the source were characterized and modeled to define new shape parameters capable of predicting the material response. Eventually, the novel profiles were utilized to explore the processability and functional properties of two representative electromobility materials. Specifically, the effect of irradiance profile on the melt pool shape and tensile properties of A357 (AlSi7Mg0.6) and the microstructure and electromagnetic shielding properties of Fe-2.9wt.%Si was investigated.
Ultimately, this dissertation provides a robust foundation to the beam shaping applicability to LPBF. The main goal is to establish beam shape as a rigorous parameter and to dictate new protocols for designing experiments and tailor functional properties in LPBF process.

Keywords: E-Mobility, Beam shaping, Iron silicon alloys, Aluminum alloys, Beam modeling

MICROSTRUCTURE, PHASE COMPOSITION AND PROPERTIES OF WC-CO AND INNOVATIVE CEMENTED CARBIDES

Ivan Goncharov - Supervisor: Maurizio Vedani

Cemented carbides, or hardmetals, represent a class of composite materials, that consist of carbide matrix and metal binder. They are characterized by high hardness and wear resistance, making them highly desirable in demanding operational environments. Conventional manufacturing methods are based on powder metallurgy methods of consolidating by pressing or extrusion and sintering, which can achieve low porosity and high mechanical properties but limit its ability to produce complex geometries. To address this problem, additive manufacturing techniques were investigated in this work. In accordance with the state of the art, one of the most promising additive manufacturing technologies for cemented carbide is Binder Jetting. It is a multi-step process, where shaping undergoes without significant heat input, using limited polymer additions and densification occurs in standard furnaces. The use of cobalt as a binder has raised concerns due to its cost and health implications. Therefore, researching alternative binders, such as high-entropy alloys is a relevant topic of cemented carbides research. High-entropy alloys could introduce higher mechanical properties and grain growth inhibition effect, which could be a significant breakthrough in the industry of cemented carbides. The research is presented in two chapters. In the first part, the experiment is planned to meet the industrial requirements of producing commercially available WCCo material using binder jetting additive manufacturing. As a result, printing parameters and sintering conditions were optimized to meet the industrial requirements for WC-Co cemented carbide. The second step is dedicated to the use of high-entropy alloys as a potential substitution of cobalt in cemented carbides. In order to achieve this, based on stateof- the-art and CALPHAD simulations, new high-entropy alloy composition is proposed. The results demonstrate significant increase in hardness, in comparison to WC-Co without noticeable grain growth. However the formation of secondary was carbides observed, that should be taken into consideration for further development.

Keywords: Cemented carbides, WC-Co, Additive Manufacturing, Binder Jetting, High- Entropy Alloys.

NONLINEAR ESTIMATION OF FORCE FIELDS FOR AERIAL HUMANOID ROBOTS

Awadalla Omer Mohamed Hosameldin - Supervisor: Francesco Braghin

FLYING humanoid robots represent a cutting-edge intersection of aerial mobility and humanoid design, offering unprecedented capabilities for navigation and interaction in diverse environments. This thesis delves into the intricate challenges and advancements in the development of flying humanoid robots, with a specific focus on thrust estimation for stable and controlled flight. Leveraging insights from flying robotics, humanoid robotics, and external wrench estimation, the study investigates various approaches to integrating sensor data with mathematical models to accurately estimate thrust intensities for jet-powered humanoid robots.

The thesis sets the stage by providing an overview of humanoid robots' capabilities and introduces the iRonCub project as a pioneering effort in this field. It poses several key research questions, addressing the applicability of existing models for thrust estimation and the potential use of sensors commonly found in humanoid robots. Further, the thesis delves into a comprehensive review of the state-of-the-art, exploring existing jet engine-based thrust estimation models and sensor-based approaches.

Experimental campaigns are conducted to assess the feasibility of leveraging force/torque sensors typically available in humanoid robots for thrust estimation. The study highlights the limitations of existing models and the challenges of in-situ sensor calibration. Innovative approaches are proposed, including the adoption of centroidal momentum-based estimation and the combination of multiple estimation methods into a unified framework.

Simulation and real-world validation experiments are conducted to evaluate the performance and robustness of these approaches. Despite promising results, challenges such as the lack of ground-truth validation and the limitations of individual methods are acknowledged. In the end, the thesis reflects on the attempted solutions to the main research question and acknowledges the inherent trade-offs and complexities involved in thrust estimation for flying humanoid robots. It emphasizes the importance of combining multiple approaches to achieve more robust and accurate estimations. In conclusion, this thesis contributes to advancing the understanding and capabilities of flying humanoid robots, shedding light on the challenges and opportunities in thrust estimation. Future work is proposed to further refine sensor calibration procedures, enhance estimation algorithms, and explore interdisciplinary approaches to address the complexities of flying humanoid robotics. Through continued research and innovation, flying humanoid robots hold the potential to revolutionize various fields, from search and rescue to environmental monitoring and beyond.

DESIGN OF INNOVATIVE SMART SUSPENSION COMPONENTS FOR RAILWAY VEHICLES

Gioele Isacchi - Supervisor: Francesco Ripamonti

Nowadays the increase of the commercial speed of railway vehicles is a global trend and major economical investments are being devoted to expand the length of high-speed railway lines. As a consequence, many research efforts have being focused on the development of innovative solutions to allow rail vehicles to properly face the additional challenges caused by higher speeds. In this context, this thesis proposes virtual and experimental methodologies to assist the development of new suspension components to improve dynamic performance of rail vehicles. Modelling and calibration methodologies based on lumped parameters approach are proposed to simulate the response of hydraulic damper prototypes, with the aim of quantifying their influence on the vehicle performances by means of co-simulation with Multibody (MB) train models. Moreover, dedicated experimental procedures based on the Hardware-In-the-Loop (HIL) methodology are proposed. A first HIL test rig to study the lateral dynamics of a rail vehicle is proposed to test yaw damper components, and comparative analyses are performed between different yaw dampers focusing on stability performance. A second HIL test rig, simulating the vertical dynamics of a rail vehicle featuring also the first deformable modes of the car body, is also illustrated. The aforementioned methodologies are implemented to study an innovative smart passive yaw damper designed to mitigate the trade off between high-speed stabilizing effect and low-speed steering resistance. Then, a semi-active secondary vertical damper designed to improve the ride comfort of rail vehicle is prototyped and tested by means of HIL approach to quantify its robustness and its capability to deal with unexpected failures. To further investigate the possibility of improving ride comfort of rail vehicles, a numerical investigation is proposed to illustrate the potential benefits of introducing a passive Hydraulic Interconnected Suspension (HIS) at the primary suspension stage. The analysis demonstrates that replacing primary vertical dampers with HIS can alleviate the trade off between ride comfort and running safety performances of high-speed rail vehicles.

Keywords: Railway Dynamics, Suspension Modelling, Multibody Modelling, Hardware- In-the-Loop, Yaw Damper, Hydraulic Interconnected Suspensions.

ON INTERACTION-AWARE MOTION PLANNING FOR AUTONOMOUS VEHICLES

Michael Kayyat - Supervisor: Francesco Braghin

Co-Supervisor: Federico Cheli

In the ever-evolving landscape of Autonomous Driving (AD) technology, achieving safe and efficient navigation in dynamic environments remains a pivotal challenge. Despite significant progress in recent years, the path towards full technological maturity is far from complete. Central to these advancements is the field of motion planning, where the goal is to generate safe and efficient driving maneuvers in environments populated by multiple interacting agents. At the heart of motion planning research is the recognition that an agent's actions influence, and are influenced by, the actions of other agents in the environment. Therefore, the effectiveness of a planning strategy hinges on its ability to accurately model and interpret the complex dynamics of this circular interplay. This dissertation endeavors to augment the strategic reasoning capabilities of Autonomous Vehicles (AVs) by integrating game-theoretic principles and Multi-Agent Reinforcement Learning (MARL) to develop frameworks that enable safe and efficient navigation in environments rich with interacting agents. We begin by resorting to game theory to model motion planning in a Multi-agent System (MAS) as a dynamic game. In our first work, we introduce a homotopy-guided decision-making framework for optimal gametheoretic motion planning in deterministic urban environments. The framework was tested in scenarios extracted from the rounD dataset [Kra+20], involving complex interactions at roundabouts to validate the model's ability to converge to globally optimal Nash Equilibrium (NE) solutions. Building upon this, we develop an alternative framework that addresses urban motion planning through the lens of stochastic game theory. This approach aims to mitigate some of the assumptions inherent in our previous work. Testing is performed on a variety of traffic scenarios, such as intersections, lane merges, and ramp merges, to demonstrate the ability of the framework to handle uncertainty and maintain effective navigation in stochastic environments. Furthermore, we introduce two novel optimization-based frameworks dedicated to solving general non-cooperative games. These frameworks are benchmarked against existing methodologies to highlight their computational efficiency and scalability in solving non-cooperative games that arise in different traffic environments. Finally, we introduce Joint Transition Dreamer (JTD), a model-based Reinforcement Learning (RL) agent that employs joint latent imagination to strategically adapt to adversarial maneuvers in highly dynamic scenarios. JTD was tested in pyBullet [CB16], a high-fidelity physics-based simulation platform, to assess the agent's strategic maneuvering capabilities and its effectiveness in real-time decision-making under competitive conditions. Testing unveiled emergent behaviors that display a high level of situation awareness, showcasing the agent's ability to respond effectively to complex, unpredictable interactions. Future work will focus on incorporating ethical considerations into our planning frameworks to increase public trust and acceptance, enhance robustness against uncertainties about other agents' cost functions and intents, and address scalability challenges in deploying sophisticated systems in real-world scenarios.

