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PhD Yearbook | 2024

DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

Chair:
Prof. Andrea Bernasconi

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 7th 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 37 abstracts belonging to PhDs of the 34th (6), 35th (25) and 36th (2) doctoral cycles (defended in 2023 and 2024) 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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PARSIMONIOUS MODELING IN TERMINAL BALLISTICS

Riccardo Andreotti - Supervisor: Prof. Marco Virginio Boniardi

This thesis represents a significant step forward in the field of terminal ballistics, providing innovative solutions to complex challenges through the development of simplified models. Terminal ballistics, as a discipline, explores the effects of projectile impacts on various targets, ranging from hard, impenetrable surfaces to soft tissues, encompassing a wide array of applications in aerospace, defense, material science, and forensic sciences (Figure 1).
Andreotti's research addresses the critical need for models that balance accuracy with computational efficiency, enabling rapid analysis and application in real-world scenarios. By adopting a parsimonious approach, Andreotti advances the field by offering models that simplify the intricate physics of ballistic impacts without compromising their predictive power. This approach is grounded in the principle of Occam's Razor, which advocates for simplicity in scientific modeling, making the complex phenomena of terminal ballistics more accessible and manageable for researchers and practitioners alike.
The thesis is structured around several key objectives: extending the range of experimental evidence available in the field, due to the inherent challenges in conducting ballistic tests; developing validated parsimonious finite element simulation models for both academic and industrial applications; and introducing a constitutive characterization of a muscle simulant that offers practical and economical advantages over traditional ballistic gelatin. These objectives are pursued through a combination of experimental research and the development of novel analytical and empirical models, including an original analytical formula for estimating load history due to bullet splash, significantly reducing the computational cost of simulations.
Andreotti's contributions are multifaceted, encompassing the introduction of a systematic approach to terminal ballistics that views the field as a continuum of interaction phenomena. This perspective allows for a more generalized approach to addressing ballistic problems, facilitating the development of parsimonious procedures that can be applied across a broad range of scenarios with minimal resources. One of the thesis's notable achievements is the engineering definition of bullet splash, which describes the scenario where a ballistic protection system completely fragments an impactor without penetration. This concept is crucial for both academic and practical applications, as it provides a clear framework for analyzing and designing effective protective structures.
The research also draws parallels between bullet splash and bird strike phenomena, suggesting that methods used for bird strike simulations can be effectively applied to terminal ballistics problems. This analogy is further explored through the development of simplified models that treat the bullet splash as a fluid-structure interaction (Figure 2), dramatically simplifying the modeling process and increasing the feasibility of simulating these events.
Additionally, the thesis introduces a novel analytical method for estimating the impact force due to bullet splash, offering a significant reduction in computational costs and enhancing the efficiency of finite element simulations for structural assessments subjected to ballistic impacts.
A key contribution of the thesis is the development of a fully characterized and validated constitutive model for an innovative synthetic muscle simulant compatible with most commercial simulation softwares. This model allowes the simulation of ballistic impacts on synthetic tissues, providing a valuable tool for wound ballistics research based on these convenient synthetic materials. The synthetic gel, known as baligel, presents in fact significant advantages over traditional biological gelatin, in particular its clarity, stability, reusability and overall cost-effectiveness, making it a promising material for both industrial and forensic applications (Figure 3).
In conclusion, Riccardo Andreotti's doctoral thesis marks a significant advancement in the study of terminal ballistics. Through the development of parsimonious models and the innovative use of synthetic materials for ballistic testing, Andreotti not only enhances our understanding of ballistic impacts but also provides practical tools and methodologies for addressing real-world challenges. The research embodies the essence of scientific progress, demonstrating how innovative thinking and a focus on practicality and efficiency can lead to groundbreaking solutions in complex fields such as terminal ballistics. Andreotti's work paves the way for future research, highlighting the potential of simplified models to revolutionize both theoretical and applied aspects of terminal ballistics and related disciplines.

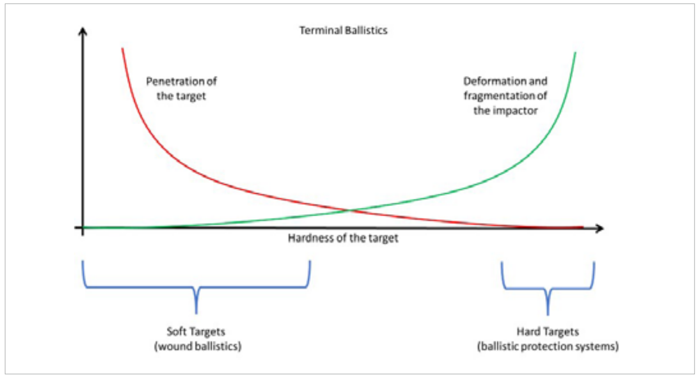

Fig. 1 - Schematic overview of the terminal ballistics fields of application depending on the hardness of the target (compared to the impactor). The red line represents the damage caused to the target in terms of penetration, decreasing with the increase of its hardness. The green line represents the damage of the impactor increasing with the target hardness. For hard targets the main research field of interest is the development of materials and structures for ballistic protection applications. On the opposite side, soft targets are studied in the field of wound ballistics and forensic science but also used in crashworthiness applications.

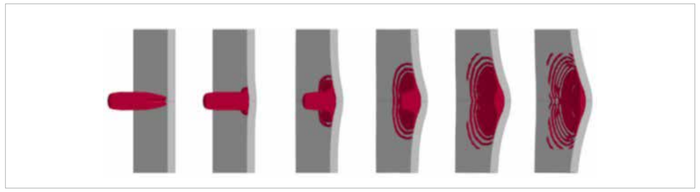

Fig. 2 - FSI simulation results showing the evolution of the interaction between a .308 monolithic brass bullet (red) and target (grey) from t=0 to t=0.05ms at constant 0.01ms time step.

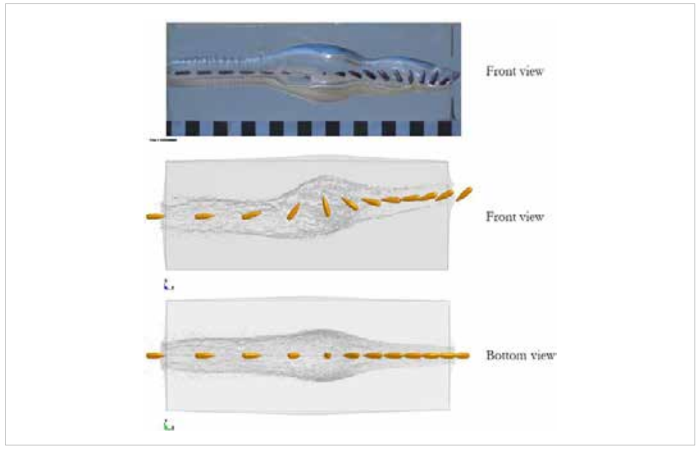

Fig. 3 - 7.62x39 mm FMJ impact. Temporary cavities at escape time: experimental results at time 0.9ms (above) compared to simulation results (below) at time 1.0ms, seen from the two cross directions. Evolution of the bullet's kinematics during the penetration superimposed to the temporary cavity captured at escape time. The resolution of the checkered ruler is 20 mm.

A POWER PREDICTION PROGRAM FOR THE OPTIMISATION OF THE USAGE OF FLETTNER ROTORS ABOARD SHIPS

Gianluca Angelini - Supervisor: Prof. Sara Muggiasca

Co-Supervisor: Prof. Marco Belloli

The relevance of maritime transport both for materials and people has always been considered, throughout history, as a determining factor for human prosperity. In fact, as confirmed by recent statistic data, transport by sea has represented about 90% of the movements of commercial materials worldwide in last two decades. Indeed, as a consequence of the recent global focus to break down the industrial polluting emissions, technical progress and research have received an important booster from the restrictive regulations ratified by the majority of the most industrialised and, therefore, most polluting countries. The attention to the shipping-related environmental implications has proportionally increased, with the pressure on the technological development sectors to research new sustainable solutions becoming more and more considerable.
Several kinds of green energy are under investigation, with researchers analysing their pros and cons in order to achieve a lower fuel consumption and an eco-friendlier base to preserve the massive maritime transport.
In this context, innovative proposals for ship propulsion are rising in importance, with special mention to the use of solar energy, sea wave energy, biomasses and wind.
Among all of these, the value of wind energy has been firmly reconsidered and recently applied to maritime transportation.
Since different types of wind energy (rigid sails, cylindrical or wing rotors) are under analysis in engineering research due to the interesting achieved results, this research focuses on the multiple experiments performed within the studies on Flettner rotors as early as 1920-1930. A description of how Flettner rotors work is followed by the explanation of why, after a period of stagnation, they were reconsidered in the last decade only, as well as how they were used in this research.
Specifically, from a physical point of view, the discriminating factors considered for the usage of Flettner rotors aboard vessels are: their weight, dimensions and the structural reinforcements; the importance of a wide wind-exposed surface leading the rotor performance; the necessity to keep the speed of the ship as constant as possible, in order to maximise their utility.
These characteristics make rotors unfeasible for oil-tanker ships, container ships and military fleets.
Instead, an interesting cost-effective use of the Flettner rotors can be considered for RoRo-type ships or ferries operating in particularly windy seas, or for general-cargo ships having empty decks.
This is why, in fact, all the physical and geometric factors regarding a cargo ship chosen as case-study for this work have been taken into consideration. Indeed, a two-rotor configuration has been considered as installed in a longitudinal manner and with a mutual 15D distance.
At the same time, technology and supercomputers, as well as computer simulations, can predict physical phenomena with increasing effectiveness, prominently contributing to highlighting the weakness of this wind solution. It is within this context that the present work has been dedicated to the creation of a Power Prediction Program, with the aim to study and optimise the use of Flettner rotors as an alternative to diesel engines on general cargo ships.
After motivating the choices about the dimensioning of the wind rotors and the type of ship, the created code has been built up to collect some weather information and execute several simulations from a departure to an arrival harbour. As an output of these simulations, the best track on a geographical map is provided to users.
From an aerodynamical point of view, the data collected in a wind tunnel campaign on models of rotors in Milan were used. To solve the mathematical problem related to the calculation of the fluid dynamics, while aiming to optimise the usage of the Flettner rotors, the vessel under exam has been firstly considered as a perfectly rigid body. In order to make the equations as easily and independently solvable as possible, an inertial reference linked to the ship was chosen, while the rotations around the reference system were illustrated through an Eulerian approach.
Indeed, the treatises available in the naval architecture literature were punctually described in the present work to define the behaviour of the forces acting on the ship, for a 1-DOF initial approach.
The 1-DOF calculation, however, can be considered reductive for a ship, whose trade routes cross seas and oceans, which can be very often stormy and put the manoeuvrability and intact stability of the ship to the test. For this reason, the calculation of the 1-DOF resistance, can lead users to incorrect and very dangerous indications, since it would trace the route without taking into account the safety of navigation.
This is why, a description of the procedures that the code implements for the verification of the manoeuvrability criteria required by the SOLAS regulations and a 6-DOF study was applied in the code.
Thanks to the PPP created and described in this analysis, the reduction in diesel consumption represents the driving factor for the calculation by the software of the best route to be suggested to the users of the code. The principal consequences of the reduction of diesel consumption are of fundamental importance in the research and in the commercial field: reduction of CO_2 and NO_x emissions and lower fuel costs for the same time required for the track.
In order to evaluate the profit provided by the implementation of Flettner rotors aboard vessels for both these aspects, important assessments will be made on the obtained outcome.
In terms of air pollution emission reductions, these results will be the basis for the verification of the minimum criteria imposed by the world regulatory apparatus, by calculating the Energy Efficiency Design Index and verifying how it varies with the use of Flettner rotors.
Regarding fuel consumption reduction, an economic analysis of the savings guaranteed by the use of rotors and a forecast of the return on investment for their installation was carried out. As a matter of fact, punctual considerations were made about the several parameters chosen to describe the economic assessments.
Lastly, several simulations varying the routes in terms of length, position of the initial and final harbours on a global scale, range of ship speed and rotor dimensions, were carried out to forecast the best wind solution to optimise the return on investment related to the installation of Flettner towers.
Several graphs representing the outputs of the calculations are available at the end of the present work, with a discussion on the related advantages and disadvantages. In general, the further the arrival point, the stricter the time in years necessary to cover the initial investment and the bigger the rotor diameter, the more effective the rotor contribution to the ship propulsion.
Considering the evident benefits, this work aims to depict how Flettner rotors are a valid solution in terms of both the environmental asset and the economic benefits, considering the free-of-charge use of the wind power, and the payback period estimations deriving from the choice of this particular but potential alternative propulsion system.

MECHANICAL BEHAVIOUR OF COMPOSITE MATERIALS UNDER LOW-VELOCITY IMPACTS

Mohammad Rezasefat Balasbaneh - Supervisor: Prof. Andrea Manes

There has been an increasing demand for composite materials in the automotive, defense, and aerospace industries over the past decades due to their distinguished mechanical properties, particularly their optimal weight-to-strength and weight-to-stiffness ratio. The main criticality of composite materials is their vulnerability to out-of-plane loads such as low-velocity impacts which in many cases limits their application and can lead to catastrophic failure. In fact, during the service life, a component made of composites is subjected to various loading conditions (including impacts) which might create damages that remain hidden if specific non-destructive techniques are not applied. This thesis aimed to assess the low-velocity impact of composites through experimental and modeling approaches focusing on characterizing the impact response and failure mechanisms. Also, providing design guidelines and optimizations to improve the low-velocity impact performance. This was achieved by high-fidelity numerical simulations of composite subjected to impacts to improve the accuracy of the models and computational efficiency. Then using the numerical models, together with experimental approaches, to study more practical engineering cases regarding the low-velocity impact performance such as hybridization and repeated impacts. Accordingly, the contributions of this thesis can be categorized into three different tasks; (i) developing Finite Element (FE) models to simulate low-velocity impact considering material non-linear behavior and initiation and propagation of multi-mode failure, (ii) investigating the effect of hybridization of different reinforcements (aramid and S2-glass fibers) to improve lowvelocity impact response of composite laminates, and (iii) evaluation of repeated low-velocity impact response of composites. The modeling part [1–4] was aimed at bringing new methodological approaches and simulation algorithms to increase the accuracy and decrease the computational effort needed for the simulation of failure in composite materials with a focus on the micromechanical and macrohomogenous approaches. In each case, the developed models were verified by doing benchmark simulations and comparisons with experimental tests. The research that was performed in this area started from the implementation of different failure criteria such as Puck and Cuntze to improve the prediction of damage caused by low-velocity impacts, and the development of a new search algorithm for finding the fracture angle of Puck failure criteria aiming to increase the computational efficiency of the models. And work in this area continued by developing a hybrid micro-macro mechanical approach for scale bridging and considering the micromechanical uncertainties at macros scale simulation and during explicit simulations, and development of a novel approach to estimate the characteristic element length for FE simulations of composite materials. Subsequently, the hybridization of different fibers (aramid and S2-glass) for the production of superior composite laminates has been a focus of the studies performed during this work [5–7]. Due to their distinctive properties and cost-effectiveness, hybrid composites have found potential use in many engineering fields, which urged the need to extensively evaluate their performance. Experimental and numerical studies on the low-velocity impact behavior of interply S2-glass/aramid woven fabric hybrid laminates were performed to fully characterize the mechanical behavior of these materials. A comprehensive study was performed to assess different interacting parameters (such as stacking sequence and hybridization ratio) in the lowvelocity impact response of hybrid laminates over a broad range of impact energies to identify the most desired hybrid laminate in terms of impact resistance. Response surface methodology and multi-criteria decision-making methods were used to evaluate the hybridization effect and propose design improvements. Also, the developed numerical models have been used to evaluate the impact performance in the case of hybrid composites to study the effect of strain rate sensitivity and material on the impacting side. The results showed that significant improvement can be achieved by hybridization which provided a better balance between energy absorption and deformation compared to single fiber laminates. Moreover, during the service life, composite laminates are subjected to various impact loads which, in most realistic cases, do not consist of a single impact case but a multiple-hit situation. It has been shown that a single impact may not lead to any serious damage, while the damage accumulation caused by the repetition of impacts may significantly reduce the load-bearing capability reduction and increase the probability of unexpected failure. Therefore, this issue was addressed by numerically and experimentally investigating the response of composite laminates subjected to low-velocity repeated impacts [8–11]. To cover a broad range of composite materials, laminates made of unidirectional carbon fiber-reinforced polymer and woven aramid/S2-glass epoxy composites were numerically and experimentally studied at different energies. The immense conclusions from this task included the influence of impact energy, impact location, pre-existing impact damage, and hybridization on the repeated low-velocity impact response In conclusion, the main objective of this was to investigate the mechanical behavior of composite materials subjected to low-velocity impact loads to provide better insight into the durability, mechanical performance, and failure of these structures. In addition, the comprehensive experimental and modeling work that was carried out paves the way for more practical application of this work for the improvement of the design of composite subjected to extreme loads.

ANALYSIS OF METAL AM ROUGH SURFACES, IMPACT ON FATIGUE PROPERTIES

Lucia Barricelli - Supervisor: Prof. Stefano Beretta

Co-Supervisor: Prof. Luca Patriarca

Metal Additive Manufacturing (AM) offers great design flexibility for industries like aerospace, automotive, and biomedical, thanks to the capability to produce freeform lightweight components. However, the process introduces inherent anomalies in the printed metal alloys causing a scatter in the fatigue properties.
In the absence of large internal defects, most of the fatigue failures start from the rough surface.
The surface quality of net-shaped metal AM parts is influenced by the process parameters and the build orientation, having a direct influence on the fatigue performance.
Identifying and modeling the "killer" surface anomalies that lead to fatigue failure and their interactions is key to predicting component fatigue life.
By incorporating surface effects for different printed alloys into existing fatigue models, the end goal would be to predict the fatigue performance of larger components based on simple non-destructive measurements of the rough surface.
This PhD study aims to assess the impact of the surface quality of net-shaped metal AM parts on their fatigue behaviour.

The main purposes are to:

- Develop and validate fatigue prediction models on various metal AM alloys, taking into account the surface effects (notch morphology, shielding)
- Assess various surface qualities of fatigue samples printed at different orientations
- Assess the capability of fatigue model to account for different surface quality based on print orientation
- Compare different computational approaches for fatigue predictions based on non-destructive measurements on rough profiles (roughness or FE on 2D real profiles)

A shielding model based on Fracture Mechanics (FM) was developed. It relies on standard profile roughness parameters and considers the interaction between adjacent valleys of a rough surface. The model was validated using Finite Element (FE) analyses on rough profiles of cylindrical Laser Powder Bed Fusion (L-PBF) AlSi10Mg samples extracted from X-ray computer tomography (XCT) scans (Figure 1).
Following, FM prediction tools were calibrated through an experimental campaign on L-PBF Ti6Al4V alloy: 4PB tests on samples printed at different orientations highlighted a ranking in the fatigue limit depending on the surface quality (Figure 2, the rougher the surface, the worse the behaviour).

The following points were covered for the FM approach:

- A theoretical shielding model was adapted to L-PBF surfaces through the use of simple roughness parameters, in order to predict global shielding behaviour.
- Fractographic analysis of rough samples was performed using a novel method for measuring the depth of surface valleys based on roughness parameters.
- Guidelines were given for the application of the shielding model in different regions of the stress-life curves.
- An equivalent initial crack size for fatigue life was introduced based on the maximum valley depth roughness parameter (Sv or Rv).

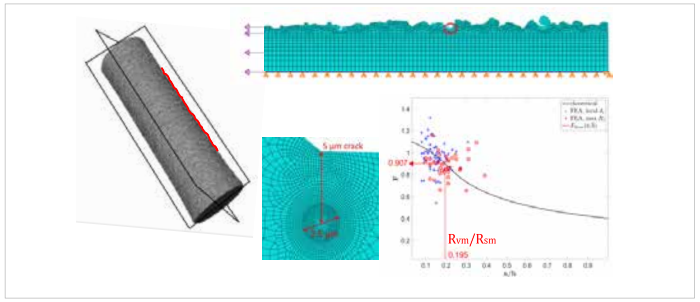

Fig. 1 - 2D FE analyses on rough profiles reconstructed by XCT. Small cracks were modelled at the root of the deepest valleys

An alternative computational method was used to make fatigue predictions on the 4PB Ti6Al4V series (Figure 3). 2D FE models simulating the 4PB loading were used to apply a point-method from the Theory of Critical Distances (TCD): using material parameters alone, the critical distance "L" was determined and the ratio of the local stress in the vicinity of a surface valley to the nominal maximum bending stress

$$\left(\frac{\sigma_{loc}}{\sigma_{nom}}\right)$$

was used to rank the criticality of the valleys.
The maximum

$$\frac{\sigma_{loc}}{\sigma_{nom}}$$

ratio served as a fatigue notch factor for the prediction of the fatigue limit of the rough samples starting from the limit of the plain alloy.
Following a rigorous calibration and validation through an experimental campaign on the alloy, both the FM and TCD fatigue prediction tools proved efficient in predicting the fatigue limit and life of the L-PBF 4PB Ti6Al4V as-built series (Figure 3).
These predictions relied on the non-destructive analysis of rough profiles reconstructed through XCT, offering a potent industrial toolkit for the qualification of larger components.
The FM method stands out for its rapid application and the simple input (profile roughness parameters), while the TCD, based on FE analyses, is computationally demanding, but provides insights about the local singularities of the L-PBF surface.

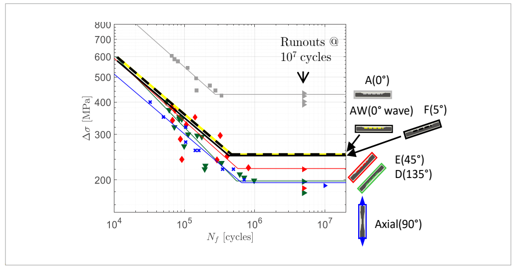

Fig. 2 - Experimental campaign on Ti6Al4V alloy

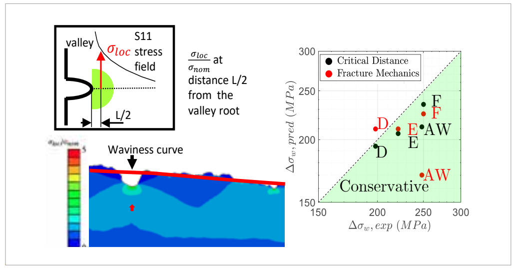

Fig. 3 - TCD point-method and predictions from rough profiles with the 2 approaches

OPTIMIZED INERTIAL MEMS GYROSCOPES: DESIGN AND TESTING OF INNOVATIVE LAYOUTS

Giacomo Bonaccorsi - Supervisor: Prof. Francesco Braghin

Micro-electro-mechanical systems (MEMS) have revolutionized the field of sensing applications by enabling the miniaturization and integration of mechanical and electronic components in compact, costeffective devices. MEMS gyroscopes, in particular, have introduced angular rate sensors to various fields, including consumer electronics, automotive, and the aerospace industry. The rising demand for advanced MEMS devices and their increasing complexity, however, introduce several challenges in their design process. This thesis explores different layout optimization techniques, namely parametric and level-set-based optimization, to aid designers in developing innovative MEMS layouts. The parametric optimization refines existing layouts starting from an initial guess, while the level-set algorithm presented is able to generate complete layouts from scratch.
Two parametrically optimized layouts were designed to improve the mechanical compensation of the Zero-Rate Offset (ZRO) or quadrature error. These layouts were then manufactured, and tested in collaboration with STMicroelectronics. Concurrently, a level-set-based topology optimization approach was developed and applied to generate novel single-axis MEMS gyroscope architectures. This method enables the discovery of innovative MEMS layouts while optimizing their performance based on a given cost function and constraints. The results indicate that level-set topology optimization is a promising technique for the optimization of MEMS devices, especially if towards higher frequencies (such as modern MEMS resonators and time-keeping devices).
Lastly, over 55,000 test structures were manufactured in collaboration with STMicroelectronics for the statistical validation of local wall-angle variations and to better understand the effect of dummy geometries placed in proximity of a MEMS spring. This thesis details the automation of the wafer-level testing program using LabVIEW and presents the preliminary results obtained, laying the foundation for further investigation.

DEEP LEARNING FOR FAULT DETECTION IN COMPLEX MECHANICAL SYSTEMS

Francesco Morgan Bono - Supervisor: Prof. Simone Cinquemani

The term "complex mechanical systems" encompasses a broad spectrum of interpretations, depending on the specific intricacies underlying a system's behavior. For instance, automated production lines illustrate complexity through the need to regulate numerous parameters to ensure product quality, while bridges exemplify behavior influenced by dynamic external factors like temperature and humidity. Monitoring such systems poses a multifaceted challenge due to their intricate nature.
This PhD thesis aims to address various types of complex mechanical systems with the objective of identifying anomalous operating conditions. An anomaly is defined as a deviation from a system's nominal behavior, often evolving over time. Early detection of anomalies is crucial to prevent widespread failures and improve system performance and availability.
The Model-based approach is one strategy to tackle this challenge. It employs mathematical models of the system, integrating a physical understanding within the monitoring framework. Techniques such as Kalman filters and parity relations are utilized for statistical estimation, facilitating the monitoring of system component deterioration. However, in cases where accurate modeling of system behavior is challenging, these models may only represent the average system behavior, limiting their effectiveness for anomaly detection.
In contrast, Data-driven approaches leverage signal processing techniques and monitoring data to detect anomalies without relying on explicit models. Technologies like the Internet of Things (IoT) enable the collection of diverse data types, which are extensively utilized for fault detection and predictive maintenance. Machine Learning (ML) algorithms play a vital role in analyzing this data, enhancing fault detection across various domains.
This research adopts an approach that integrates both Data-driven and Model-based methods to overcome the limitations of individual approaches. By combining these approaches, algorithm performance can be enhanced.
The Model-based approach, typically favored by engineers, faces limitations in accurately modeling complex systems. Conversely, the Data-driven approach, often favored by data analysts, relies on complex algorithms (often based on ML) but may overlook the physical behavior of the system.
The methodology of this research is developed through logical and sequential steps, employing different use cases to validate the approach's generality. These steps include defining sensor setups, applying Data-driven supervised models, verifying approach generality, employing Data-driven unsupervised models for bridge behavior analysis, combining numerical models with Data-driven models, training Data-driven models on numerical data, and exploring Physics Informed Neural Networks (PINN) for anomaly detection in unsupervised problems.
Overall, this research endeavors to bridge the gap between Data-driven and Model-based approaches, offering a comprehensive framework for fault detection in complex mechanical systems. By integrating insights from both worlds, it aims to enhance anomaly detection and contribute to advancements in system reliability and performance.
Specifically, machine learning algorithms serve as pivotal tools, harnessing data from various domains to bolster fault detection and prediction capabilities. As a result, the principal objective achieved in this study is the formulation of a methodology that transcends the limitations inherent in both model-based and data-driven approaches. Through rigorous testing across different scenarios and systems, a unified framework emerges, amalgamating the strengths of these methods to furnish a more holistic and efficacious approach to anomaly detection within complex mechanical systems.
This framework encompasses the diverse approaches delineated within this thesis, applicable to a generalized system where the goal is the detection of anomalous working conditions. Notably, it is elucidated that these algorithms possess versatility, proving applicable not only to specific cases or systems but adaptable to diverse conditions with minor adjustments in data treatment methodologies.
Moreover, in instances where a hybrid approach is employed across all application cases, it is demonstrated that this mixed methodology surpasses singular model-based or data-driven approaches in terms of performance.
The research aims to continuously refine and advance the methodology, fostering innovation in the realm of anomaly detection across complex systems.

AN INNOVATIVE HUMAN-LIKE DRIVER MODEL

Antonio Cioffi - Supervisor: Prof. 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.

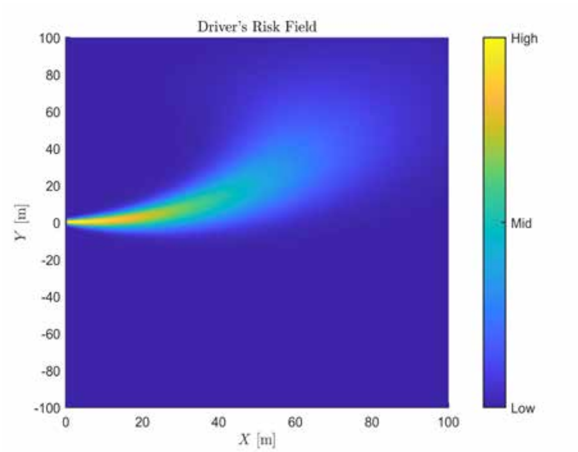

Fig. 1 - Kolekar's et al. Driver's Risk Field.

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.