LEARNING-BASED SOFT SENSING AND PREDICTION FOR INDUSTRIAL APPLICATIONS

Yongxiang Lei - Supervisor:Hamid Reza Karimi

In many industrial processes, some key quality variables are difficult to measure due to harsh environment, high temperature or magnitude, or high artificial operation and device cost. However, there may be some link between these complex coupled process variables which inspires us to develop some nonlinear mapping models to solve these issues. This thesis focuses on the development of soft sensing and prediction frameworks for two industrial processes. With the data-driven machine learning methods, these hard-to-measure processes can be identified by the easy-to-measure process variables, which are named as "soft sensor" models. However, the process industry needs an accurate prediction that could provide information on the production situation, production monitoring, production efficiency improvement, and safety hazards avoidance. Accurate prediction can also provide information for control strategies. Explicitly, the proposed soft sensing and prediction algorithms are disseminated through the following two industrial case studies. Industrial Case I: Aluminum electrolysis process is a multi-variable coupled, harsh environment, with large time delay. Therefore, it is hard to measure the complex keyquality variables due to the complex reaction mechanism. Furthermore, the cost of direct manual detection would cause inaccurate detection and high cost. In many industrial models, accelerating the inference ability and the speed in the massive model is commonly the bottleneck. Model aggregation is the main method that can be used to reduce the computational burden on the system. Knowledge distillation is a popular topic that transfers knowledge from the teacher network to the student network, making the student network a superior model for learning using soft labels. When multiple teacher nets are available, the interpolation ability of the whole model would be improved, thus producing a more robust state-of-the-art model. However, the main existing methods are using the single teacher net single student net architecture or using the same weight allocation for every teacher net. In this part, we present a novel adaptive dual architecture. The proposed architecture leverages the complexity of training images and differences in student model capability; adaptively allocating weights between multiple teacher nets can lead to better performance of the distilled student model. To make a better selection performance, reinforcement learning for the controller/agent policy framework is also given. The proposed framework implements the systematically dynamic weight allocation to teacher models for different training samples and finally optimizes the performance of the student model in an iterative way. The proposed method also guarantees convergence, robustness, and feasibility. Finally, the effectiveness and efficacy are demonstrated by the practical industrial aluminum case. Industrial Case II: Underflow concentration is an important factor that reflects the performance of the deep cone thickener control and optimization. However, the existing measurement cannot meet the high quality of the prediction. Additionally, measurement error is hard to quantify with an inaccurate device, a harsh environment, and manual operation cost. Therefore, the significance of the study of underflow concentration prediction and forecasting has a great value for industrial applications. The validation and verification of these proposed methods are based on two different process industry cases: The mining paste filling process and aluminum electrolysis. Due to inaccuracy and significant disturbance of the complex and harsh environment in actual industrial processes, traditional sensor devices ignore the model error and hardly measure the certainty of key quality variables. However, in practical industrial thickener cone systems, the underflow concentration is estimated using normal regression models that minimize the residual mean square error to obtain a point estimate of some interdependent variables. The recursive strategy also causes residual error accumulation, which degrades the accuracy of recursive-based prediction models. Furthermore, the complex high-quality features representation is critical to obtain an accurate prediction model, while the multiple horizon prediction is required for the hierarchical optimal control. This thesis provides a novel efficient data-driven forecaster framework for predicting the concentration of deep cone thickeners. The designed model implements direct data-driven regression prediction while fully exploiting the temporal machine learning model's ability to extract features. Additionally, instead of the probabilistic Bayesian model, which is more efficient in implementation and deployment, the proposed framework is used to quantify uncertainty forecast using interval prediction. At last, the presented model directly predicts the multiple horizons, compared to the traditional recursive single point forecasting, which is much more training-efficient and memory-efficient. The above three characteristics will be demonstrated and verified by an industrial experimental deep cone thickener, the performance is thoroughly compared to other state-of-the-art counterparts. In summary, this thesis deals with the problem of developing soft sensor and prediction frameworks to solve practical tasks in the aluminum electrolysis industry and the mining paste-filling industry. For more abstract details, please refer Abstract of Paper A- Paper E.

TOWARDS THE ADOPTION OF UPPER-LIMB REHABILITATION EXOSKELETONS IN RELEVANT ENVIRONMENTS

Beatrice Luciani - Supervisors: Francesco Braghin, Marta Gandolla

The adoption of upper-limb exoskeletons for rehabilitation offers a promising solution for the growing demand for effective therapeutic interventions, especially for people suffering from the motor consequences of stroke or other neuromuscular conditions.

However, challenges such as high costs, limited clinical evidence of superiority over traditional therapy, and reduced therapist acceptance have hindered the widespread use of this technology.

While the first two factors are largely due to the relative novelty of rehabilitation exoskeletons, and will likely improve with further time and technological advancement, overcoming therapists' lack of appreciation and trust towards robotics remains a challenge.

This research seeks to overcome this barrier by developing a therapist-friendly exoskeleton that closely integrates the therapist's approach through innovative technological implementations. Specifically, it focuses on enabling the exoskeleton to mimic therapist movements, support and haptic-interaction strategies, and to provide real-time feedback about patient's conditions.

Our therapist-friendly concept includes:

- A trajectory learning machine-learning-based framework to learn the most representative trajectory for rehabilitation exercises from the therapist's demonstrations. This framework uses Hidden Markov Models to extrapolate rehabilitation exercises, defining the movement that corresponds the most to the therapist's intentions. The system, tested with 5 therapists and with the AGREE exoskeleton against literature approaches, obtained better kinematic and human likeness results and higher therapists' appreciation.
- A novel force-mimicry framework to let the robot autonomously tune its support to the arm in a therapist-inspired way. After the development of a sensor-less system to extract the therapist's manipulation force contribution (resulting in a 0.31 Nm precision), we exploited the Machine-Learning Vector Search approach to apply therapist-inspired and kinematic-coherent support to the patient's arm. The system was developed and tested on the arm exoskeleton ANYexo, by ETH Zurich.
- An augmented reality feedback platform to provide kinematic performance insights to the therapist. This system, including an application for the HoloLens 2 headset, by Microsoft, provides tridimensional kinematic guidance to patients, improving their accuracy in the execution of rehabilitation exercises (as we verified with experiments on 15 healthy subjects). It also improves the therapist's appreciation of rehabilitation technologies, as confirmed by the usability and acceptability evaluations of 12 clinicians.

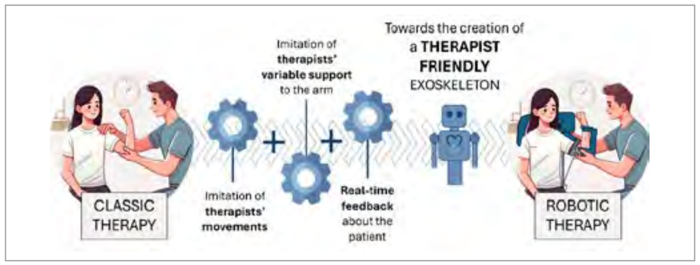

Fig. 1 - Concept of the development of a therapist-friendly exoskeleton: to go from classic therapy to robotic therapy, we need a robot that can comply with therapists' desires, imitating their approach to rehabilitation and providing complete feedback.

The experiments conducted with the AGREE and ANYexo robotic platforms to validate our frameworks reveal that these approaches improve therapist satisfaction, marking a significant step toward the broader clinical application of rehabilitation exoskeletons.

The findings suggest that a synergistic design, combining therapist imitation and responsive feedback systems, can facilitate greater acceptance and efficacy of robotic rehabilitation solutions.

Fig. 2 - Therapist-robot interactions: the therapist manipulates the robotic system to teach trajectories and support profiles to support the patient during the therapy.

DRIVER-AWARE TORQUE VECTORING CONTROL DEPLOYMENT TO ELECTRIC VEHICLES

Mohammad Mehrabi - Supervisor: Michele Carboni

Co-Supervisor: Andrea Bernasconi

Adhesively bonded joints offer distinct advantages in various industries, including high strength, lightweight design, and suitability for joining dissimilar materials. However, their susceptibility to environmental factors and inconsistent mechanical behavior due to defects present challenges in maintaining their long-term reliability and safety. This requires the implementation of effective damage monitoring techniques, such as Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM). These techniques particularly aid in detecting and characterizing cracks, which are essential for evaluating the residual strength and longevity of the adhesive joints. Various promising methods based on strain analysis, elastic waves, dynamic responses, and impedance variation have emerged for assessing bonded joint integrity. However, a deeper understanding is needed for crack initiation and propagation within the adhesive bondline under different loading modes. While most studies have focused on mode I loading (the most common and detrimental loading mode), some have shown that mode II loading can also significantly contribute to joint failure.

This research aims to investigate the crack length estimation in an adhesive bonded joints subjected to mode II quasi-static and fatigue loading conditions. For this purpose, a combination of experimental, numerical, and analytical methods is used to monitor the initiation and propagation of cracks. This combination allows for a thorough comparison of crack tip position estimation using various monitoring approaches. Optical backscatter reflectometry and digital image correlation were proposed as novel strategies, compared and verified by other established method included visual testing, a different digital image correlation technique, along with compliance-based beam method as analytical approach. All methods were employed under both quasi-static and fatigue loading types. Additionally, in quasi-static loading, a finite element analysis was conducted to provide further insights into the interpretation of the positions detected by experimental techniques in relation to the numerical crack tip and the state of damage within the bondline, both before and after propagation.