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

RECOGNITION OF MACHINERY HEALTHY STATE THROUGH THE FUSION OF PRODUCT INSPECTION AND PROCESS MONITORING DATA

Chiara Conese - Supervisor: Prof. Marco Tarabini

This PhD Thesis presents an alternative approach of multi-sensor data fusion, that makes use of both machine-related data and product-related information. This method offers a comprehensive overview of the overall state of complex production machineries, diverging from the conventional attention to individual components or subsystems as commonly seen in existing literature.
The complexity of this type of systems have driven the proposed methodology towards the necessity of modelling in a proper way the classification uncertainty. Indeed, a monitoring system heavily relies on measurements from a limited set of sources, leaving many others unobservable or unknown. Additionally, discrepancies may arise among the known sources themselves regarding the estimated condition. This heterogeneity of information required the use of techniques capable of optimally quantifying the predictions of individual sensors and all that cannot be controlled and observed. In parallel the combination of all the information at disposal can enhance the prediction accuracy of the monitoring system.
With this aim, a two-level monitoring strategy has been developed based on Bayesian and Dempster-Shafer theory of evidence. In particular, the Bayes approach was used to give a local probabilistic estimation that quantify the effectiveness of individual sources to predict the target condition (i.e. prioritizing on the confidence in the sources' prediction rather than on simply accuracy or score values). The Dempster-Shafer theory was adopted to combine the information obtained from each source by intelligently weighting the various sensors, so those that perform worse are considered with less importance. In addition, it is a framework that considers conflicting estimates from various sources (through conflict management in the combination rule).
Having demonstrated its effectiveness in an authentic industrial context, this approach holds potential for adaptation across diverse assessment domains, contingent upon the consideration of relevant indications and constraints.
The main limitations associated with the proposed method relates first to the challenging of looking at process and product together: it is fundamental to clarify the target to be addressed by the monitoring, the sensors type and location, the experiments and tests to be performed. In this context, gathering useful data can be a non-trivial and demanding task which requires the design and installation of fit-to-purpose hardware or the synchronization of the various sources with themselves and with the industrial plant databases.
Another issue encountered was related to the context on which the work took place, that is the application of a monitoring system for a new production machine. Plant costs, waste of time and resources while performing tests, impossibility of applying modifications to the machine designed parts are just some of the concerns that can cause unavoidable compromises to be made during the design of the final monitoring system.
Some of the problems were for instance: the impossibility to mount too many sensors due to space limitations or physical adaptation impediments; the installation of multiple sources entailing stops in both production and pre-scheduled testing; the difficulty in performing a multiclass classification which would have required to simulate all the different conditions on the machine and to acquire data in faulty states to perform model's training, which consequently means a waste of time and resources. Consequently, it was necessary to simplify the problem, considering one or, at most, two conditions that still serve as indicator of potential component malfunctions and that directly impact the product quality.
Future developments could focus on overcoming the identified limitations. For instance, exploring the effectiveness of the method under different and several anomalies' configurations on varied machine operative conditions, or integrating additional sensors, may lead to adjustments and improvement of the proposed approaches, in terms of estimation accuracy or computation efficiency.

PREDICTIVE MAINTENANCE ARCHITECTURE FOR VALVE WEAR SUPERVISION

Fabio Conti - Supervisor: Prof. Marco Tarabini

This work describes the measurement system for the condition-based maintenance of industrial machineries. The architecture is designed to be integrated in the industrial plant and to provide on-line monitoring of industrial components for the prediction of faults and estimation of the remaining useful life. Hardware and software components are designed to fulfil these specific purposes. The architecture is tested in different industrial use-cases, internal leakage of valves in die-cast aluminium processes is chosen to show the predictive and wear estimation capabilities of the architecture. As first step, we identified different fault detection methods for the internal leakage of valves; three main monitoring techniques are identified through a literature review analysis based on acceleration, temperature, and current sensors. The identification and refinement of the monitoring techniques to extract data regarding internal leakage fault detection from a 4/3-way solenoid operated directional control valve was carried on through laboratory experiments on a hydraulic block. The analysis of the results showed that acceleration and current monitoring can be used to extract meaningful features for the fault identification task. As second step, we compared different machine learning algorithms to identify the optimal predictive model to solve the monitoring task and to address the missing data problem that may affect online monitoring. The random forest algorithm provided the best performances out of all the algorithms considered and was therefore identified as the one that best fits the predictive maintenance task. Random forest was modified to ease the missing data problem during online acquisitions. The modified algorithm can indeed, be used when some features are not available, at a cost of a reduced accuracy in prediction. As third step, we identified a suitable method for remaining useful life estimation, through the application of the particle filter algorithm with Monte Carlo simulations. It was possible to estimate
with simulations the remaining useful life of solenoid valves. Particle filter was used with simulated data to test the theoretical equations. The architecture was applied on valves in a real industrial framework and it was able to identify leak-related frequencies. Through the observation of these frequencies, it was possible to characterize the theoretical measurement and process equations and observe that the model can be generalized to different valves of the same type, at different operating conditions. About the hardware architecture, we created a suitable system to host the predictive maintenance infrastructure, to process the data coming from the acquisition nodes and broadcast the results to HMIs or PLCs. Measurements node hardware was created ad hoc for the task, embedding high-frequency ADC and filtering stages to achieve the optimal acquisition task. The hardware architecture can be either industrial PC or smart nodes for data elaboration and algorithm computation, additionally equipped with measurement nodes if high frequency sensors must be connected to the condition-based maintenance architecture.

METROLOGICAL OPTIMIZATION OF A SPACE DUST ANALYZER FOR MARS

Marco Giovanni Corti – Supervisor: Prof. Diego Scaccabarozzi

Introduction

A particulate system is an environment hosting a cloud of particles having negligible size with respect to the liquid/gaseous surroundings. Those environments are widespread in nature (e.g., the particles dispersed within the planetary atmosphere, the interstellar matter) and in the industry (e.g., the powder in metal additive manufacturing, the undesired particulate in the clean rooms). Therefore, the latter investigation is fundamental to deeply understanding the origin and the evolution of such systems, typically relying on particles size as the main parameter to infer other relevant characteristics of the fines. Among the multitude of techniques devoted to particle sizing, amplitude-dependent Single Optical Particle Counters (SOPCs) constitute one of the most significant classes of devices. The latter infers about the size by measuring the intensity of the light scattering beams produced during the interaction of a collimated laser light with the investigated particles. This research work deals with MicroMED, an amplitude-dependent SOPC selected for the ESA ExoMars mission to measure the airborne dust size in-situ at the Mars lower troposphere. A numerical model was developed to simulate the instrument working principle and to provide an estimate of the particle size measurement, enriched with the corresponding uncertainty budget. The designed tool can be exploited to complete the MicroMED calibration procedure or as a support for the feasibility design of similar instruments.

Methodology

Following a comprehensive literature review about the light scattering by small, rounded particles, the amplitude-dependent SOPCs working principle was modelled by applying Mie Theory for light scattering to the architecture of the instruments. Following its validation against literature study cases, the simulator was tailored to the MicroMED SOPC and a Monte Carlo engine was included in the code to draft the latter uncertainty budget. Indeed, the variabilities related to the instrument measurement principle (i.e., lasing wavelength, complex refractive index, and photodiode responsivity), fluidic system (i.e., particles trajectories), and thermomechanical behaviour (i.e., laser optical power stability and density distribution in temperature) were identified and quantified. Since the thermoelastic deformations influenced the light-particles interception locus, fluid dynamics and thermomechanics highlighted a synergistic effect on the measurement variability. Moreover, the Optical Power Density Distribution (OPDD) of the laser at the instrument sampling volume shifted from the ideal-uniform one, further contributing to the overall framework complexity. The challenge was tackled by designing a Computational Fluid Dynamics (CFD) model representative of the MicroMED fluidic system, supported by extensive experimental activity on a mockup of the instrument to validate the former. The CFD model was adopted to simulate the trajectory distribution for three particles (selected within the MicroMED sensible range) in Martian environmental conditions. In parallel, the expected thermoelastic deformation between the laser collimation group and the fluidic system was determined by relying on a Finite Element Analysis (FEA) simulating the instrument's operative conditions. Merging the CFD and FEA findings with the OPDD of the MicroMED laser (i.e., modelled adopting a generalized bell-shaped distribution) a resampling of the latter was performed, leading to a new OPDD for each of the simulated particles, in operative conditions. The quantified uncertainties were propagated via a Monte Carlo simulation running the Mie Theory-based numerical code for 10^6 iterations split on an 8-core parallel engine, obtaining the MicroMED detector output current vs. particle size curve. Finally, a quadratic fitting of the curve allowed evaluating a local sensitivity at each of the investigated particles, leading to the size measure of the latter.

Results and discussion

The validation of the numerical code was based on the scattering phase function comparison against literature study cases and, exploiting the Root Mean Squared Error (RMSE), provided the robustness of the developed tool. Following, the quantification of the identified uncertainty sources was carried out. The incident light wavelength, the photodetector responsivity, and the particle's complex refractive index were ready-available (i.e., including their variability) within the MicroMED photodetector and laser datasheets, and Martian simulant data found in the literature. The CFD model, designed to cope with the instrument fluid dynamics, was validated relying on a testing campaign running a mockup of the MicroMED fluidic system, obtaining an error smaller than 5% between the numerical and the experimental results. The latter was exploited to simulate a representative Martian study case (i.e., 9 mbar and -20 °C using CO_2 as working fluid) and injecting separately small-size (i.e., $2 \cdot 10^{-7}$ m), medium-size (i.e., 10^{-6} m), large-size (i.e., $5 \cdot 10^{-6}$ m) radius particles, obtaining the corresponding trajectories distribution. The FEAs ran to estimate the thermoelastic deformation and pointed out that the current MicroMED mechanical design was not sensitive to the investigated temperature range (i.e., -20 °C to +40 °C). Therefore, a fictitious misalignment of 250 µm and 500 µm was introduced to probe the effect on the instrument performance and to perform the OPDD resampling. The obtained OPDD was characterized by a relative standard deviation lower than 5% for all the investigated particles. The incident light optical power measure was estimated following the statistical investigation of batches of experimental data belonging to an extensive testing campaign on eight MicroMED laser mockups, obtaining a standard deviation of about 1.6% of the average power value and a systematic error of about 1.7%. The uncertainties were propagated running a Monte Carlo simulation integrated into the numerical code, obtaining the detector current measure for each of the investigated particles and thermal misalignment. The largest standard deviation (i.e., about 14% of the average) affected the small-size radius particle that, on the other hand, presented the smallest systematic error (i.e., about 2.5% of the average). Moreover, the standard deviation appeared to reduce with the particle radius. This eventuality was explained by analyzing singularly the variability contributors, highlighting that the complex refractive index had a strong dependency on the particle radius, according to the literature.

A COMPARATIVE DYNAMIC ANALYSIS OF FLOATING PLATFORMS FOR 15 MW WIND TURBINES

Simone Di Carlo - Supervisor: Prof. Marco Belloli

Offshore floating wind turbines represent the key technology to expand the exploitation of wind power in vast sea areas, even where the high water depth makes economically unfeasible the installation of fixed foundations. Being deployed far from the shores, floating farms have a reduced visual and acoustic impact on populations, and can benefit from stronger, more constant and less turbulent wind inflows with respect to onshore generators. Industrial deployment of floating farms is expected in the next years, and many demonstrative projects are already delivering power to the electric grid; many of the technological challenges have been solved, but some refinement to the current state of the art must be pursued to finally achieve sufficiently low energy costs and a full availability of the technology.

One of the key components of a floating turbine is the floater, which on one side is impacting considerably on the cost of the entire system, and on the other side is determining the dynamic behaviour of the floating turbine under wind and wave actions, then ultimately on the efficiency of power production. Several floater concepts have been proposed up to now, each one claiming better dynamic performance or cheaper construction costs, but no definitive response on what is the best among them has been formulated. In this framework, the aim of this work is to perform a comparison of dynamic performance and power production of a 15 MW wind turbine on four different platforms among the ones more adopted in already existing demonstrative projects, and that will probably be adopted in next future industrial installations. 15 MW wind turbines, featuring a hub height of 150 m and a rotor diameter of 240 m, are still in their prototypal phase, but are considered the standard wind turbine size for next future floating installations. Comparison of dynamic performance is performed in OpenFAST, a state-of-the-art numerical solver for floating wind turbines, released as open-source by NREL, and thinking to a realistic site of deployment.

Since floater models for 15 MW wind turbines are still lacking, or at least are not publicly available, especially for some platform families, the first part of this work is focused on the upscaling of platforms designed for lower rating wind turbines (5 or 10 MW) to the wind turbine size of 15 MW. Upscaling is carried out by increasing floater dimensions till static stability requirements are met, and the dynamic behaviour of the floater is sufficiently good. Upscaling process regards the geometric dimensions of the platforms and the mass properties, while the mooring systems are designed from scratch. The wind turbine tower must also be adapted to the floating installation, and the power control system must undergo a proper tuning to avoid well-known instability phenomena given by the coupling between blade pitch actuation and floater

Fig. 1 - A floating wind turbine on a semisubmersible platform

rigid motions. In order to derive consistent wind and wave conditions for the simulation campaign, the site of deployment is characterized with state-of-the art statistical techniques to draw the conditional probability of occurrence of main environmental parameters like wind speed, wind turbulence, vertical wind shear, wave height, wave period. Numerical simulations are carried out both in the operative conditions of the wind turbine, when the generator is producing power, and in the extreme conditions, when the rotors are idling to protect the machines from excessive loading. Dynamic analysis of floater reveals excellent stability and sea-keeping characteristics of the TLP, which is characterized by negligible tilt angles under the rotor thrust and limited excursions in all the degrees of freedom. The other floaters, or the semisubmersible, the barge

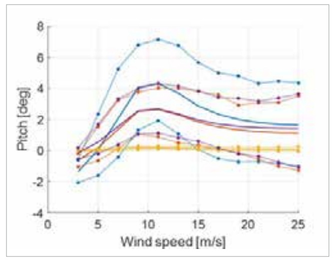

Fig. 2 - Average, max and min pitch angle of the upscaled platforms

and the spar, are pretty similar in the amplitude of motions, of course with different levels of static stability. Among them, the barge is the more stable floater, followed by the spar and then by the semisubmersible, which is the worst. Conversely, drivetrain dynamics and power production is not affected by the platform type, and is pretty similar on all the floaters; average values of power, specifically, are very similar in all of them.

Spectral analysis of signal reveals how floater displacements, accelerations and loads are highly influenced by wave action and by floater rigid dynamics, while rotor speed and power production are sensitive to turbulence and power controller settings.

To draw some conclusions, it could be said that this work has two main outcomes: the upscaling procedure and the dynamic analysis of floaters. The upscaling procedure is probably not corresponding to any kind of industry practice, when higher power rating floater designs are needed, but it allows to obtain in a fast and straightforward way a floater model with realistic data, at least useful for preliminary screening of the performance of the concepts. On the other side, the dynamic analysis is surely influenced by how floaters have been upscaled, but nevertheless is revealing the main trends in the platforms behaviour. Main outcome is that platform type, despite differences in stability and dynamic behaviour, is not affecting much the power production of the generator.