Regarding the analysis of quasi-static loading, finite element analysis revealed that a significant portion of the crack propagation region in the adhesive is occupied by the fracture process zone whereas only a relatively small portion of the adhesive experienced complete separation. The experimental methods appeared to be influenced by this large process zone and possible damage within it, with optical backscatter reflectometry being more affected, and visual testing and digital image correlation techniques being less affected.

Optical backscatter reflectometry showed its ability to detect potential damage within the adhesive that other methods may not capture, both before and after unstable propagation. This capability is especially advantageous for identifying early-stage damage in practical applications, such as crack initiation, before it progresses to complete failure.

Under fatigue loading condition, both digital image correlation methods estimated slightly larger length than visual testing, a trend also observed under quasi-static loading. However, optical backscatter reflectometry estimated considerably larger crack lengths compared to other methods, albeit lower than its estimation under quasi-static loading. This suggests that the quasi-static loading condition potentially provides a larger process zone compared to fatigue loading. In the dynamic regime, optical backscatter reflectometry data revealed a different trend, suggesting additional factors influencing its behavior beyond the process zone. Yet, it remains the only method for continuous monitoring without interruption, making it a valuable tool for early damage detection during fatigue tests. Moreover, the compliance-based beam method, despite its simplicity, had limitations. Nevertheless, its alignment with optical backscatter reflectometry under both loading types supports the notion that optical backscatter reflectometry is effective in detecting process zone damage and estimating a larger process zone under quasi-static loading than fatigue loading.

TRANSFERABILITY OF SPECIMENS' DATA FOR STRUCTURAL INTEGRITY ASSESSMENT OF AM COMPONENTS

Giuliano Minerva - Supervisor: Stefano Beretta

Additive manufacturing (AM) of metallic components revolutionized many industrial sectors with its unprecedented freedom of design. However, the inherent presence of volumetric defects induced by the process may significantly hinder structural properties and introduce new challenges for the assessment of components. To this end, recent standards dedicated to AM components manufactured by laser-powder bed fusion provide a reference framework for the qualification of the process and for design and verification of the component. However, many gaps are present in the structural assessment procedures. In fact, no information is given on how to carry out the static assessment of components nor on how to introduce safety factors. Moreover, for probabilistic fatigue assessment, no indication on how to treat multiple inherent defect types is provided. This research work aimed at covering these open points and focused on two main objectives: i) identify a suitable fracture-based static assessment method that could be easily employed on complex-shaped components and with a straightforward application of safety factors; ii) address the transferability of fatigue properties from specimens to components in presence of multiple defect types. For static assessment, different fracture-based methods already in use for conventional materials were investigated and compared, such as Engineering Critical Assessment tools, Theory of Critical Distances and Imaginary Crack Method (ICM). A modified ICM, named Fictitious Crack Length (FCL), was proposed and validated, first on ad-hoc specimens and then on a real component. The FCL method allowed to estimate resistance to static fracture by simply providing as input the stress distribution from linear elastic Finite Element simulations, without the need of explicit modelling of cracks. Moreover, the FCL method allowed to directly derive the newly proposed Limit Load Diagram, for which the application of safety factors was straightforward. For fatigue assessment, supervised machine learning (ML) was employed to classify the defects on fatigue specimens, then extreme value statistics (EVS) was applied independently on the defects' distributions for each defect type. Finally, the maxima defects distributions were combined by means of a weakest-link approach and used as inputs to defect-based fatigue models, such as the Shiozawa law and the El-Haddad model. After validating the ML-assisted EVS model on specimens, the correct description of the size-effect was successfully proven on component-like specimens. In conclusion, the research addressed the important problem of transferability of properties from specimens to components, effectively covering the gaps present in the normative framework for static and fatigue assessments.

Keywords: metal AM, static assessment, fatigue, fracture, extreme value statistics

PLANNING SAFELY AND EFFICIENTLY IN AUTONOMOUS DRIVING BY EXPLOITING MODEL-BASED AND DATA-DRIVEN PREDICTION

Luca Paparusso - Supervisor: Francesco Braghin

Safety is a key requirement in motion planning for autonomous driving, due to the involvement of human beings. In the existing literature, we can distinguish two primary paradigms to ensure safety: robust and probabilistic. Robust approaches typically employ formal methods to provide safety assurances in all possible scenarios. Probabilistic approaches, on the other hand, exploit the recent advances in data-driven models and Artificial Intelligence (AI) to handle uncertainties in dynamic environments through the prediction of the likely behavior of the traffic participants and statistical reasoning.

In this work, we contribute to both Backward Reachability Analysis (BRA)—a robust method—and trajectory forecasting—a probabilistic method. We extend backward reachability analysis to multi-agent scenes, by introducing a prioritization method that classifies agents according to their dangerousness. The corresponding safety constraints are injected into a Model Predictive Control (MPC) planner that prioritizes the surrounding agents accordingly. Regarding trajectory forecasting, we bridge the representational gap between existing prediction models and safe planning. In prediction, numerical tractability is usually achieved by coarsely discretizing time, and by representing multimodal multi-agent interactions as distributions with infinite support. On the other hand, safe planning typically requires very fine time discretization, paired with distributions with compact support. We propose ZAPP, a framework to align prediction and planning preserving real-time performance. A schematic representation of ZAPP is provided in Figure 1.

ZAPP is showcased in Figure 2, completing the task of collision-free navigation in a crowded hallway, with complex interactions between the agents. Probabilistic methods for prediction and planning offer better scalability. The latest prediction-planning models are ever more based on Deep Learning (DL) and Generative Artificial Intelligence (Gen-AI), which follow probabilistic modeling. This setting also favors the introduction of foundation models, one of the latest and most promising trends, into prediction-planning schemes.

However, advances in data-driven prediction and planning models introduce new challenges in cybersecurity. Specifically, the ability to predict interactions from data can be exploited to launch specific cyberattacks that we name interaction attacks. Given the ability of AI prediction models to probabilistically learn the causality between actions and reactions of the traffic agents, cyberattacks leverage it to manipulate the behavior of autonomous systems through deception, posing significant risks that need to be addressed.

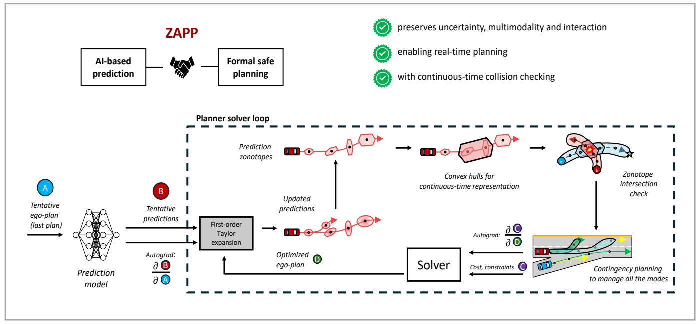

Fig. 1 - Schematization of the implementation steps of ZAPP. First, to enable real-time planning, we keep the prediction model out of the planner solver iterations. The prediction model is therefore run only once per planning cycle, using a tentative ego-plan. At each solver iteration, we then use a first-order Taylor expansion to update the predictions given the new optimized ego-plan computed by the solver. In this way, we preserve interaction still enabling real-time planning. For each mode, the prediction uncertainties are then converted into finite sets using zonotopes, a convex set representation. We then leverage differentiable zonotope operations, such as convex hull computation, to extend motion to the continuous-time domain. Finally, we are able to write collision avoidance constraints by imposing that intersection between zonotopes is empty. Computing zonotope intersections is again a differentiable operation. Therefore, we end up with differentiable collision-avoidance constraints. Using the differentiable collision-avoidance constraints, we create a differentiable constrained optimization problem using MPC. To jointly plan for all the modes, we use contingency planning. As all the operations described so far are differentiable with respect to the ego-plan, so the optimization variables, we can leverage automatic differentiation to provide the solver with cost and constraints Jacobians. This helps the solver converging faster and favors real-time planning.

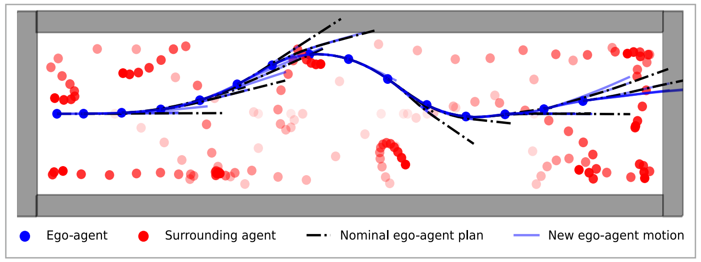

Fig. 2 - Example of a completed scenario. ZAPP can lead ego to the goal (from left to right) without crashes, implementing receding horizon motion planning (trajectories at each time step shown in blue). To ease visualization, the surrounding agents' trajectories are shown at discrete times with color fading from dark to light as time passes.

TRUCTURAL HEALTH MONITORING AND BEYOND: DEEP LEARNING APPROACHES FOR SMART IDENTIFICATION AND PREDICTION

Marc Parziale - Supervisors: Marco Giglio, Francesco Cadini

The characterization of anomalies in mechanical, civil, and aeronautical domains has emerged as a captivating and extensively debated topic. Recent advancements in sensor technologies have yielded vast amounts of data, characterized by valuable diagnostic information crucial for assessing the health state of systems. Furthermore, the development of new deep learning-based algorithms has enabled the accurate processing of these signals, leading to significant predictive outcomes that have surpassed conventional methods requiring extensive pre- and post-processing steps. However, gaps have been encountered in the literature regarding the use of deep learning approaches for anomaly characterization. Specifically, the main challenges that have served as the foundational motivation for this thesis can be succinctly summarized as follows: (i) the characterization of damage under changing environmental conditions, (ii) the implementation of intelligent algorithms capable of diagnosing damage without relying on labelled data, (iii) the necessity for the development of explainable artificial intelligence (XAI) methods, and (iv) the integration of established physical knowledge into the neural network training process. Hence, this thesis has aimed to address these challenges by advancing novel deep learning frameworks for enhancing anomaly characterization within mechanical, civil, and aerospace systems. It has specifically targeted safety-critical systems such as structural beams, frames, panels, and rotating machinery, which have played vital roles in various industrial applications and processes. Figure 1 depicts the conceptual framework used to guide this research, comprising two main parts: the direct problem, concerning the design of the structural health monitoring (SHM) system, and the inverse problem, which pertains to the effective utilization of the developed monitoring tool on the analysed system.
Different contributions have been published. First, a novel deep learning approach has been developed, designed to effectively characterize damage under varying environmental conditions. The main objective of this method was to identify and localize structural beam damages by processing transmissibility functions (TFs) data, even in scenarios with temperature fluctuations, which may complicate the analysis. To accomplish this, a hybrid model combining a convolutional neural network (CNN) with autoencoders (AEs) was utilized to mitigate the influence of temperature on the predictions made by the CNN-only framework, ultimately improving the accuracy of damage diagnosis.
Then, a groundbreaking unsupervised approach for detecting and localizing damage in composite plates has been proposed. This method harnessed the power of conditional generative adversarial networks (CGANs) to process Lamb wave (LW) signals, allowing for damage characterization without requiring prior knowledge of the system damaged states, thereby eliminating the dependence on labelled data. Indeed, the deep neural networks utilized in this method were exclusively trained using data from the system healthy states.
XAI methods have also been implemented to elucidate the functionality of CNNs across three distinct applications: (i) detecting and localizing crack-like damages in metal plates by processing LWs, (ii) detecting, localizing, and quantifying damage in structural beams, as well as identifying loosened joints in structural frames by processing TFs data, and (iii) characterizing anomalies associated with various faults in a rotating shaft system by processing multiple signals of different nature (e.g., strain, accelerations, audio, etc.) combined in the time domain. In particular, XAI techniques were applied to trace the CNN output back to the input layer, allowing for the assessment of the importance of each input feature for the provided predictions, leading to the generation of what is commonly known as a heatmap. Analysing recurring patterns identified in these heatmaps facilitated a comprehensive understanding of the CNNs behaviour, thereby bolstering confidence in their application.
Finally, a physics-informed framework (PINN) has been developed to enhance the fusion of data-driven methodologies with the foundational physics governing the system under investigation. Specifically, PINNs were employed to predict five critical parameters essential for assessing the health states of a rotating shaft system under different constant rotational speeds. These parameters encompassed the radial and angular positions of the static unbalance induced by the disk attached to the shaft, along with the stiffness along the principal axes of elasticity and the non-rotating damping coefficient. The estimation procedure relied exclusively on the displacement signals originating from the centre of the disk.
These methodologies have been applied to both numerical and experimental case studies, demonstrating their efficacy through comparisons with conventional approaches and validation against experiments.

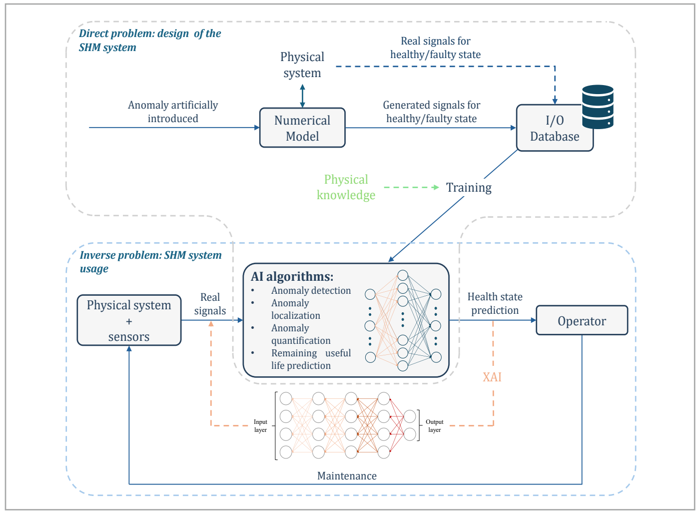

Fig. 1 - Scheme outlining the comprehensive framework employed for enhancing systems anomaly characterization.

IMPROVING INVERSE FINITE ELEMENT METHOD ALGORITHMS FOR STRUCTURAL HEALTH AND USAGE MONITORING

Dario Poloni - Supervisor: Claudio Sbarufatti

In the past twenty years, the push for more efficient maintenance strategies across civil, mechanical, aerospace, and naval sectors has driven remarkable innovations. Structural Health Monitoring (SHM) has become a cornerstone in this evolution, aiming to transition maintenance policies from scheduled to condition-based approaches. SHM entails installing permanent sensors on structures to continuously assess their health through sophisticated algorithms. A key breakthrough within SHM has been the rise of fiber optic strain sensing, which has significantly enriched the quality and density of strain data available for algorithms. The inverse Finite Element Method (iFEM) stands out in the SHM framework for its unique ability to reconstruct the structural displacement field from strain data regardless of the applied load or structural dynamics, at minimal computational costs. This feature is especially valuable for assessing fatigue life in sensor-less regions of a structure. Nonetheless, the reliance of the iFEM on extensive sensor networks for optimal performance has traditionally been a limiting factor, which has been mostly tackled by utilizing pre-extrapolation strategies to augment the data available to the iFEM. In this thesis, significant steps forward are taken in further enhancing the inverse Finite Element Method. A Gaussian Process is introduced as a novel strain pre-extrapolation method to quantify the uncertainty introduced by the data augmentation procedure. This improvement enhances the accuracy of fatigue life predictions. To tackle the challenges of applying pre-extrapolation in components with variable thickness, a novel strategy to pre-extrapolate is developed, broadening the applicability of the iFEM to more complex structures. Additionally, the iFEM is exploited in damage identification, focusing on estimating debonding in adhesive-bonded joints — a critical factor in maintaining structural integrity and preventing failures in modern composite structures. Finally, the iFEM is tested in a real-world application scenario: monitoring deflection in a full-scale bridge. This application proves the iFEM's operational feasibility but also showcases its potential in the civil engineering field. The novel contributions of this thesis to the field of the inverse Finite Element Method span from theoretical developments to the validation of the iFEM in real application scenarios. While valuable on their own, these novel contributions achieve their full potential when integrated and implemented into a cohesive and unified framework, suggesting a holistic approach leveraging the combined strengths of these advancements.

VEHICLE TELEOPERATION UNDER NETWORK DELAYS : COMPREHENSIVE FRAMEWORK FOR IMPROVED CONTROL AND SAFETY

Jai Prakash - Supervisor: Edoardo Sabbioni

Vehicle manufacturers invest considerable resources in vehicle design, yet on an average staggering 95% of a car's lifespan is often spent parked, highlighting a paradoxical underutilization. Taxis, once a solution to increase utilization, introduced a new challenge: the underutilization of human resources due to the authoritative responsibility of drivers, imposing unseen costs on customers. Car sharing, propelled by the advent of electric vehicles, offers self-driving opportunities to customers, yet retrieving vehicles from non-demanding locations remains a hurdle. Amidst these challenges, autonomous vehicles hold promise for the future, although concerns persist regarding their adaptability in unforeseen situations. This doctoral project identified the potential of vehicle teleoperation as a solution. It can increase vehicle utilization, can eliminate driver redundancy, can facilitate direct vehicle delivery to customers' doorsteps, it can act as a bridge between conventional in-vehicle driving and the futuristic vision of autonomous transportation.
Vehicle teleoperation, the remote control of vehicles in real-world environments, is a transformative technology. It has wide-ranging applications, from fleet management to autonomous driving support. This doctoral thesis follows a multi-sided exploration designed to improve the teleoperator's experience, increase overall operation stability, refining the feedback to human operators, and contribute to safety in human-controlled remote vehicles. "Operation stability," which refers to control-loop stability, is the central theme addressed throughout this research.
The research documented into five distinct research papers addressing specific aspects of the comprehensive goal, accompanied by the development of an "Environment Reconstruction" framework dedicated to hazard identification and protection during vehicle teleoperation. Acknowledging the challenges posed by network latency, the initial focus lies on solving the issue of instability induced due to delayed feedback to the human operator during direct vehicle teleoperation. Innovative solutions, including predictive displays and the novel Successive Reference-Pose Tracking (SRPT) strategy, are proposed to address these issues.

Instead of transmitting control inputs such as steering commands, SRPT transmits reference poses to be tracked by the remote vehicle (Figure 1). The approach, validated through simulations under variable network delays, emerges as a robust approach, particularly performing well during demanding manoeuvres and environments. The thesis then advances into human-in-the-loop performance assessments, showcasing SRPT's contributions to operation stability, safety, and cognitive load reduction. Sixteen volunteers drove through a track consisting of progressively challenging manoeuvres. SRPT significantly improved teleoperation performance by reducing cross-track error while simultaneously diminishing steer effort, thereby reducing the cognitive load of the human operator (Figure 2).