INVESTIGATING THE DYNAMICS OF EMOTIONS, VISUOSPATIAL ATTENTION, AND THEIR SYNERGISTIC ROLE THROUGH VIRTUAL REALITY

Nicolò Dozio - Supervisor: Prof. Francesco Ferrise

In today's rapidly evolving world, our interactions extend beyond the physical realm, ranscending traditional boundaries and entering the realm of eXtended Reality (XR), characterized by the seamless integration of physical and virtual elements.
As the relationship between people and XR is strengthening, it is important that the research world focuses no longer purely on the "physical" aspects of the interaction between humans and technologies, but also on higher human characteristics and cognitive functions, such as perception, attention, emotions, cognitive workload, expectations, and many more.
The research works performed in this PhD project focuses on exploring XR, especially in its immersive Virtual Reality (VR) declination, as an experimental tool that would allow investigating effectively and safely emotional, attentive, and perceptual aspects that are involved in the interaction between humans and technology in increasingly varied fields, with particular attention to the context of driving and mobility. When considering the research work focused on solutions that involve human interaction, or that should cooperate with the attentive, perceptive, or emotional characteristics of the final user, VR proves to be a precious tool for researchers, because it allows to handle several features that are difficult or sometimes impossible to control in the real world (e.g., external agents, distractions, traffic flows, spatial and temporal features, etc.), resulting in an improvement in terms of reliability, standardization, and repeatability. However, human perception works differently in reality and in immersive virtual environments. Therefore, to obtain reliable data it is important to better characterize the relevant attentive and perceptive parameters, together with new methodologies that allow to effectively test and collect measures on attentive and perceptive human attributes.
VR is also a powerful tool when it comes to elicit emotional responses, but it is still underused if compared to other media content such as images, sounds, and videos, which are frequently collected in affective databases specifically for the purpose of induce emotional responses.
The starting point of this research work consists in the definition of a design methodology for the design and development of 10 affective VR environments linked to five distinct emotions, whose validity has been assessed in two simultaneous experiments involving more than 70 participants.
Subsequently, the research work shifts on the individuation of the cognitive variables that influence driving behavior in terms of safety and efficiency. The validated affective VR environments have been integrated into an experiment related to the use of VR for the assessment of visuospatial attention and perception in the driving contexts, providing the chance to induce two opposite emotional responses in the study participants before performing a divided attention task, constituted by a central and a peripheral task, in a VR driving simulation. This procedure also allows to avoid interruptions between the different stages of the experiment, providing therefore a new and more straightforward methodology to explore the interaction between emotions and other cognitive processes in immersive environments. The results obtained highlights a significant effect of the emotional state in the central task, where relaxed drivers react significantly slower than scared drivers. At the same time, the performance at the peripheral task is affected only by the eccentricity of the visual stimulus, independently from the emotional state of the driver.
Finally, visuospatial attention and the mechanisms that influence the perception and localization of objects in the surrounding environment, especially in urban scenarios or applied to the driving context, is investigated in greater details in a research work that explores the possibility of using VR as a reliable tool for the design and testing of technological innovations, such as a new generation of ADAS, considering the variables that most influence the human ability to perceive and locate static and dynamic objects in real-world and virtual environments. The experimental procedure has two stages: the first focuses on exploring the ability to perceive and localize static visual targets in a VR urban environment depending on visuospatial features known to affect visual perception in real-world scenarios, such as targets' egocentric distance and horizontal eccentricity. The second stage introduces temporal features and investigates how the accuracy in predicting the future position of a moving visual target is affected by the amount of time that the objects are seen, as well as other factors, such as the time horizon in which the movement is performed, and the effect of contextual information available from the environment (e.g., road markings).
Results of the first experiment provides a reference measure of the significant effect that distance and eccentricity have on localization error for static visual targets, while the second experiment shows the effect of time variables and contextual information on the localization accuracy of moving targets.
To conclude, these experimental works provide insightful data on the reliability of VR technologies for the design, development, and testing of new technological solutions that must assist and adapt users' cognitive and perceptive characteristics. The data collected constitutes the starting point for the development of a cognitive model of drivers' attention capable of better characterizing important aspects related to human perceptive and predictive capabilities linked to the visuospatial and temporal variables explored in the presented research works.

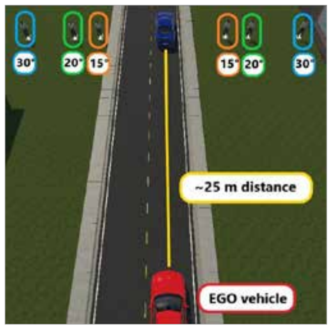

Fig. 1 - Overview of the VR environment and the peripheral target positions for the divided attention task.

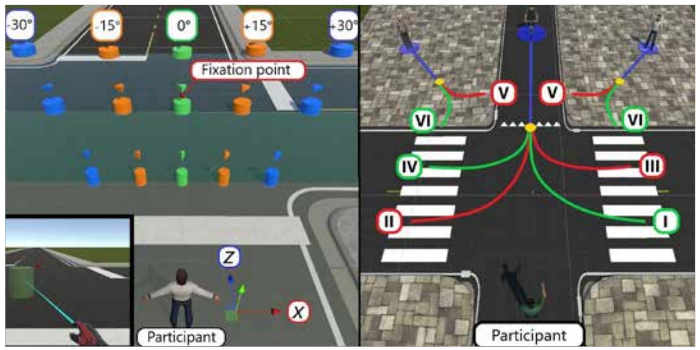

Fig. 2 - The two VR environments developed to explore attentive and perceptive parameters in the mobility context.

TECHNOLOGICAL DEVELOPMENT AND METROLOGICAL CHARACTERIZATION OF A 3D SCANNER BASED ON STRUCTURED LIGHT

Davide Maria Fabris - Supervisor: Prof. Marco Tarabini

This thesis focuses on the creation of a measurement model, on the optimization and metrological characterization of a 3D scanner based on the structured light technique. The first part of the work analyses the state-of-the-art of the stereoscopic 3D reconstruction technology. Moreover, the scientific literature concerning the field of 3D reconstruction metrology and the technical standards on the metrological characterization of 3D scanners are studied and reported. After analysing the uncertainty model of the 3D reconstruction, we consider the case study of an existing instrument. Thanks to the learnings derived from the uncertainty model, we propose different improvements of the system, allowing to obtain a better reconstruction accuracy, repeatability, information density and completeness. Developments entail the modification of the system calibration procedure, the implementation of a novel reconstruction algorithm based on the High Dynamic Range paradigm, and the speedup of the scanning process. The final part of the work focuses on the metrological characterization of 3D reconstruction devices, granting the possibility to objectively investigate their measurement capabilities, despite the complex nature of their metrology. The implementation of a software for the metrological characterization of similar 3D reconstruction devices is also presented.

Keywords: Measurement, 3D Scanner, Structured Light, 3D Vision, High Dynamic Range, Metrology, Design of Experiments.

MOVEMENT ANALYSIS AS A TOOL FOR THE QUANTIFICATION OF MOTOR IMPAIRMENTS CAUSED BY DIFFERENT PATHOLOGIES

Cristina Ferrario- Supervisor: Prof. Marco Tarabini

Co-Supervisor: Prof.ssa Manuela Galli

The use of quantitative and multi-factorial movement and posture analysis in clinical rehabilitation has gained increasing attention in recent years. Subjective and qualitative video recording methods are no longer considered sufficient for providing an adequate characterization of a patient's motor and postural condition. The growing number of movement analysis laboratories within clinical rehabilitation centers is indicative of this trend. One of the most commonly evaluated movements in subjects with functional limitations is walking. Through the use of quantitative analysis, several studies have characterized the typical motor strategies of walking in healthy individuals and identified deviations from normality in individuals with specific pathologies. Gait analysis, widely used in clinical settings, has been applied for evaluating the degree of functional limitation associated with pathologies, enabling the selection of the most appropriate rehabilitative treatment and quantifying the effectiveness in a variety of conditions in both children and adults [3], [4], [5]. These evaluations are important because pathological conditions are often associated with alterations in movement and posture, resulting in functional limitations in performing daily life tasks. The goal of rehabilitation is to intervene on the systems involved in the pathological condition in order to improve the functional state and the quality of life of the subject. Thus, it can be affirmed that one of the key advantages of movement analysis is the ability to objectively evaluate the effects of rehabilitation treatments and target them for optimal results. This type of analysis, in fact, not only allows the quantification of motor impairments caused by specific pathologies, but also tracks the progression of the pathological condition over time. In addition, a quantitative measure of the patient's motor status before and after rehabilitation treatment can be used to determine the real effectiveness of the therapy. However, the use of gait analysis alone may not be sufficient to comprehensively evaluate all individuals and all daily life situations such as climbing up and down the stairs or rise from a chair. When evaluating movements different from gait, it is important to factors such as the marker positioning, the trial modality, the model definition, and the identification of parameters of interest.
This work aims at investigating the application of motion analysis in the examination of pathological conditions, and is based on the analysis of a vast amount of data acquired on human subjects. Specifically, the study aimed to use motion analysis in a more target and innovative manner, by selecting appropriate methods that correspond to the condition under investigation. This approach enabled a more specific biomechanical characterization of the subjects, which in turn allowed for a more accurate evaluation of impairment. The findings of this research were then used to predict and asses rehabilitation treatments that were tailored to the specific needs of the subjects. This ultimately resulted in a more precise monitoring of the progression of the pathology and the implementation of treatments that could be really effective in improving the quality of life of the subjects.
The proposed method has been applied to different pathologies, with particular focus on Down Syndrome (DS), Cervical Dystonia (CD), Lower Back Pain (LBP) and Obesity.

INSIGHT INTO NOVEL AGE-HARDENABLE COCUFEMNNI-BASED HIGH-ENTROPY ALLOYS

Jacopo Fiocchi - Supervisor: Prof. Riccardo Casati

1. Introduction

In recent years, the development of high-entropy alloys (HEAs) has opened up a huge research field in metallurgy. Initial research efforts were driven by the search for alloys displaying stable, disordered solid solutions, but more complex microstructures are now being sought to improve the mechanical and functional behaviour of HEAs in the hope of outperforming conventional alloys. The microstructure of an alloy can be tailored through several methods, among which the implementation of dedicated heat treatments stands out as an effective one. Given these premises, it was decided to focus on on the formation of second phases through precipitation or spinodal decomposition during dedicated thermal treatments. This study could also possibly yield information about how, and if, said transformations are influenced by the peculiar properties of HEAs. Therefore, the aim of the present doctoral thesis is to design, produce, and test new HEA compositions, which are meant to be strengthened through the formation of second phases during dedicated thermal treatments. As a side activity, two advanced processing methods, namely laser welding and laser powder bed fusion, were applied to the selected HEAs with two main objectives. On one hand, this allowed to expand the possibilities of really fielding HEAs by better establishing highly sought after processing methods; on the other hand, it aimed to explore the effect of out-of-equilibrium processing conditions, i.e. rapid solidification, on the metallurgy and, therefore, the mechanical behaviour of the selected HEAs.

2. Design and characterisation of a Ti-modified CoCuFeMnNi HEA

Instead of designing a new alloy from scratch, it was decided to choose an already known HEA and modify it through selected elemental additions. The CoCuFeMnNi alloy, a variant of the Cantor alloy, was selected because Cu presents a large and positive mixing enthalpy with respect to the other elements, which may help phase separation and thus makes the alloy at hand a possible candidate to be strengthened by second phases. It was modified by the addition of Ti, which is known to produce $D0_{24}$ η Ni_3Ti precipitates in Ni-based alloys [110] and marageing steels [111]. The effect of such elemental addition on the phase composition of the CoCuFeMnNi alloy was predicted by CALPHAD method, leading to the selection of a $CoCuFeMnNiTi_{0.13.}$ This alloy, and its unmodified counterpart were subjected to solution and ageing thermal treatments, resulting in a significant hardening, with an evident improvement related to the presence of Ti. The performed ageing treatment strongly enhanced the mechanical resistance of the alloys, as the yield strength of the CoCuFeMnNi alloy was improved by almost 100 % with respect to the solution-treated condition. Concurrently, the modification of the alloy by the addition of Ti was able to induce a significant increment of mechanical resistance as well, in both the solution-treated (+ 29 %) and peak-aged (+ 47 %) conditions. Microstructural analyses (high resolution synchrotron X-ray diffraction and atomic-resolution scanning transmission microscopy), were coupled to semi-empirical models describing strengthening mechanisms to establish a relation between microstructural evolution and mechanical properties. It was shown that Cu-rich clusters, resulting from spinodal decomposition in solution-treated samples, create a periodic compositional modulation (amplitude of 23 at.% in Cu), which results in a periodic modulation of local elastic properties. Ageing treatment lead to the formation of Cu-rich discs, resulting from spinodal decomposition, which create again a periodic compositional modulation with similar amplitude and larger wavelength, which causes a periodic modulation of both elastic properties and lattice parameter. Finally, Ni_3Ti $L1_2$ coherent nanoparticles, resulting from precipitation in the peak-aged, Ti-modified alloy, give rise to discontinuous, localised and very intense peaks in elastic properties and shallower, almost negligible rises of lattice parameter. In essence, second phases oppose dislocation motion at long range through the continuous modulation of local lattice strain and elastic properties.

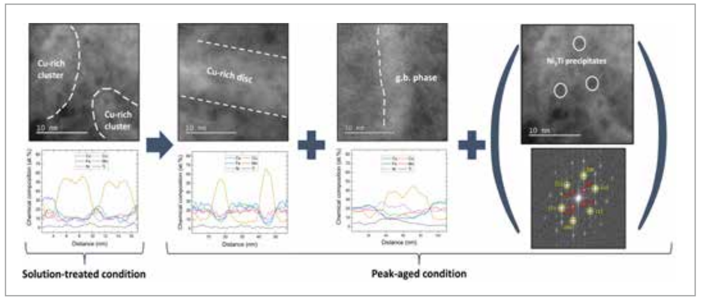

Fig. 1 - Schematic depicting the microstructural features observed in solution-treated and peak-aged CoCuFeMnNi and $CoCuFeMnNiTi_{0.13}$ alloys.

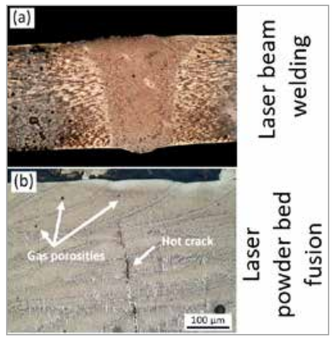

Fig. 2 - Representative micrographs depicting the microstructures of (a) laser beam welded CoCuFeMnNi alloy, and (b) the CoCuFeMnNiTi0.13 alloy produced by laser powder bed fusion.

3. Laser-based processing of the CoCuFeMnNi and $CoCuFeMnNiTi_{0.13}$ alloys

Laser beam welding of the CoCuFeMnNi alloy was selected as a first step. The laser beam welding processability window of the CoCuFeMnNi alloy was explored, leading to the definition of optimised parameters able to produce flawless, regular, and repeatable welded beads. The microstructural evolution resulting from the welding process and successive thermal treatments was studied and the observed features were related to both average and local mechanical properties, thanks to the implementation of direct image correlation. The tensile behaviour was found to be mainly dictated by local strengthening produced by spinodal decomposition and changes in strain hardening capability depending on the crystalline structure of the material.

LPBF processing of the $CoCuFeMnNiTi_{0.13}$ alloy proved problematic because of the low quality of the procured powder and the formation of hot cracks. Nevertheless, the obtained samples were characterised and subjected to both thermal treatments and hot isostatic pressing. The spinodal decomposition and precipitation processes were found to be essentially insensitive to the rapid solidification characterising the LPBF process, while HIP was instrumental in healing the defects of as-built parts and granting satisfactory mechanical performance.

COMPLEX DATA MODELLING AND MONITORING FOR SMART MANUFACTURING IN INDUSTRY 4.0

Federica Garghetti - Supervisor: Prof. Bianca Maria Colosimo
Co-Supervisor: Prof. Marco Luigi Giuseppe Grasso

The digital transition as well as new production capabilities within the Industry 4.0 framework are reshaping the complexity and volume of data used for discrete manufacturing quality monitoring and modelling. On the one hand, advanced manufacturing and additive manufacturing methods are used to produce more and more complex products, which require novel non-destructive inspection methods, leading to quality data in the form of computed tomography volumes, 3D meshes and point clouds. On the other hand, advanced sensing tools enable big and fast streams of sensor data like high-dimensional signals, images and videos gathered during the process, while the part is being produced. The result is a novel level of quality data complexity, which gives rise to industrial challenges, namely the lack of appropriate statistical process monitoring methods, the difficulty to manage such high dimensionality of in-process and post-process data, and the difficulty to deal with multi-sensor data stream in an efficient and effective way. This PhD thesis aims to tackle these challenges by exploring and testing novel solutions for big and complex data reduction, modelling and monitoring. Novel methods are presented for two major production frameworks, i.e., traditional manufacturing via flexible systems and metal additive manufacturing. All proposed approaches share the same underlying idea of transforming high-dimensional data into a lower dimensional format (profiles) that is easier to handle and more efficient to analyse while capturing the relevant information content suitable for fast and accurate anomaly detection.

3D BIOPRINTING: FROM NOVEL SOLUTIONS FOR IN-SITU MONITORING TO THE BIOFABRICATION OF DRUG-RELEASING BIOMIMETIC SCAFFOLDS

Simone Giovanni Gugliandolo - Supervisor: Prof. Bianca Maria Colosimo

Co-Supervisor: Prof. Davide Moscatelli (CMIC)

The landscape of the medical and pharmaceutical industries is currently witnessing a profound transformation, with a departure from the conventional "one-size-fits-all" paradigm to a more personalized and tailored approach to the development of products, drugs, and medical treatments. This paradigm shift, commonly referred to as personalized medicine, encompasses a spectrum of technologies, including precision medicine, regenerative medicine, and systems biology. Of particular significance in this evolving landscape is the role played by 3D printing. Regenerative medicine, a vital component of personalized medicine, leverages cells, tissues, and organs to repair and replace damaged biological structures. As the field of personalized medicine continues to expand, 3D printing technology, specifically 3D bioprinting, is emerging as a crucial tool driving knowledge forward in this context. Furthermore, 3D bioprinting contributes to developing personalized drug delivery systems and drug testing platforms. It involves the computer-aided transfer processes for patterning and assembling living and non-living materials with a prescribed 2D or 3D organization to produce bio-engineered structures for applications in regenerative medicine, pharmacokinetics, and basic cell biology studies. In essence, 3D bioprinting stands at the intersection of engineering, material science, and biology, aiming to create functional living tissues and organs. Its interdisciplinary nature positions it as a groundbreaking technology with the potential to revolutionize drug discovery, medical treatments, and significantly enhance the quality of life for individuals grappling with various diseases. The ultimate goal of 3D bioprinting is to produce functional biological structures applicable in tissue engineering, drug screening, food printing, and, most ambitiously, in regenerative medicine for the replacement of damaged or diseased organs. The industry surrounding 3D bioprinting has recently extended beyond the realm of high-end systems confined to university research and has entered the commercial sector. This evolution is fueled by the advent of more financially accessible technology, the standardization of commercial materials, and the anticipation of early commercial applications. Consequently, the bioprinting industry is experiencing robust development, fostering innovation across technology, materials, and application fronts. Despite these advancements, bioprinted structures remain inherently complex, often comprising diverse materials and cell types arranged in regulated spatial patterns, with designed porosity, reinforcing structures, and mechanical property gradients. This complexity necessitates the establishment of rules governing the bioprinting process, ensuring biocompatibility, and adhering to stringent quality standards, especially when considering the potential clinical and pharmaceutical applications of bioprinted constructs. As mentioned, this significant set of complexities affects monitoring methods in several ways. However, over the last few years, the first attempts at implementing quality assessment approaches have been established, with different kinds of monitoring sensors. Within this context, this thesis will provide a comprehensive overview of the current state of the art in monitoring techniques of 3D bioprinting processes, highlighting the challenges and opportunities in the field. The main significance of this thesis lies in its potential to provide new solutions for in-situ monitoring of extrusion-based bioprinting (EBB) processes. In summary, from a methodological standpoint, the research and the contributions are devoted to the development of methodologies for monitoring such kind of bioprinting processes. To do that, this thesis delves into various aspects of bioprinting. It starts with a literature review for exploring process engineering advancements and identifying the state-of-the-art, research gaps, and new questions, focusing on analyzing the state of the art in bioprinting process monitoring, emphasizing advancements in control and optimization techniques, particularly in printability, defect detection, and material deposition strategies. Part of the work is dedicated to exploring various monitoring methodologies, including visible light imaging, infrared imaging, and fluorescence imaging, addressing distinct aspects of bioprinted constructs. It introduces an in-situ visible light camera and image analysis for bioprinting monitoring, aiming to create a genuine in-situ monitoring platform. A thermal imaging system is employed to enhance geometry reconstruction, paving the way for new research avenues in the in-line monitoring of transparent bioinks. It is also presented a new method for monitoring cell distribution in EBB using fluorescence imaging, adding another layer of sensor technology to the bioprinting process. Another part of the thesis shifts attention to the biofabrication of drug-releasing biomimetic scaffolds introducing the utilization of 3D printing for producing nanoparticle-loaded scaffolds designed for sustained drug release. This novel approach involves chemically linking therapeutic agents to biodegradable polymeric nanoparticles, showcasing the potential for a customizable localized drug delivery system. In conclusion, this work contributes significantly to the field of 3D bioprinting by providing a comprehensive overview of monitoring techniques and offering innovative solutions for in-situ monitoring of EBB processes. The potential applications of this research extend beyond monitoring to the development of drug-releasing biomimetic scaffolds, promising advancements in the efficiency and effectiveness of medical treatments. All features presented in these chapters try to innovate the state of the art. In general, the proposed in-situ monitoring systems would fit into the context of intelligent biomanufacturing solutions, enhancing the digitalization of processes and systems and the integration of information from multiple sensors. We plan to develop alert systems able to identify several parameters at a time, geometric and non-geometric, detected by multiple types of sensors to realize a real in-situ monitoring platform, possibly based on machine learning and data fusion approaches following the path of process digitalization. The challenges, accomplishments, and future directions discussed in this thesis underline the significance of these contributions to the dynamic and expanding field of 3D bioprinting.

Keywords: 3D bioprinting, bioink, in-situ monitoring, defects, biomimetic scaffolds, drug delivery

PARTICLE FILTER-BASED DAMAGE PROGNOSIS IN ENGINEERING STRUCTURE SUBJECTED TO FATIGUE LOADING

Tianzhi Li - Supervisor: Prof. Claudio Sbarufatti,
Co-Supervisor: Prof. Francesco Cadini

Degradation is an inevitable phenomenon in structures, where damage can evolve over time or with the number of load cycles. Eventually, safety may no longer be guaranteed when the damage state reaches a predefined threshold. Regular inspections should be carried out to evaluate functionality but they require high financial expenses and unwanted system shutdowns. One possibility for simultaneously ensuring structural safety and reducing maintenance costs is to schedule maintenance just before the damage state reaches the critical limit. In this context, the structure's remaining useful life (RUL), i.e., the time required by the component or structure to reach its operative limit, is desired to be estimated online by an advanced damage prognosis technique.

To achieve this, a reliable and accurate prognostic technique must be developed that incorporates uncertainties arising from the sources like complex fatigue degradation, environmental factors, loading conditions, and material properties. The development of a typical damage prognosis method involves four main steps, as shown in Figure 1. First, a deterministic damage evolution model is developed to describe the evolution of fatigue damage with time or the number of load cycles. Next, its probabilistic form is proposed to include uncertainties arising from the degradation process. The third step involves quantifying the damage state through a direct or indirect measurement system and updating the damage evolution model using a suitable state estimation technique. Finally, the updated model is used to predict the future state and RUL of the structure. To improve the robustness of the prognostic method, three potential paths are explored in my thesis: *damage evolution modeling*, *damage quantification*, and *model updating algorithm*.

The first contribution to *damage evolution modeling* considers the delamination shape in composites as a damage state to be predicted. A method for predicting the delamination shape growth is proposed and validated by the composite fatigue test with ultrasonic C-scan monitoring. Then, in order to avoid the need to collect experimental data for modeling, a dataset containing sufficiently enough delamination images is created by some numerical simulation of fatigue delamination growth in composites, and then adopted for training the delamination shape evolution models. Finally, a method by fusing multiple physics-based and data-driven damage evolution models is proposed to enhance the prognostic performance, and then validated by an aluminum fatigue test with Lamb wave monitoring.

As to *damage quantification*, aiming to address the measurement uncertainties arising from various sources such as temperature variation, the

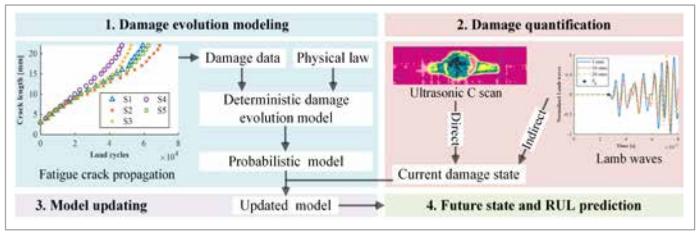

Fig. 1 - Four main steps in a typical prognostic method

author developed a bias-based prognostic model accounting for those uncertainties. Additionally, a dataset of some numerically simulated Lamb waves is used to build the damage quantification model, avoiding the need to collect experimental data for modeling. Finally, as the selection of a proper damage-sensitive statistical feature is crucial to the performance of the prognostic model, an online bias-based feature fusion and selection method is proposed to fuse multiple features and select the best one. All three contributions are tested by the aluminum fatigue test with Lamb wave monitoring mentioned above.

Targeting high-dimensional system identification, the author developed a new *particle filter* method of simplifying the identification of one high-dimensional system into that of multiple lower-dimensional systems, allowing for more efficient state and parameter estimation. This is validated by a numerical simulation of a twenty-story Bouc-wen frame structure under seismic excitation.

The discussions presented in this thesis are anticipated to enhance the robustness of damage prognosis for metal or composites undergoing fatigue degradation by introducing and implementing some improvements towards the three paths. Although the ultimate goal, beyond the scope of this thesis, is that the structural health monitoring (SHM) community should strive to provide benefits that outweigh the costs and accelerate the adoption of SHM as a transformative engineering methodology.

RISK-BASED SCHEDULING IN THE REMANUFACTURING OF TURBINE BLADES

Lei Liu - Supervisor: Prof. Marcello Urgo

The remanufacturing model aligns with the circular economy model and has gained significant attention, particularly in the realm of high-value manufacturing parts such as turbine blades. This approach recognizes the immense value and potential for extending the life cycle of critical components like turbine blades through refurbishment, repair, and reconditioning. By implementing remanufacturing practices, manufacturers can effectively reduce waste, conserve resources, and minimize environmental impact while still meeting the demands of the high-value manufacturing sector. However, compared to the production of new parts, remanufacturing involves uncertainties due to the variable and unpredictable wear of parts whereof processing time is one of the most significant factors. Decision-makers are requested to balance the pursuit of production performances and, at the same time, mitigate the risks associated with uncertainty. Therefore, a scheduling approach is required to address these uncertainties and ensure optimal performance to reduce the resource consumption and adhere to the specified delivery time. This thesis aimed to develop an integrated risk-based robust scheduling approach for the remanufacturing operations of gas turbine blades, considering uncertainties such as the occurrence of rework activities and the probability of blade rejection during the remanufacturing process.

The risk measure-based scheduling approach, i.e., Value-at-Risk, is exploited in this thesis (see Fig. 1), which can compensate for weaknesses of alternative robust scheduling approach, with this risk measure, we can derive VaR value is the maximum makespan we can experience in the best percentage of the scenarios. The level confidence that the makespan will not excess the VaR value.

Phase-type distributions are exploited to fit the real general distributions in the remanufacturing activities, this can be used to fit the general distributed processing time distributions with multi-mode or heavy tail, which are more relevant in the real manufacturing plants (see Fig. 2). The non-independent property among various critical paths is addressed taking advantage of Markovian activity network (MAN) approach, by taking into consideration all the possible conditions of all the activities, the process can be modelled as a continuous time Markov chain, and the distribution of the makespan can be calculated by an equation with exponential of matrix operation.

To exact algorithm which can find the optimal solution, i.e., branch-and-bound is firstly developed, with a proved lower bound (see Fig. 3).

To improve the computational efficiency, heuristic algorithms, i.e, IG and NEH, are developed to fast find the sub-optimal schedules. The efficiency of the proposed approach is demonstrated through a set of computational experiments and comparison with alternative methodologies. The proposed approach has been tested extensively through computational experiments.

The algorithm employed in the approach has been optimised to reduce the processing time and achieve faster scheduling results. By utilising stochastic scheduling techniques, the proposed approach optimises the allocation of resources in remanufacturing plants. It effectively assigns tasks to available re- sources, minimising idle time and maximising the utilisation of machinery, equipment, and personnel. The approach demonstrates a high level of robustness in handling uncertainties and variations in the remanufacturing process.

By incorporating stochastic elements, it can accommodate fluctuations in demand, supply, and other factors that affect scheduling decisions. This adaptability ensures that the proposed approach can be applied in dynamic and real-world remanufacturing environments.

In addition to the computational experiments, the dissertation presents case studies conducted in real remanufacturing plants. These case studies serve as practical validations of the proposed approach.

The proposed approach precisely captures and models uncertainties, allowing for an accurate estimation of the distribution of the objective function. It effectively addresses scheduling challenges that arise from various uncertainties.

By devising robust schedules, the approach supports the trade-off between pursuing production performance and mitigating risks associated with uncertainty. It specifically aims to minimize the value-at-risk of the makespan. The proposed approach offers higher accuracy in estimating the selected risk measures, providing managers with reliable information to make informed decisions. It has been integrated into a scheduling software and extensively tested using historical data from our industrial collaborator. The results of the testing demonstrate an average improvement of 8-10% in completion time, showcasing its effectiveness in meeting deadlines and enhancing overall service levels in the remanufacturing of gas turbine blades. Therefore, these findings provide promising solutions for the challenges faced in the remanufacturing process, enabling manufacturers to meet deadlines and improve overall service levels.