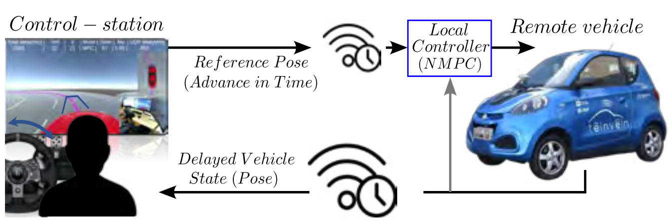

Fig. 1 - SRPT vehicle teleoperation control loop. The remote vehicle receives reference-poses instead of steer commands.

Beyond stability, the thesis addresses challenges related to network disruptions and sudden obstacles. An environment reconstruction framework equips remote vehicles with a degree of autonomy, enabling them to execute emergency manoeuvres autonomously in such scenarios, thus enhancing safety. A sensor fusion framework is developed employing image-based and radar-based detection, which increases accuracy and redundancy (Figure 3).

Operator feedback is augmented through innovations in steering torque and video feed. The proposed exponential decay model for pivot steering torque specifically targets the improvement of steer feel during low-speed manoeuvres. Additionally, a unified steering force feedback model is introduced, capable of seamlessly accommodating both off-centre and on-centre manoeuvres. The video feed is enriched with an intuitive steer indicator, serving a dual purpose. Firstly, it provides the remote operator with a visual indication of the anticipated direction resulting from their steering action. Secondly, it operates as a reference pose generator, significantly enhancing driving confidence, in the context of the SRPT strategy.

In summary, the main achievements of this dissertation lie in addressing critical challenges associated with vehicle teleoperation. The SRPT strategy improves the teleoperation performance as the remote vehicle follows operator's intended path closely while the operator is in control with the dynamic adaptation of the vehicle behaviour that too in the presence of variable network delay. A unified steering feel for both off-centre and on-centre manoeuvre keeps the operator engaged with the task. A safety layer is also present in the vehicle performing emergency stop in case of sudden obstacles. These strategies refine operator experience, tackle network latency-induced instabilities, and lay the groundwork for safer and more efficient teleoperated vehicle systems.

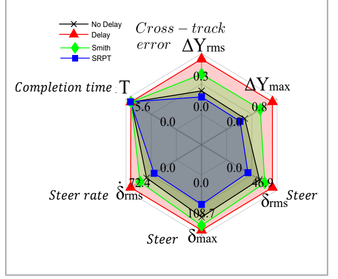

Fig. 2 - SRPT reduces cross-track error, enhancing operator confidence, while also alleviating cognitive load by minimizing the necessary steer effort.

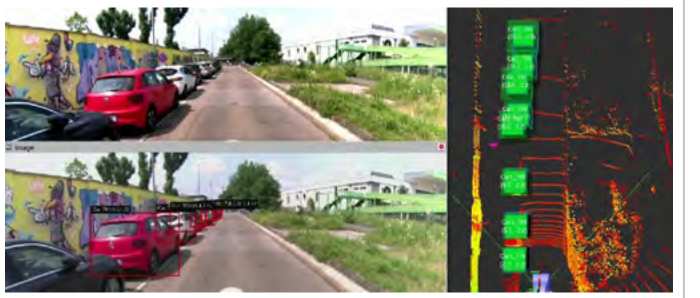

Fig. 3 - Real-time obstacle detection using vision-radar sensor fusion.

MULTIAXIAL AND FRACTURE MECHANICS CRACK GROWTH CRITERIA UNDER ROLLING CONTACT FATIGUE, SPECIFICALLY APPLIED TO PLANETARY GEAR BEARINGS FOR AEROSPACE APPLICATIONS

Prasad Mahendra Rao - Supervisor: Stefano Foletti

This thesis presents the partial deliverables and my academic contributions towards the assessment of a novel alternate assessment of planetary gear bearings (refer Figure 1), a core component in the epicyclic module of high power transmission gearboxes for aerospace applications. It is in response to the Innovative DEsign for Reliable PLANEt bearings (IDERPLANE) research project which is formulated to address the concern of high rolling contact fatigue (RCF) in integrated planet gear-bearings in the epicyclic modules of aerospace applications such as geared turbofan (GTF)s and main gearbox (MGB)s in aircraft. The project is funded under the Clean Sky 2 Horizon 2020 call and its consortium is headed by the Politecnico di Milano (PoliMi). This project does not analyze the problem statement in a conventional stress-based approach but rather on damage tolerance concepts. Now, due to RCF, crack propagation of inevitable surface and subsurface defects in the race can lead to either spalling, or also in-core propagation, causing gross failure. Hence, an understanding of the behaviour of how subsurface cracks propagate under RCF which drives them under its stress state is needed. The phenomenon being studied here is RCF and the component it is applied to in this thesis is the planetary gear bearing (a.k.a the main planetary gear bearing (MPGB)). Refer Figure 1 left. It is the full-scale test article which will be used for final verification of our methodology in the presence of manufactured defects. It is made of the same aerospace-grade treated alloy steel that is case carburized, subjected to the same service loads, but in our novel testing setup! In this research project, the methodology presented was not only verified theoretically but also experimentally, using both small-scale and full-scale testing campaigns. Different partners of the consortium worked together to accomplish this common goal. While the theoretical part was developed by the consortium, the experimental part was carried out by its partners. All testing was carried out in the presence of manufactured defects. Small-scale testing on standard rounded specimens was performed by PoliMi. Small-scale testing on bi-disk specimens was carried out by UniBs. Full-scale testing of the test articles was finally conducted at PoliMi. Various simulations on this were run by UniBz. Imaging of the defects in the tested specimens was done by INSA Lyon. Post conclusion of all activities, the methodology was delivered to the ERC. In regards to this research project, the thesis starts of with the introduction to small-scale testing on standard rounded specimens. Then proceeds to elaborately explain on the design and development, installation and commissioning of the test gearbox (TGBX) on the test rig in our lab for full-scale testing which was also a major part of this research project. Next, the results of the full-scale testing campaign are discussed. For the theoretical approach, the modified multiaxial fatigue criterion by Dang Van is employed. Also, the use of a fatigue fracture material characterization-based approach is also presented. Both of them have been verified experimentally and are presented as defect acceptance maps. In the last part, based on previous evidences, again a linear elastic fracture mechanics (LEFM)-based approach is applied, but this time considering the crack front to be coming from ejected spalls that have left behind crater-deep sharp-edged bottoms (refer Figure 1 right). The hypothesis is that in such thin-rimmed components such as the MPGB, the loading and hence the stress state can cause an anomalous behaviour wherein such crack fronts can propagate in-core causing uncontained failure of the component. This has been experimentally studied and proven, and is coined the RANK methodology.

MODELLING APPROACHES FOR THE INVESTIGATION OF TYRE ROLLING NOISE

Luca Rapino - Supervisors: Roberto Corradi, Francesco Ripamonti

Car tyres are complex mechanical components, designed to satisfy several performance requirements simultaneously. From the point of view of vehicle dynamics, handling and braking performance are fundamental, both for dry and wet road conditions. To guarantee sufficient tyre mileage, also the wear rate and the capability of withstanding extreme manoeuvres and mechanical fatigue are important. Then, tyres with low rolling resistance are preferred to improve the fuel efficiency of vehicles. Finally, tyres must be optimized in terms of exterior noise levels and passenger comfort inside the vehicle cabin.
Indeed, tyre exterior noise is a major concern in terms of environmental impact and public health. Several studies revealed that tyres are the main cause of road traffic noise, with a contribution higher than the powertrain and the aerodynamic noise for most of the driving conditions. Furthermore, it has been shown that prolonged exposure to high levels of road traffic noise, especially during the night, is correlated with sleep disturbances and cardiovascular diseases. Moreover, high levels of traffic noise are also a risk to the biodiversity of wildlife, due to the reduced reproduction rate of some species of birds and mammals.
To reduce these problems, standards and regulations have been introduced and tyres must comply with specific noise level limits. In Europe, tyres are also labelled with a score ranging from A (low noise) to C (not compliant). This aims at fostering competition among tyre makers, as well as driving the consumers' decisions during the sales.
Nonetheless, designing a low-noise tyre while satisfying also the other performance requirements is challenging. Due to its high complexity, tyre design is an iterative process supported by computer-aided design tools, advanced models and extensive testing activities based on various methodologies. In this framework, a model of the tyre rolling noise would be beneficial, as it would speed up the design process and reduce the number of tests, with a positive impact on the costs and timings of the product development phase.
Ideally, a unified modelling approach for the prediction of tyre rolling noise would be preferred. However, several generation and amplification mechanisms are involved, each one having different dependencies on the tyre design, operating conditions and environmental parameters. For this reason, and taking into account also the current state of the art and the actual product development scenario, a reliable unified modelling approach would require considerable effort and time to be developed. As a consequence, multiple models for the investigation of specific aspects of tyre rolling noise are currently preferred.

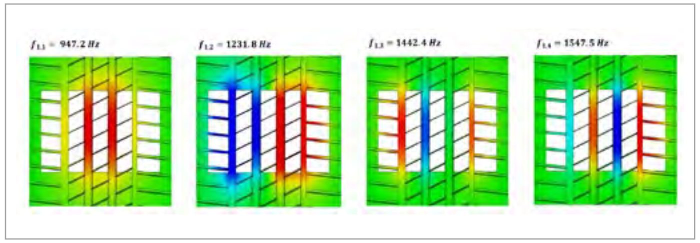

Fig. 1 - Acoustic modelling of the footprint region and analysis of the tread grooves' acoustic resonances.