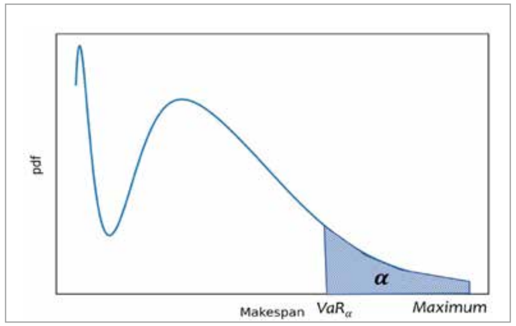

Fig. 1 - Value-at-risk of the makespan in scheduling problems

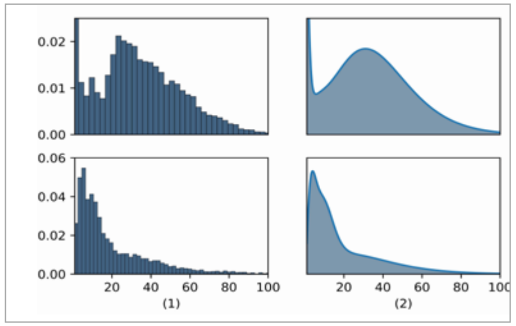

Fig. 2 - Phase-type distribution fitted real processing time distributions

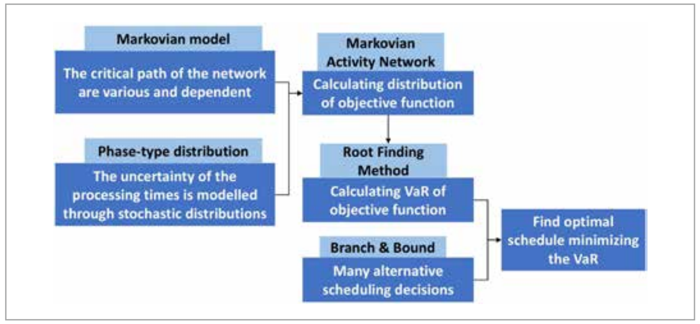

Fig. 3 - The solution framework for the stochastic scheduling

REINFORCEMENT LEARNING FOR ENERGY-EFFICIENT CONTROL OF PRODUCTION SYSTEMS

Alberto Loffredo - Supervisor: Prof. Andrea Matta

Nowadays, energy efficiency has become a critical issue in industry, with rising energy costs, environmental concerns, and stricter regulations. In particular, manufacturing accounts for a considerable portion of global energy consumption, and reducing energy usage in this sector can improve production systems sustainability. In this context, energy-efficient control (EEC) of manufacturing equipment has emerged as a promising solution. EEC aims to minimize the energy consumption while maintaining production targets. However, traditional EEC methods face several barriers and limitations, including the stochasticity of manufacturing systems, the limited control actions available, and the unknown system dynamics.
Recent research has demonstrated the applicability and potential of Reinforcement Learning (RL) to successfully control production systems. RL is a type of Machine Learning that enables agents to learn from their environment by interacting with it, providing an alternative method to handle incomplete or uncertain information. RL algorithms are indeed adaptive, designed to deal with the system dynamics during the learning process and to adjust their strategies accordingly over time. RL adaptability and effectiveness in addressing control problems that entail high levels of stochasticity make it a suitable candidate for effectively applying EEC policies to manufacturing equipment.
The research goal of this thesis is to develop novel RL-based models that overcome the actual EEC barriers and are capable of dealing with the EEC task for one, more or all the machines in a manufacturing line. The system of interest are workstations composed of several machines in parallel, a widely used layout to obtain a balanced production system in terms of workstations workload. Despite their widespread use and high energy consumption, there is a lack of research that focuses on the potential for energy savings for this system type. Additionally, there has been no exploration in literature of the potential for RL to apply EEC in manufacturing.
The proposed and innovative RL-based models apply EEC to single parallel machine workstations and multi-stage production lines with parallel machine workstations. These models are adaptive and general, enabling them to identify suitable EEC policies for various performance indicators while maintaining production constraints. Numerical results confirm model benefits when applied to a real line from the automotive sector. Further experiments confirm effectiveness and generality of the approach. The results of this research will contribute to the development of more efficient and sustainable production systems, enabling manufacturers to reduce their energy consumption and increase their competitiveness.

DEVELOPMENT OF ADVANCED COMPUTATIONAL METHODS FOR STRUCTURAL INTEGRITY ANALYSIS: INTEGRATING HIGH-FIDELITY MODELS AND DEEP LEARNING TECHNIQUES

Luca Lomazzi - Supervisor: Prof. Andrea Manes

Co-Supervisor: Prof. Francesco Cadini

Designing structures that can withstand blast loading requires a thorough examination of both traditional materials under extreme loading conditions and the potential benefits of newer, stronger, and lighter materials. To accomplish this, accurate and efficient predictive methods are essential for evaluating and developing solutions that can improve the structural performance. While traditional analytical and empirical methods are still used for initial assessments, the need for precise evaluations of complex materials and scenarios has led to an increased use of numerical simulations. These simulations have become more advanced over time, allowing for the accurate description of the dynamics of blast loaded structures, including the effects of fluid-structure interaction (FSI) and nonlinear behavior due to material nonlinearities, albeit at the cost of computational efficiency. Moreover, studying structures subjected to extreme loading conditions also requires characterizing structural damage, which can compromise structural safety. As such, the ability to diagnose damage is crucial in ensuring the safety of critical infrastructure, as targeted maintenance can be performed as soon as any anomalies are detected and identified. Recently, numerical simulations have been used to generate high-fidelity data of structural dynamics with and without damage. Deep learning (DL) methods have been trained on these data, leading to the development of frameworks that overcome the limitations of traditional damage diagnosis approaches. However, despite the good performance, these DL methods require a large amount of data for training, and numerical simulations may not be computationally efficient enough to generate the large and detailed datasets needed.

In this context, this PhD work had the following objectives: (i) to investigated high-fidelity numerical simulations of blast loaded structures, (ii) to improve our understanding of FSI effects on blast loaded structures, (iii) to develop DL-based fast running engineering tools for improving the description of blast loaded structures, especially when lightweight solutions are considered, and (iv) to develop DL-based structural health monitoring frameworks.

Analytical predictive methods and high-fidelity numerical simulations of blast-loaded structures were leveraged to give guidelines on the selection of the most efficient approach for simulating such extreme scenarios, depending on the blast and structural properties. Moreover, a regression law for predicting the permanent transverse deflection of flat quadrangular metal plates subjected to blast loading when the hemispherical detonation of carpet-like charges is considered was proposed. Validated numerical simulations were also employed to study complex phenomena that arise when composite materials under blast loading are considered. This allowed identifying FSI effects in composite structures in conditions where metal plates do not experience such effects.

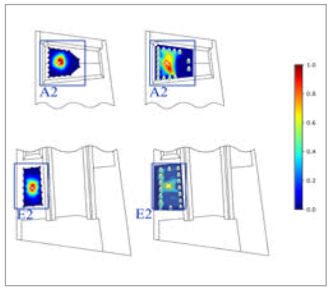

Fig. 1 - Damage probability maps of a full-scale composite wingbox. Left: unsupervised learning method - right: traditional tomographic algorithm.

With regard to damage diagnosis, a robust probabilistic indicator based on the combination of autoencoders and particle filter was proposed. The tool allowed performing damage diagnosis of a system under varying temperature conditions. Later, the research was more focused on plated structures. In this context, convolutional neural networks (CNNs) were shown to outperform other machine learning methods, such as feed-forward neural networks and regression trees, in terms of damage characterization in plated structures through Lamb waves. As a result of the analysis, a CNN-based framework for damage diagnosis was developed. The framework brought evidence that damage localization and quantification can successfully be performed through regression methods. Furthermore, the layer-wise relevance propagation explainability algorithm was used to make the CNNs of the supervised learning framework transparent and interpretable. The explainability algorithm brought evidence that CNN-based structural health monitoring approaches do not merely overfit the signal noise. The approach was then improved by replacing the supervised learning algorithms with unsupervised tools. That is, an unsupervised learning framework combining convolutional autoencoders and an in-house tomographic algorithm based on Gaussian distributions was proposed. It successfully localized damage in metal and composite plate-like structures, as shown in Figure 1 for a full-scale composite wingbox.

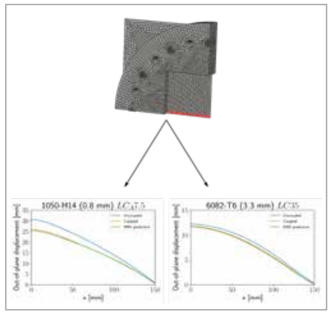

Fig. 2 - Prediction of FSI effects on blast loaded plates using the DL-based framework algorithm.

Furthermore, the expertise in high-fidelity numerical simulations and DL was leveraged to study complex phenomena characterizing the blast response of lightweight structures. That is, numerical simulations of blast loaded plates in the SIMLab shock tube facility were performed. The results were processed to train feed-forward deep neural networks that can indicate and predict FSI effects in uncoupled simulations, starting from the results of costly coupled simulations. Representative results are shown in Figure 2. Evidence was brought that the neural networks can predict FSI effects on metal plates with material, thickness and loading condition different from those seen during training. Also, mass-per-unit-area was identified as one of the parameters that play a role in determining FSI effects, along with the peak overpressure exerted on the structure, and the deflection velocity.

Future work will be focused on the investigation of physics-informed machine learning and graph neural networks to (i) generate parametrized surrogate models of costly numerical simulations, and (ii) perform high-quality full-field reconstruction of physical quantities of interest, such as full-field surface pressures on plate-like structures. Particularly, it is believed that physics-based deep neural networks can be successfully employed to quantify dynamic surface pressures and the influence of FSI effects during extreme dynamics. This will allow bridging the gap between simulations and experimental measurements in extreme loading events.

DEVELOPMENT OF THE LASER METAL DEPOSITION PROCESS FOR THE EFFICIENT PRODUCTION OF LARGE COMPONENTS FOR THE OIL & GAS SECTOR

Simone Maffia - Supervisor: Prof. Barbara Previtali

Co-Supervisor: Prof. Valentina Furlan

Production of large gas turbine components requires a delicate balance of innovation and optimization in the domain of advanced manufacturing engineering. Nowadays, these components are mainly realized by forging, for the superior mechanical properties this technology provides. However, the mold reliance and the large material waste typical of the forging process is driving the search for alternative techniques. In the pursuit of sustainability, a new manufacturing technology has emerged: Laser Metal Deposition (LMD). This Additive Manufacturing (AM) technique, offering freedom in design, reduced material waste, and environmental sustainability, holds the promise of reshaping the industry. This dissertation takes a multidimensional approach to investigating the potential of LMD as a manufacturing catalyst for turbomachinery components. The research encompasses three interconnected themes, delving into optimizing the Conventional LMD (C-LMD) process, advancing monitoring capabilities, and comparing motion systems.

The first theme delves into optimizing the C-LMD process for Inconel 718, with a focus on productivity and efficiency enhancements. Through experimentation and innovative data recovery methods, the research refines the process to meet industry demands, reaching deposition rates of 1.5 kg/h and efficiency of 70%. The second theme introduces a novel coaxial multi-sensor monitoring system that provides real-time insights on the height, area, and temperature of the molten pool. This approach allows defect prevention and enhanced comprehensive process control. Finally, a critical juncture in the dissertation lies in the comparison between articulated robots and CNC gantry machines for LMD. By analyzing their performance in fabricating large axisymmetric components, the research sheds light on the interplay between flexibility and accuracy.

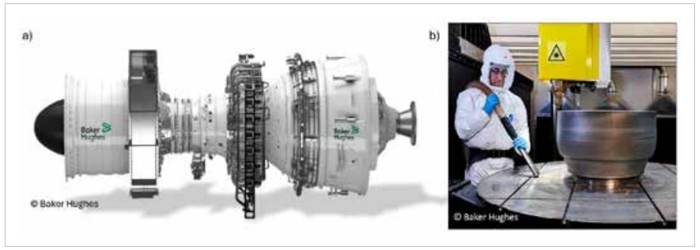

Fig. 1 - a) a gas turbine; b) a component of a gas turbine realized with LMD

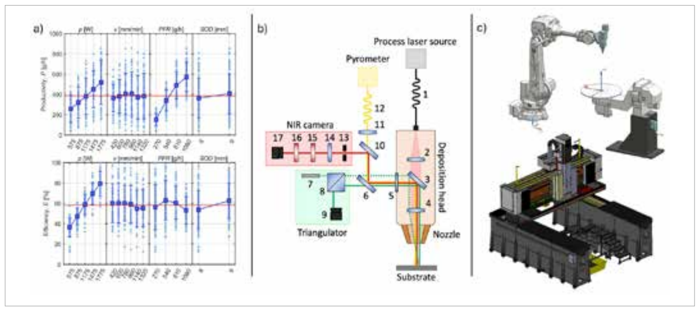

Fig. 2 -a) graphs representing the influence of the process parameters on the deposition performance; b) the coaxial multi-sensor monitoring setup; c) the two LMD machines compared under the geometrical accuracz point of view.

Thanks to this approach, the lead time for large turbomachinery components is expected to be reduced from five months to six weeks, complemented by cost reduction and material savings of up to 30% and 50%, respectively. Ultimately, this dissertation outlines a roadmap for future LMD research, envisioning a path toward continued process refinement, advanced monitoring and control systems, diversified applications, and seamless integration into industrial settings. This research serves as a comprehensive guide to unlock the full potential of LMD, poised to transcend from a promising technology to a transformative force in the manufacturing world.

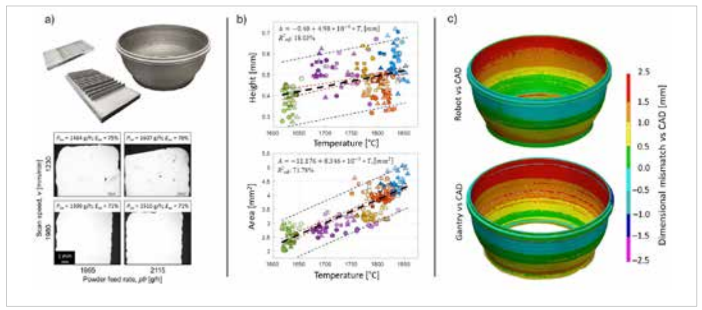

Fig. 3 - a) pictures f the realized specimens and of their cross-sections; b) correlations between monitored variables; c) 3D scans of the two gas turbines components realized on the two LMD machines.

3D-BASED VISION MEASUREMENTS IN DYNAMIC ENVIRONMENTS: DEFECT AND VIBRATION MEASUREMENT FOR GLOBAL AND LOCAL DAMAGE IDENTIFICATION

Daniele Marchisotti - Supervisor: Prof. Emanuele Zappa

Structural health monitoring (SHM) is essential to evaluate possible changes on a structure response to the external ambient and also to schedule periodical maintenance interventions and inspections. However, the monitoring is strongly based on qualified personnel inspections or on the measurements with sensors directly applied on the structure. This approach involves large efforts to place sensors over structures with corresponding data acquisition systems. At the same time, the equipment for measurements for long-term monitoring can be expensive, while visual inspections of qualified personnel could not be always reliable. For this reason, the application of non-contact measurement techniques can largely improve SHM since they do not need to be placed directly on a structure and they can be used for more than one structure. Moreover, the diffusion of more and more reliable Unmanned Aerial Vehicles (UAVs) allows to perform measurements close to a structure and to move the measurement system along the structure for multiple inspections.
In this research, the application of combined vision-based measurement devices on UAVs was investigated to obtain more reliable measurements of defects in concrete structures or to obtain vibration measurements. Therefore, the focus of this research work was oriented mainly to two different strategies: (i) local damage identification, to provide more accurate 3D shapes of local damages and (ii) global damage identification, to identify possible changes in modal parameters.
The first part was tackled by using 3D reconstruction and Simultaneous Localisation and Mapping (SLAM) algorithms, starting from point cloud sensors acquisitions. On the other hand, the concept behind global damage identification is modal analysis, to monitor resonance frequencies, mode shapes and other modal parameters, e.g. damping. In this research, it was demonstrated that modal analysis can be obtained from tracking of features on images taken from UAVs. In this case, the main issues are to convert vibrations measured from cameras from pixels to millimetres and to compensate the motion of the drone. Indeed, since the measurement system is placed on a UAV, which is a moving reference system, the drone vibrations could impact of the vibration measure. For this reason, the main challenge is to track the position and orientation angles of the drone to remove the drone motion component from vibration measurements.
The 3D reconstruction was obtained with SLAM, for 3D defects evaluation. Algorithms used for this purpose are SLAM, Visual Odometry and Loop Closure algorithms, with the possibility to add the information acquired from other onboard sensors, as IMU and GPS.
An analysis of available drone components and characteristics was investigated. The main characteristics of the drone prototype are (i) a payload (3D cameras and acquisition system) of 2~3kg, (ii) an estimated autonomy of about 15 min with 2kg of payload and (iii) the possibility to acquire data from onboard sensors, as IMU and GPS. The autonomy was greatly improved by adding a tethering cable, to power the drone from ground.
The SLAM and 3D reconstruction algorithms were chosen among the open-source ones, to maintain our system low-cost. The output of these algorithms are a 3D map and a sensor trajectory. The input can be RGB and depth frames or only depth frames and in some cases also IMU and GPS data. All data acquired need to be synchronized and referred to the same reference system.
Regarding the choice of SLAM and 3D reconstruction algorithms, an emerging one is the Open3D reconstruction system, that has a particular focus on obtaining the best results for 3D map. For testing these algorithms, a 3D acquisition simulator has been developed. This simulator allows to sample a dense 3D coloured point cloud, in order to generate the acquisition of a 3D camera.
Then, drone tests referred to the acquisition of artificially-created concrete defects are presented. The RMS of the distance between the ground truth and the 3D reconstruction obtained from the sensors is similar between outdoor and indoor tests. On the other hand, results about the standard deviation of raw scans, have larger uncertainty, as expected, due to sunlight disturbance.
On the other hand, for measurements of real defects on a building, 7 defects were detected on the B16A building and a comparison between the 3D reconstruction obtained with FARO Freestyle 2 (ground truth) and the one obtained with the drone and the sensors under evaluation.
For global damage identification, the first objective of the procedure is to accurately measure the natural frequencies of the structure. The error in terms of frequencies with respect to the accelerometers is at most 0.2% for the flying camera. The results were obtained both in laboratory with the drone measurement system moved by hand to simulate a drone acquisition and outdoors with the drone prototype. The outcome of this research part is shown in order to highlight the innovative improvements of vibration measurement with drones:

1) the compensation of the drone vibrations to reduce the impact of the drone on vibration measurement;
2) modal analysis from drones;
3) 3D geometry reconstruction of the structure to be used for modal analysis.

The structure under investigation has 6 resonance frequencies. The latter frequency is affected by noise for the case of drone test and, therefore, the mode shape at that specific frequency could not be reliably reconstructed. This is probably caused by the drone air flow affecting the structure vibrations and also disturbing the fixed camera.
Regarding the compensation of drone vibrations, the presence of the VIO sensor allows to track the trajectory of the drone. This information could be useful to the purposes of this research to remove the effect of the drone motion from vibration measurements. For both laboratory and drone tests, it can be clearly observed a reduction of amplitude related to noise, with consequent ability to better detect resonance frequencies, especially the ones at lower frequencies.
The modal analysis results were obtained with LMS Test.Lab software. Frequencies measured by accelerometers and camera are very close, since the difference is on average of 0.28 % and 0.23 % of frequencies measured with accelerometers (corresponding to 0.018 and 0.033 Hz). On the other hand, the comparison of mode shapes has been handled with the Modal Assurance Criterion (MAC). By looking at the data, it is possible to conclude that all modes detected by cameras can be correctly reconducted to the correct vibration modes. This confirms that is possible to retrieve the correct mode shapes from the proposed method.

Fig. 1 - The drone prototype during data acquisition

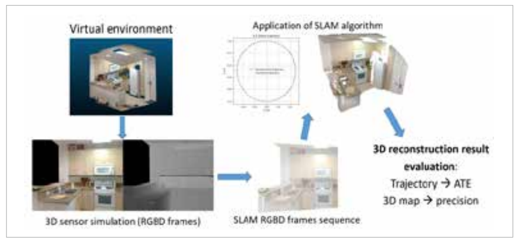

Fig. 2 - A scheme of the testing procedure of SLAM algorithms with the simulator

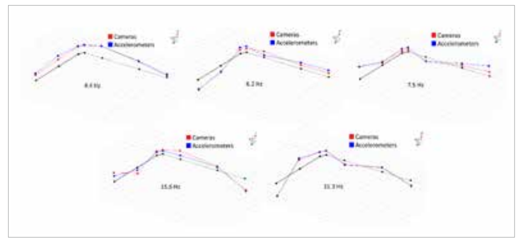

Fig. 3 - Mode shapes from mode 1 to 5 measured by cameras and accelerometers for drone tests. The undeformed geometry is given in black in the graphs.

MODELLING AND EXPERIMENTS ON THE EFFECTS OF FOOT-TRANSMITTED VIBRATION WHILE WALKING

Stefano Marelli - Supervisor: Prof. Marco Tarabini

Foot transimitted vibration (FTV) refers to the mechanical stimulus transmitted to the human body as a whole through the supporting surface. FTV has been recently classified as a separate cathegory from Whole-Body vibration (WBV), that is the vibration transmitted to the subject through the seat. FTV and WBV have both been associated with health risks, including fatigue, discomfort, and an increased risk of injury or aggravation of existing conditions such as herniated discs or cardiovascular disease. This work focused on the development of a walking humanoid model to predict the effects of FTV on balance and fall probability. The model benefits from a realistic real-time physical simulation and a direct dynamics approach and is derived from 3D models available in the literature to generate a human-like gait. It has 23 degrees of freedom, which are controlled by proportional and derivative controllers and muscle-tendon units (MTUs). There are 8 MTUs to control sagittal motion for each leg. The control parameters of the PD controllers and the MTUs are optimised thanks to a genetic algorithm called Covariance Matrix Adaptation Evolutionary Strategy (CMAES). The controller has been optimised in the case of sinusoidal roll WBV with 4° amplitude and 0.25-1 Hz frequencies. In the second part of the work, 40 healthy subjects were exposed to 71 different vibration conditions, including sinusoidal and random stimuli with roll, pitch and vertical motion. Participants were exposed to vibration frequency between 0.25 and 1 Hz; the vibration amplitude was between 4° and 8° for roll and pitch, and 4 cm and 8 cm for vertical motion. The main result is that sinusoidal roll motion at 1 Hz and 8° significantly increased step width and step frequency and decreased step stance and step length in up to 40% of subjects. The experimental gait metrics during roll FTV were compared with the corresponding numerical simulations obtained with the model developed in the first part, showing similar adaptation patterns to vibration. Finally, we investigated the effect of FTV on cognitive performance with two sets of experiments. In the first, we studied the effect of vibration along different axes on the response time (RT) of 25 standing subjects during a customised psychomotor vigilance task (PVT). A second series of experiments focused on analysing the effects of medio-lateral vibration on the RT of 20 walking subjects. The 10% increase in mean RT during walking exposed to WBV, compared to baseline, suggests that the cognitive reaction is delayed due to: additional musculoskeletal recruitment, head motion due to the presence of WBV and increased attention to peripheral cues to maintain the balance. However, walking with WBV doesn't necessarily reduce vigilance compared to walking without WBV or standing with WBV.

Keywords: whole-body vibration; walking; gait metrics; physics-based humanoid, cognitive performance, PVT, standing.

TRIBOLOGY OF ENERGY SAVING OILS

Davide Massocchi - Supervisor: Prof. Paolo Emilio Lino Maria Pennacchi

Tribology has changed from the Jost report (1966) to today. While in the past it was related to the concept of reliability and the idea was to reduce breakdowns and maintenance shutdowns, today tribology is more related to two themes: efficiency and environmental impact. Holmberg's work estimates that tribology is responsible for 23 % of global energy consumption, and many efforts are still being made by researchers and developers around the world to reduce the carbon footprint associated with this science. Especially in some applications (mining, drilling, paper industry, rolling mills) a small increase in the overall efficiency of machinery can be beneficial in terms of energy consumption and CO2 emissions. As far as efficiency is concerned, the trend among machinery manufacturers is the downsizing of components (same load for a smaller contact area or higher load for the same contact area) and low viscosity or energy-saving oils. As far as environmental impact is concerned, a major challenge for lubricant manufacturers is to try to replace some sulphur and phosphorous containing additives to meet exhaust emission standards. Tribological applications are very diverse in terms of mechanical and environmental requirements, which is why specific materials have been developed. As far as linings for fluid-film bearings are concerned, the conventional white metal, also called Babbitt for its inventor, for very demanding applications has started to be replaced by polymer-based materials such as PTFE and PEEK. These materials are self-lubricating and have very high mechanical properties, suitable for aerospace, medical and automotive applications. In this context, the PhD research project has the ambition to develop innovative and smart tools/procedures for lubricant manufacturers to formulate energy-saving oils and evaluate their compatibility/synergy effect with new coating materials.

Results:

1) New coating PEEK-based has been studied in three lubrication regime.

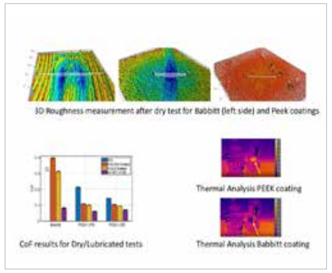

Fig. 1 - PEEK coating in dry, grease and oil lubrication & Thermal analysis of dry tests.

2)New methodology: Scale down from a rig test to a lab test.

Fig. 2 - FZG bench test VS SRV lab test

A HYBRID METHOD COMBINING ANALYTICAL AND SIMULATION MODELS FOR PERFORMANCE EVALUATION OF LARGE MANUFACTURING SYSTEMS

Matteo Mastrangelo - Supervisor: Prof. Tullio Antonio Maria Tolio

The current industrial context is highly dynamic, with frequent variations in product portfolios and rapidly increasing customer demands. To thrive in this environment, manufacturing companies must continuously adapt their systems through frequent reconfigurations. In order to support performance evaluation and continuous improvement, modeling of manufacturing systems has emerged as a common practice, facilitated by the development of digital solutions. As a result, many different models are often present in modern manufacturing systems, but their integration remains challenging.

This doctoral thesis addresses the issue of model integration by proposing a hybrid method that combines models of different sub-systems, independently developed with analytical or simulation approaches, into a unified system modeling architecture. The method provides steady-state performance evaluation to support long-term configuration management of evolving systems.

The proposed method is based on a decomposition approach, implemented through the formalization of general interfaces that rely on the state-based representation of material inflow and outflow dynamics at the borders of the various sub-systems.

Integrating diverse models into a cohesive framework, the method offers a comprehensive evaluation of system performance, considering the interdependencies between sub-systems.

Numerical evaluations demonstrate the accuracy of the proposed method compared to more commonly employed tools, such as discrete event simulation. Analysis of the solution algorithm reveals its robustness to the propagation of uncertainty deriving from the presence of simulation models in the algorithm itself and characterizes the variability of output performance indicators.

The method is applied to the reconfiguration analysis of a manufacturing systems for electrical distribution equipment. Specifically, it is adopted to evaluate the impact on system performance of major and minor reconfiguration actions, in presence of increasing customer demand, proving the utility of the approach in real industrial contexts.

A VOXELIZATION AND ONTOLOGY-BASED APPROACH FOR PRINTING HETEROGENEOUS OBJECTS

Riccardo Pigazzi - Supervisor: Prof. Giorgio Colombo

Unlike traditional engineering parts made from uniform materials, Heterogeneous Objects (HOs) are specifically designed with spatial variation in material composition or structure to exhibit a corresponding variation in mechanical and/or thermal properties, tailored to meet specific requirements. HOs include multi-material objects where the transition between different materials is continuous, referred to as Functionally Graded Materials (FGM) objects, which are particularly challenging because they require precise control of material composition at a very fine scale. The goal in fabricating FGM objects is to exploit the properties of different materials in different regions of the object while mitigating potential incompatibility issues at material interfaces through gradual material variation.
Among the various manufacturing methods available, Additive Manufacturing (AM) has emerged as the most promising technology to realize HOs, as it enables the fabrication of complex-shaped objects with precise local control over material composition.
This study focuses on Polyjet, a cutting-edge material jetting technology known for its ability to create complex objects with varying material properties and colors. Like inkjet printing, it works by depositing droplets of photo-polymeric materials layer by layer onto a build platform, which are then solidified using ultraviolet light. The materials can be deposited in the voxels (volumetric pixels) of a 3D regular grid that partitions the building volume.
A single type of material can be jetted into each voxel, but different types of materials can be used for different voxels. Multi-material Polyjet printers offer a voxel printing modality that involves importing a stack of bitmap images, each representing a slice of the object, with pixels containing information about the location and the materials of the voxels in that slice. By controlling the material assigned to individual voxels, it is possibile to create HOs objects with nearly continuous variation of properties, such as stiffness, across different regions of the object.
Despite the potential of HOs, their adoption in industry remains limited, primarily due to the lack of a well-defined workflow for their fabrication and a scarcity of readily accessible software tools for their design. Additionally, the information required to effectively design and manufacture HOs is scarce, scattered, and unstructured. To address these critical gaps, this research develops a methodology and software tools to support the design and production of HOs using multi-material voxel printing.
The methodology encompasses a digital workflow that spans from the geometric model of the object to the generation of printing instructions. Furthermore, an ontology is employed to establish a conceptual framework for the domain, which serves to organize and access relevant information throughout the various stages of the workflow. The phases of the workflow are: Voxelization, Material Assignment, Material Dithering, and Bitmap Generation (Figure 1).
Voxelization involves determining which voxels from a regular grid surrounding the object are either internal or external to the object. Unlike traditional voxelization algorithms, which operate on triangular meshes, this work proposes direct voxelization of the Boundary Representation (B-Rep) model underlying CAD system, using the methods exposed by the software API, with the aim of reducing inaccuracies and preserving geometric and topological information of the original model, which is useful in the subsequent material assignment phase. Several algorithms, based on different principles, are implemented and compared in terms of time efficiency across varying voxels size. Additionally, a benchmark with a state-of-the-art algorithm designed for triangular meshes is included. The results demonstrate the feasibility of voxelizing a B-Rep model directly within the CAD system. In the material assignment phase, each internal voxel is assigned a specific material, which, with the proposed assignment methods, is generally a mixture of the printer's primary materials. Specifically, the material distribution is defined by specifying the material composition (i.e., the mixture of primary materials) at each internal voxel as a function of a parameter previously calculated in the voxel, which depends on the methods adopted. In the first method, the parameter is the distance of the voxel from a B-Rep entity (e.g., face, edge, vertex) or a reference geometry (e.g., plane, line, point). In the second case, the parameter is a numerical simulation result mapped to the voxel. Since 3D printers cannot mix primary materials within a voxel, material dithering is used to convert the resulting material blend into one of the primary materials. For this phase, well-known image processing algorithms, such as Floyd-Steinberg dithering, are used. Finally, for each layer of the grid, a bitmap image is generated by matching each pixel to a voxel and assigning the pixel a color that identifies the material of the voxel.
The developed ontology is based on the foundational ontology DOLCE, adapted to engineering applications by design patterns for clean ontological modeling of qualities and values in OWL, along with rules for reasoning about values and value ranges. DOLCE is then enriched with knowledge relevant to voxel printing domain, including classes and relations pertaining to products, printers, CAD parts, their features and qualities, as well as printer and material specifications (Figure 2).
To validate the proposed methodology, two case studies are conducted, corresponding to the two methods for material assignment. The first consists of a specimen with a gradual material variation between two opposite faces. The second is a prosthetic socket for transfemoral amputees, where material distribution was defined based on contact pressure derived from FEM (Figure 3).