According to this paradigm, different modelling approaches may also be selected depending on the target of the analyses, enabling the possibility of ranging from physical models to statistical models.
In this context, this PhD thesis was carried out in cooperation with Pirelli Tyre S.p.A., to develop innovative modelling approaches for the investigation of tyre rolling noise and to deal with specific aspects of the problem:

- development of numerical approaches for the acoustic modelling of the footprint region and the analysis of the tread grooves' acoustic resonances;
- definition of a modelling approach based on a set of equivalent point sources, whose volume velocities are identified from indoor tests, which allow performing simulations of the coast-by test;
- prediction of tyre rolling noise in indoor conditions employing a regression model based on supervised machine learning, with a high level of detail in terms of the description of the tread pattern geometry and other noise-related tyre features.

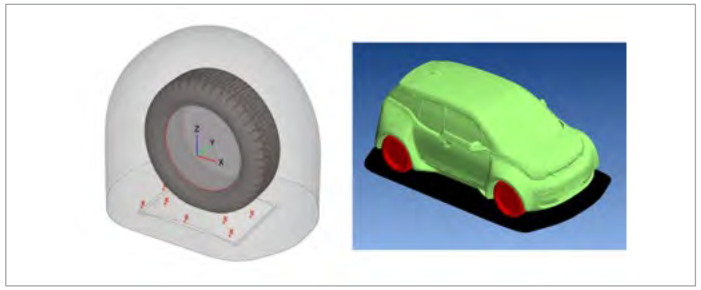

Fig. 2 - Coast-by noise predictions through the synthesis of equivalent point sources from indoor tests and numerical models.

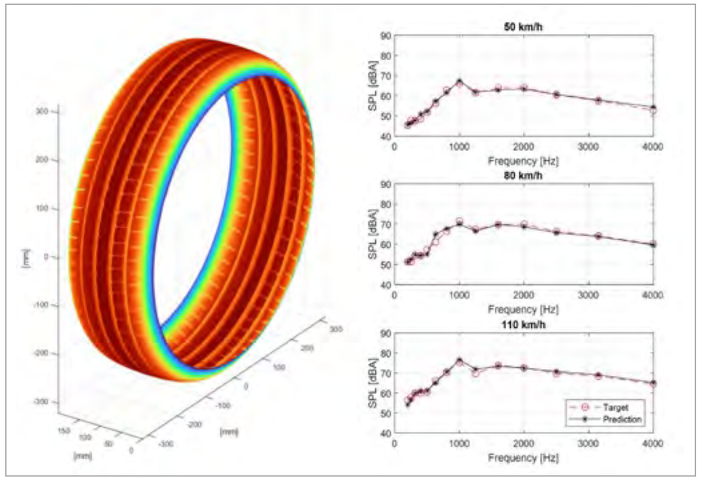

Fig. 3 - Description of the tread pattern geometry and a machine learning approach for the prediction of tyre rolling noise.

COMPUTER VISION SOLUTIONS FOR REAL-TIME FURNACE MONITORING AND SUSTAINABILITY IN ALUMINUM MELTING

Yuvan Sathya Ravi - Supervisors: Marco Tarabini, Paolo Chiariotti

Introduction

Aluminum is a highly recyclable metal, with 75% of all aluminum ever produced still in use. Recycling saves 95% of the energy required for primary production. The goal is to reduce GHG emissions from recycling to 390g CO_2 equivalent per kg of aluminum ingot. Aluminum melting furnaces play a key role in the melting process, in terms of energy optimization and sustainable production. In industrial practice, the furnace door is frequently opened for manual inspections, leading to thermal loss, stoichiometric ratio alterations, and operator safety risks. High temperatures in melting furnaces make contact-based sensors impractical for monitoring. A vision system, appropriately designed, can function as a non-contact sensor for furnace monitoring. This research proposes innovative, real-time, computer vision (CV)-based solutions for aluminum melting furnaces to enhance efficiency and sustainability. A vision system was designed for high-temperature environments (up to 1000°C), with image and data processing algorithms applied to furnace monitoring tasks, including melt level measurement, scrap melting monitoring, and process time estimation. CV algorithms were developed using image processing and AI techniques.

Furnace Camera

A camera system was designed exclusively for high-temperature furnace environments, addressing limitations of existing solutions such as overheating and inconsistent images due to smoke, dust, and flames. The furnace camera system was designed with three requirements: 1) Continuous high-temperature operability, 2) Design simplicity, and 3) Cost-effectiveness. The design was carried out in 2 phases – thermal analysis and mechanical design. Heat transfer dynamics were studied using conductive and convective simulations, determining the refractory material and component dimensions. In the mechanical design (Figure 1(a)), protective elements were implemented to shield the camera and optics from extreme heat. The optical elements were enclosed in alumina refractory material, with a Quartz layer protecting the lens tip from direct heat. To ensure continuous operation, an air-flow pathway was integrated for efficient heat dissipation. The system was tested in an 800°C furnace, demonstrating continuous operation for 4 hours without cooling system support. When cooling was enabled, heat dissipation occurred at 10°C/min. The temperature profile (Figure 1(b)) confirmed that the optics and camera remained within operational limits, thanks to the protective design elements and cooling. The camera is now deployed in multiple industrial furnaces, operating reliably without failures.

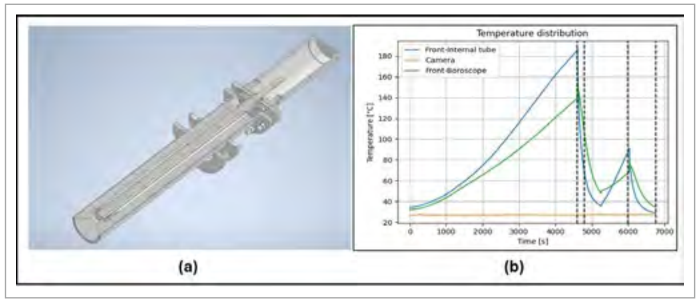

Fig. 1 - (a) Half-section view of the camera system. The optics and electronics are protected with refractory shields and an air-cooling system; (b) temperature evolution of the system's crucial components at an operating temperature of 800°C. The time window marked in black dashes represent the time in which the air-cooling system was enabled.

Algorithms

Using the furnace camera's image stream, a melt level measurement algorithm was developed. Inside the furnace, the melt surface and lateral wall have different pixel intensities. The melt level line was detected by identifying the boundary between these regions using image processing techniques such as de-noising, histogram stretching, edge detection, and line detection with probabilistic Hough transform. A reference system was calibrated using an empty furnace image and known furnace dimensions, allowing conversion of pixel measurements to real-world height in mm. Measurement repeatability analysis on videos with constant melt level showed a standard deviation of 2-3 mm (Figure 2(a)), with an average processing speed of 0.4 s/frame. The computed melt level is displayed as text alongside the detected line in the result image (Figure 2(b)).

Next, a scrap monitoring algorithm was developed using image processing and AI. The algorithm provides: 1) Localized scrap monitoring and tracking, 2) Scrap quantification, and 3) Melt time estimation. A dataset of furnace images under various operating conditions was acquired and pre-processed. A multi-class segmentation model, trained using DeepLabv3, identified scrap pixels in different classes with distinct colors. The segmented scrap pixels were quantified to compute the liquid aluminum area. Based on this segmentation, a melt time estimation model was built. A dataset covering 8 operational days was processed, with outlier removal and median filtering applied as pre-processing steps. Features for predicting melt time were extracted: 1) Scrap %, 2) Time elapsed, 3) Melting batch ID, and 4) Time remaining in the melt cycle. Feature correlation analysis revealed a strong correlation (0.82) between *Scrap %* and *Remaining melt time*. A prediction model was trained to estimate *Remaining melt time* using *Scrap %* as input. The model was tested on 20 batches, achieving a MAE of 3.6 minutes and an estimation uncertainty of 5 minutes. The segmented scrap pixels and estimated melt time were displayed in the result frames (Figure 3), enabling real-time, localized scrap monitoring thereby optimizing the melting process workflow and efficiency.

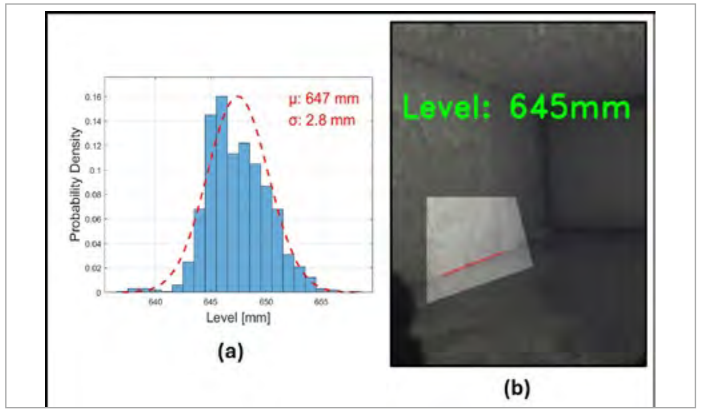

Fig. 2 - (a) Distribution of the melt level measurements from a furnace with a constant melt level, indicating a standard deviation of 3 mm; (b) screenshot of the result image frame in which the measured melt level is displayed along with the identified line.

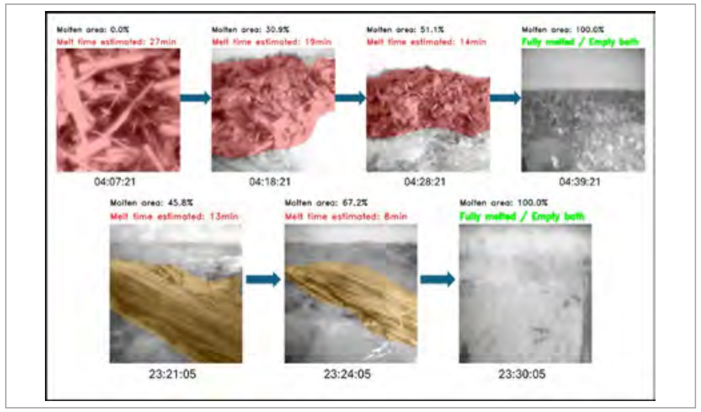

Fig. 3 - Screenshots from the result videos in which aluminum scrap of scrap class 1 (top row) & scrap class 2 (bottom row) melts into liquid aluminum from large solid scrap pieces. Melt bath area & the estimated process time are displayed as textual information in the result frames. Timestamps of the image frames are provided below each image in HH:MM:SS format.

INNOVATIVE MECHATRONIC SOLUTIONS TO IMPROVE PERFORMANCE AND RELIABILITY IN SECURITY DEVICES

Federico Maria Reato - Supervisor: Simone Cinquemani

The complex process of designing and analysis of modern miniature mechatronics mechanisms is influenced by evolving performance standards, encompassing different fields of application and strongly coupled physical phenomena. Within this context, the mechatronic field met an even increased widespread adoption, such as in automotive, robotics, prosthetics, and security filed. This growing demand along with the fact that most of these applications concern solutions embedded in miniature systems, in the order of mm and sub-mm size, highlighted that the design process cannot longer be achieved only through a pure experimental approach, thus the introduction of a much more computational-based design workflow is considered a must. Among the others, a very important scenario in which this type of miniature mechatronics represents a disruptive technology is certainly the field of security and access control. In the last decades, traditional and purely mechanical access control systems have evolved into mechatronic and IoT embedded systems. This transformation involved seamless integration of electro-mechanical components and devices with external and networked electronics, such as passive transponder, electronic keys, encrypted communications, and smartphones, leading to reliable and elevated safety standards.
The present thesis, carried out through a collaboration between the Politecnico di Milano, ISEO Serrature Spa and Microhard Srl, aims to investigate and solve problematics issued by this peculiar industrial sector, as well as to design innovative solutions to improve the reliability and security level of mechatronic-based access control devices. These targeted topics, introduced the necessity to solve further scientific and numeric unresolved issues, pushing towards the implementation of innovative simulation platform and algorithms for the analysis of coupled electro-magneto-mechanical applications, and thus paving the way for novel results in the state of the art of multi-physics co-simulation. Within this work, a series of peculiar components and physical phenomena specific to this field of application are presented, highlighting the accuracy and advantages of a numerical methodological approach, and highlighting some intrinsic limitations of the purely experimental path considered obsolete and not reliable.

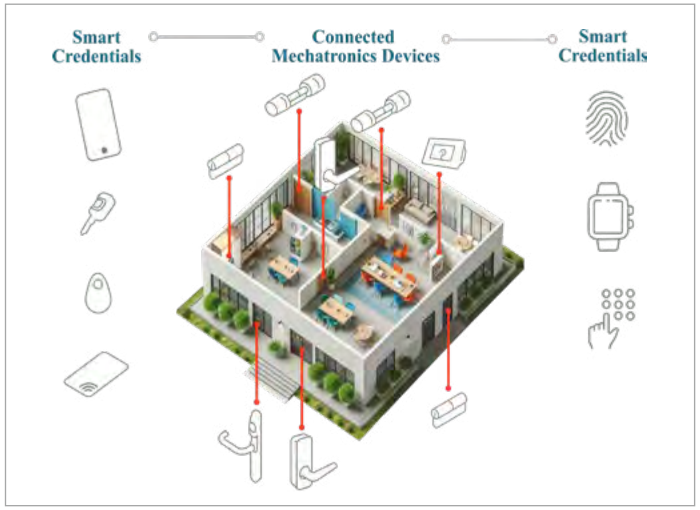

Fig. 1 - Schematics of a connected system for smart control of access points of a facility.

To achieve a high-fidelity understanding of the physical phenomena occurring in these types of devices, two dedicated co-simulation architectures are introduced. These architectures integrate magneto-dynamics and analog electronics within a new multi-domain, multi-scale simulation platform. These utilize an innovative bidirectional communication routine, developed in Python, which enables the exchange of "effort and flow" variables. This approach facilitates the integration of the mechanical domain, modeled using Multi-body Dynamics (MBD), with the magnetostatic/electromagnetic domain, simulated via 3D Finite Volume Analysis (3D FVM), and the analog electronics, modeled using the SPICE Equivalent Circuitry Approach (ECA).
The results obtained and the related experimental campaigns, achieved through indirect measurements of the phenomena, highlight the potentiality and reliability of this co-simulation architecture, validating this tool as a possible standard for the analysis of miniaturized mechatronic applications within security systems and beyond.

Fig. 2 -Detailed characterization of the main physical phenomena constituting a mechatronic security device.

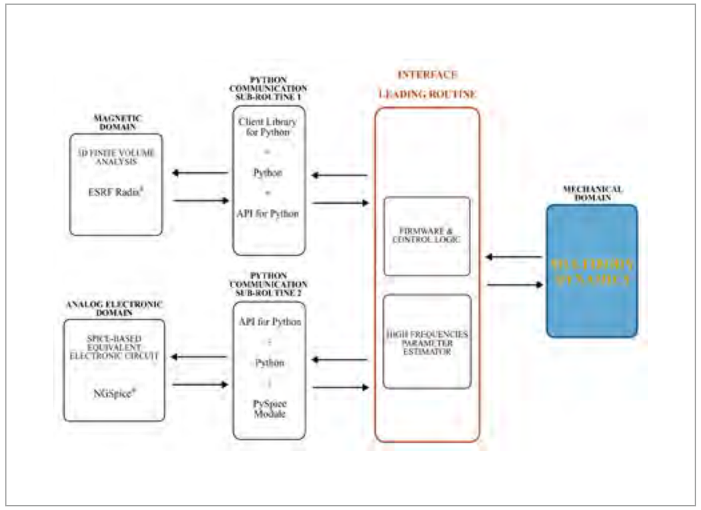

Fig. 3 - The proposed multi-scale multi-physics co-simulation architecture.

Keywords: Multibody dynamics; SPICE Analog Electronics; Electromagnetic Finite Volume Analysis; Multi-physics co-simulation; Security devices; Mechatronic locks.

A MULTIBODY MODEL TO STUDY THE POST-DERAILMENT DYNAMICS OF RAILWAY VEHICLES AND THEIR INTERACTION WITH CONTAINMENT STRUCTURES

Matteo Santelia - Supervisor: Stefano Bruni

Derailment events are a significant challenge for railway safety due to their diverse causes, which include mechanical failure of the running gear, track defects, and extreme environmental conditions. While completely preventing derailments is not feasible, containment devices such as derailment containment walls (DCWs), guard rails, and kerbs are employed in high-risk areas to mitigate their consequences. However, designing these structures is complex since performing in-field tests is impractical, which makes it difficult to quantify the impact loads and to obtain standardized design guidelines. Consequently, numerical simulations are crucial for assessing different derailment scenarios and containment structures. This thesis presents mbDD (Multibody for post-Derailment Dynamics), a nonlinear multibody dynamics model developed to analyze the post-derailment behavior of railway vehicles and their interaction with containment devices, to enhance the structural design of DCWs and other mitigation devices. This would allow to design effective safety devices, both on the vehicle and infrastructure sides, to mitigate the severity of off-track derailment accidents. Post-derailment dynamic simulations would allow to design effective safety devices, both on the vehicle and infrastructure sides, to mitigate the severity of off-track derailment accidents. The methodology adopted in this thesis is based on multibody and finite element (FE) simulation techniques to solve complex problems related to vehicle dynamics and impact-contact mechanics in the post-derailment phase. However, the numerical modelling and simulation of post-derailment dynamics remain highly challenging and require complex mathematical models that account for the large motion of the bodies within the system, significant deformations of suspension components to be considered, and the diverse contact-impact behaviours that can occur after a derailment. In addition, it is crucial to consider potential interactions between derailed vehicles and elements of the infrastructure that normally do not come into direct contact with the train, such as sleepers and ballast. Thus, specific contact models have been developed in this research.

The main original contributions of this thesis can be summarized as follows:

- a systematic description of the MBS modelling of a complete rail vehicle system and trainsets thanks to the introduction of specific models accounting for coupling system between vehicles
- a simple yet accurate wheel/rail contact model, enabling a fast simulation of the pre-derailment and derailment phase
- a simple and efficient contact algorithm for dealing with interactions between derailed vehicle model and FEM of the containment structure and consequently the estimation of the bending stresses produced in the containment wall when impacted by the derailed vehicle: this is the key output to the sizing of the derailment containment device
- a new contact management algorithm and new contact-impact models to consider interactions between derailed vehicle and railway infrastructure elements, such as sleepers and ballast
- a validation of the model through comparison with results from a commercial software, for standard running conditions, and from experimental tests for the post-derailment phase

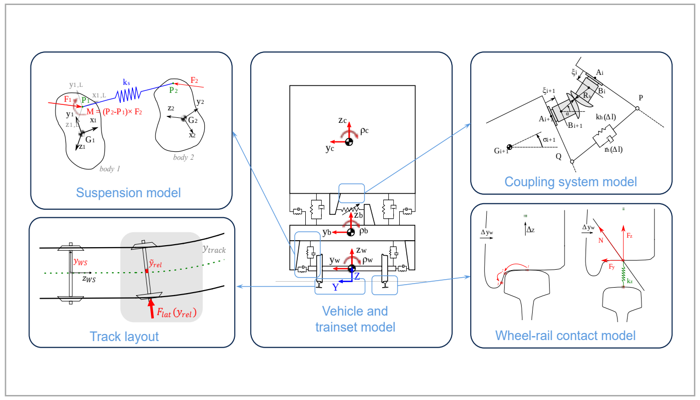

Fig. 1 - mbDD model framework.

Finally, the mbDD has been used to analyse a derailment scenario caused by the sudden failure of the second axle for a high-speed ETR-500 class locomotive travelling at 300 km/h in a HS curve, typical of Italian railway network under different condition. In summary, it is possible to establish a range for the maximum impact forces and bending moments based on the different scenarios simulated.

The research resulted in the development of a reliable and versatile multibody model to analyze post-derailment dynamics and subsequent impact with containment structures. This model can consider various combinations of track and DCW layouts as well as different vehicle or trainset compositions. The goal is to use this model for the structural sizing of the containment structure itself in different scenarios. When simulating a complex phenomenon like the post-derailment behavior of a railway vehicle, it is inevitable that several effects are simplified or even neglected. The model presented in this thesis is no exception, but it aims to consider various aspects related to derailment that were disregarded in previous works. The goal is to understand the different contributions of the modeling choices to the key outputs of this research, which are the loads that the containment wall needs to withstand during an impact with a derailed vehicle.

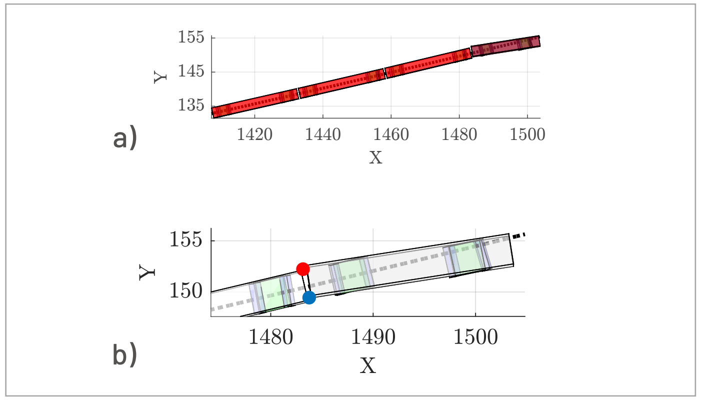

Fig. 2 - (a) Scheme along the track of the first part of the trainset after the derailment: 3D view. (b) Zoom of the first and second vehicle of the trainset in the post-derailment condition: with right (blue) and left (red) buffers highlighted (top-view scheme).

METHODS FOR ROAD VEHICLES RIDE COMFORT OPTIMIZATION

Haoxiang Xue - Supervisor: Massimiliano Gobbi

Ride comfort significantly impacts occupant experience, safety, and health. The thesis focuses on optimization methods for enhancing ride comfort in road vehicles, with a focus on improving computational efficiency in suspension optimization, balancing energy savings with longitudinal comfort in eco-driving strategies, evaluating ride comfort by using driving simulators, and optimal design of the driving simulator to enhance the ride comfort and NVH evaluation.

From the perspective of improving computational efficiency, a multi-fidelity surrogate-based optimization framework, which combines extended kernel regression (EKR) and approximate normal constraint (ANC) method, is proposed for a suspension optimization problem. The proposed framework is compared with well-known algorithms.

A linear quarter car analytical model and a nonlinear multibody model are selected as the low-fidelity and high-fidelity models, respectively. The efficiency of the proposed optimization framework is evaluated against well-known optimization algorithms and applied across various vehicle types. Results indicate that, when used for suspension optimization, the proposed method requires less high-fidelity simulations on average to obtain a single Pareto point than other algorithms, demonstrating strong potential for effectively and efficiently addressing suspension optimization problems.

To investigate an eco-driving cruise strategy, so-called pulse and glide (PnG), a single objective optimization considering the ride comfort constraint on longitudinal jerk was performed to balance energy consumption and longitudinal comfort in a battery electric vehicle (BEV). A two-step optimization method was employed to obtain the optimal solution. In the first stage, a neural network (NN) is generated and trained to get an approximated optimal solution by using a genetic algorithm (GA), and in the second stage, the optimization is performed on the physical model and the optimal solution of the first stage is used as a starting point. The result shows that the optimal PnG strategy can save up to 5% of energy compared with the constant speed (CS) strategy without the constraint of ride comfort. If comfort is considered, a reduction of about 1\% can be found. Furthermore, a subjective experiment for subjective-objective correlation is conducted by using a dynamic driving simulator at DriSMi of Politecnico di Milano. The result shows that the numerical result of the optimization has been correlated to the occupants' subjective comfort perception, demonstrating the driving simulator is a promising tool for a fast and reliable subjective evaluation

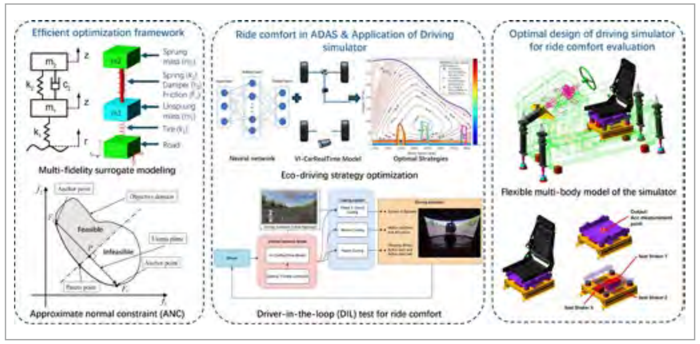

Fig. 1 - Main research activities

of longitudinal ride comfort. To confirm the simulator's role in evaluating comfort thresholds, a comprehensive experiment using the up-down method identified jerk thresholds, aligning well with thresholds obtained from real cars. Finally, a multi-objective optimization of the PnG strategy provided a Pareto optimal set balancing energy efficiency and comfort, with points near the subjective annoyance threshold verified through simulator testing, further confirming these thresholds.

With the aim of reducing cross-directional responses to the input and ensuring that input and output directions align to be effectively transmitted to the target location in a full-spectrum simulator for ride comfort and NVH evaluation, a comprehensive optimization approach of seat bushings is presented. A flexible multibody dynamic model is first created and validated through a modal experiment. To enhance optimization efficiency, a surrogate model based on the response surface methodology (RSM) is employed, replacing the physical model during the optimization process. To solve the multi-objective optimization problem, the weighted sum method is utilized. The optimal design achieves a maximum of 57.7% improvement in terms of crosstalk reduction. Finally, considering the significant difference in optimal stiffness between the front and rear bushings, the layout of the seat bushings has been modified, adding two extra bushings in the rear and evenly distributing the optimal stiffness. The modified layout is still effective in reducing vibration crosstalk.

LIDAR-ASSISTED WIND FARM CONTROL IN EXTREME COHERENT GUSTS

Zhaoyu Zhang - Supervisor: Alberto Zasso
Co-Supervisor: Paolo Schito

With the international trend toward carbon neutrality and the rapid growth in energy demand, wind energy technology has been booming. The size of wind turbines, power generation capacity, and the scale of wind farms have all expanded rapidly, bringing new challenges to wind farm control, simulation, atmospheric measurement, and related technologies. This study explores the feasibility and effectiveness of Doppler LIDAR (Light Detection and Ranging) technology in improving wind farm power generation and safety. The research integrates the entire design process, including wind environment simulation, simulated LIDAR measurement, and wind farm control simulation, enhancing key technologies at each stage to significantly improve the reliability of design and simulation. First, wind field simulation is constructed by coupling atmospheric forecasting data from the Weather Research and Forecasting (WRF) model. A coupling tool is developed to transfer mesoscale simulation data to microscale simulation, which is realized on the SOWFA platform and incorporates turbulence information. This approach makes the simulation more representative of real wind conditions, aiding wind farm operators in better preparing for coming extreme environmental events. Second, a turbine-nacelle-mounted LIDAR is analyzed for its significant measurement uncertainty in wind direction estimation caused by horizontal shear. To address this issue, LIDAR simulations are conducted using three turbulence models with varying fidelities: the Kaimal model, the Mann model, and Large Eddy Simulation (LES). The results indicate that increasing the complexity of turbulence models does not resolve the uncertainty issue. Subsequently, an optimal scanning pattern for LIDAR is determined through a brute force method by adjusting the open angle between laser beams and measurement distance. While this improves the situation, it does not completely solve the problem, suggesting that more advanced wind reconstruction methods for LIDAR are needed in future research. Lastly, the wake steering control strategy is developed on the Floris platform and validated using the high-fidelity LES approach on SOWFA. Compared to Sonic anemometer-assisted wind farm control, LIDAR-assisted control results in higher power generation due to more accurate measurements of wind velocity and direction. Additionally, an Extreme Coherent Gusts condition is applied to test the LIDAR's capability in rapidly changing wind speed and direction scenarios. The results show that LIDAR-assisted control responds more quickly to extreme environments, providing smoother load transitions on turbines due to wind preview from LIDAR measurements. In conclusion, LIDAR measurement offers significant advantages in wind farm control for both power generation and safe operation. Future work will focus on integrating LIDAR-assisted individual turbine control and wind farm control by enhancing LIDAR's wind field reconstruction methods.