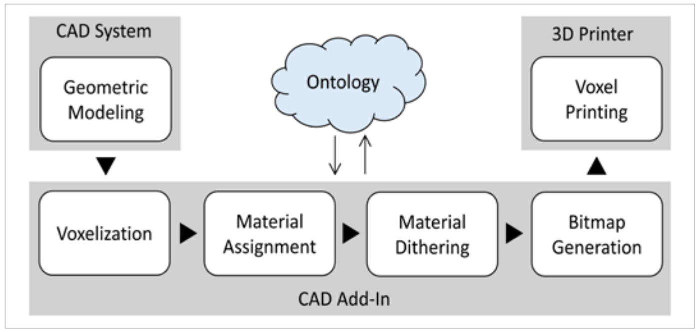

Fig. 1 - Workflow for voxel printing of heterogeneous objects. The object's geometry is voxelized and the internal voxels are assigned a material, usually a mixture of the printer's primary materials. Material dithering converts this mixture into one primary material, and the results are encoded into bitmap images for the printer.

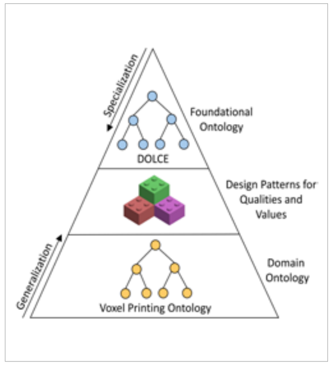

Fig. 2 - Ontology-based information management. Building upon the foundational ontology DOLCE, design patterns for representing engineering quality and values in OWL are developed. DOLCE is then specialized with voxel printing domain knowledge.

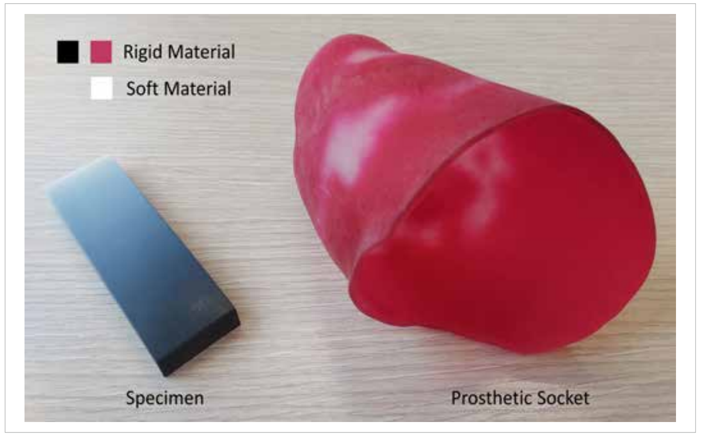

Fig. 3- A specimen (left) and a prosthetic socket (right), both with variable stiffness, printed using voxel printing technology. The black and magenta materials are rigid, while the white material is soft. Both objects exhibit a gradual transition between materials, controlled at the voxel level.

INFLUENCE OF HEAT TREATMENT ON METALLURGICAL CHARACTERISTICS OF IN625

Luís Henrique Pizetta Zordão - Supervisor: Prof. Barbara Rivolta

The nickel super alloy 625 is commonly used in structures on solid solution state but has its applicability widespread in aeronautic, aerospace, marine, chemical and petrochemical industries when improvement on mechanical resistance increased by age-hardening treatments are performed. In this study the grain growth, precipitation and phase transformation was evaluated in a commercial superalloy 625. Grain growth at 980 °C, 1038 °C, 1100°C and
1150 °C and the correspondent phase transformation was evaluated during the solubilization times of 0, 30, 60, 180 and 360 minutes. A comparison between single aging at 621 °C, 732 °C and 855 °C and the double aging heat treatments combination at 621 °C and 732 °C was investigated by SEM, hardness test and tensile tests. As a consequence of heat treatment in nickel alloys the high temperature can influences negatively reducing the corrosion resistance, an important characteristic for this group of alloy that was evaluated according the ASTM G28 method A.
Alloy 625 is classified as nickel based superalloy able to provide high strength, corrosion resistance with good fabricability and weldability. Due to the presence of different chemical elements the alloy tends to form a combination of microstructure and precipitates during its manufacturing and post heat treatments. Some of the phases present in the microstructure can be obtained from isothermal aging, as can be seen on the TTT diagram, Figure 1.

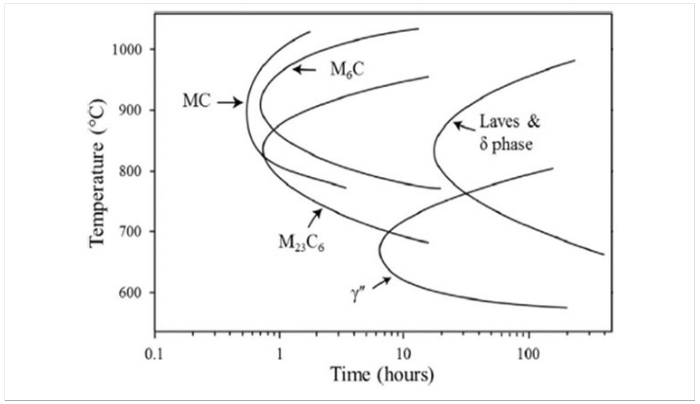

Fig. 1 - Schematic Time-Temperature-Transformation (TTT) diagram.

The 625 alloy is designed to be applicable in the solid solution state. Indeed, it also have been applied in an aged condition by the precipitation of intermetallic phases and carbides, usually in the range between 550 °C – 750 °C (823 – 1023 K), based on the TTT curves available on the literature (Figure 1). Precipitation hardening in this alloy at elevated temperatures (823 - 923 K) is mainly derived from the metastable phase γ″ [Ni_3(Nb,Al,Ti)] into δ-phase [Ni_3(Nb,Mo)] upon prolonged aging or from direct heating of the supersaturate solid solution at high aging temperatures. Carbides can be present as undissolved during annealing or decomposed if prolonged exposure at elevated temperatures. As indicated on Figure 1, a number of different carbides and intermetallic phases can precipitate in IN625 alloy after isothermal exposures, for times on the order 0,1 to up to 100 hours.
The combined heat treatment of solubilization and aging process were performed on the samples to study grain growth and hardening respectively, the temperatures and time applied during the solubilization process are present on Table 1.
The temperatures selected to perform the aging process were studied based on the possibility to evaluate different combinations of microstructure according to Figure 1.

TEMPERATURE [°C]	TIME [H]
980	0.5; 1; 3; 6
1038	0.5; 1
1100	0.5; 1; 3; 6
1150	0.5; 1; 3; 6

Tab. 1 - Temperature and time adopted for solubilization process.

The isothermal grain-coarsening behavior shows that high-temperature exposures affect the grain size depending on the soaking temperature and time. The Arrhenius type constitutive equation shows a good agreement in describing the grain-coarsening behavior of this alloy. The grain-coarsening process exhibits a more pronounced growth with increasing temperature; however, the grain-coarsening rate is progressively reduced over time at a given temperature as the grain size approaches the related steady-state value.
The experimental results support the loss of mechanical strength with increasing grain size due to a decrease in grain-boundary density. Hardness, yield strength, and ultimate tensile strength decrease as grain size increases.
The samples response to the hardness test after single aging showed a higher hardness values for the cases where the same isothermal aging temperature was adopted and the solubilizing temperature were lower, demonstrating the initial grain size impact on the test. Besides, considering the same solubilizing temperature, the differences on the hardness response during single aging demonstrate an increase as the isothermal treatment proceeds and the second phases were been developed.
Grain boundaries, investigated by SEM analysis, represent the preferential precipitation sites for secondary carbides, which are especially enriched in Cr and Mo, according to EDXS analyses.
Double aging treatments allow an appreciable improvement in mechanical strength, as demonstrated by Vickers hardness and tensile tests, with respect to the single-aging response. The hardening effect of the second aging step is more significant and it shows the highest response already after 3 h at 732 °C.
Grain boundary precipitation at 732 °C determines a detrimental reduction in the intergranular corrosion resistance due to precipitation of carbides formation. Instead, single aging treatment until 72 h at 621 °C does not significantly affect corrosion rates.
The inverted double aging (621 °C + 732 °C) was not able to change the preferable location for carbides precipitation. The SEM images with the EDXS results showed a thin dispersion of γ″ within the matrix and carbides on grain boundaries.
The industrial heat-treating cycle duration ensures adequate solubilization time and temperature. Moreover, water cooling is quick enough to prevent formation of secondary phases throughout the entire section till a maximum diameter of approximately 450 mm, according to the thermal analysis. For these reasons, it can be said that thermo-metallurgical modeling is a crucial instrument for evaluating heat treatment cycles, saving materials and energy.

HEAT TREATMENT	YS [MPA]	% INCREASE	UTS [MPA]	% INCREASE
1038 °C – 30 min	351,5		817,7	
+732 °C 3h + 621 °C 8 h	411,5	17,1%	864	5,7%
+732 °C 3h + 621 °C 24 h	561,3	59,7%	971,1	18,8%
+732 °C 3h + 621 °C 72 h	621,7	76,9%	1027,8	25,7%
+732 °C 16h + 621 °C 8 h	421,85	20,0%	866,1	5,9%
+732 °C 16h + 621 °C 24 h	571	62,4%	991,6	21,3%
+732 °C 16h + 621 °C 72 h	646,3	83,9%	1047,8	28,1%
+732 °C 48h + 621 °C 8 h	446,6	27,1%	893	9,2%
+732 °C 48h + 621 °C 24 h	580,7	65,2%	991,4	21,2%
+732 °C 48h + 621 °C 72 h	633,6	80,3%	1043,7	27,6%

Tab. 2 - Tensile test results after double aging process.

ALIGNMENT AND INTEGRATION OF LARGE OPTICAL SYSTEMS BASED ON ADVANCED METROLOGY

Edoardo Maria Alberto Redaelli - Supervisor: Prof. Bortolino Saggin
Co-Supervisor: Prof. Marco Tarabini

The alignment of optical systems is a crucial aspect to be considered in the design phase of astronomical instruments. As the size of telescopes and the related instruments is increasing, also the needs to have flexible measuring tools is developing in parallel to satisfy the scientific requirements. The development of the alignment techniques for small instruments is well validated throughout the history of the Optomechanical and astronomical instrumentation, nevertheless those techniques cannot be applied on large ones. This thesis proposes a procedure that allows to evaluate the position of optical elements in large volume very precisely. This enables the achievement of the scientific goals by minimizing the alignment procedure duration the costs. In this work it is evaluated the possibility to use a laser tracker as essential embedded tool for the alignment and for the monitoring of the instrument. The case study presented here is MORFEO which is a first-light instrument for the European Extremely Large Telescope. The study consists in the realization of a software that optimizes the position of the tracker inside the instrument considering the nominal position of the targets measured (SMRs) and the possible vignetting based on the prediction of the accuracy and repeatability of the measurements. This analysis is made by steps: the first one considers the error model gave from the manufacture of the tracker. The second one is based on a series of tests and characterizations performed in laboratory to determine more accurately the performances. The results obtained have been validated using a dummy version of an optomechanical element measured by using a Coordinate Measurement Machine (CMM).

A COMBINED APPROACH OF IN SITU MONITORING AND POLYMER SYNTHESIS FOR 3D BIOPRINTING APPLICATIONS

Silvia Santoni - Supervisor: Prof. Bianca Maria Colosimo

Co-Supervisor: Prof. Davide Moscatelli (CMIC)

In the last years, research on 3D bioprinting has been gaining attention thanks to its potential for regenerative medicine and the production of biological models for high throughput studies.
By combining approaches of tissue engineering and additive manufacturing, this technique aims at replicating complex three-dimensional tissues and organs similar to the physiological ones by spatially depositing in a defined manner a bioink composed of cells and polymers in the hydrogel form. Despite the great potentialities, some technical challenges still need to be addressed. Among those, a crucial issue is to create a bioink formulation that can ensure replicability and reproducibility of the process, as well as good biocompatibility for cell encapsulation. Within this context, thermoresponsive polymers are being introduced for 4D bioprinting applications because of their advantages, such as physical crosslinking and the possibility of responding to external stimuli, as native tissues are capable of. Here a PEG-based formulation of a synthetic thermoresponsive bioink that shows high reproducibility and good control over the properties in the synthesis obtained via RAFT polymerization is presented, as well as good printability properties assessed through in situ imaging thanks to a sol/gel transition temperature adjusted to the environmental one. In addition, the thermoresponsive properties of this polymer enable cell retrieval after incubation.
At the same time, even though cells are a crucial component in 3D bioprinting, assessing their correct positioning within the constructs while printing is challenging due to their micrometric size and transparency. However, it is pivotal to understand whether the construct has a good chance of developing into a high-quality construct after incubation or if it is defective and should be discarded. In this work, fluorescent nanoparticles were synthesized and used to understand cell positioning within bioprinted constructs in different applications. On the one hand,they were used to label cells in a proof-of-concept system to monitor in-line cell distribution in extrusion-based 3D bioprinted construct. . On the other hand, they were used as part of an alternative cell viability assay and to discriminate between different cell types in multicellular bioprinting

A DECOMPOSITION METHOD FOR THE ANALYSIS OF GENERAL MANUFACTURING SYSTEMS

Salvatore Scrivano - Supervisor: Prof. Tullio Antonio Maria Tolio

In the rapidly evolving landscape of the manufacturing industry, there is a growing demand for fast and reliable methods to evaluate the performance of manufacturing systems. These methods play a critical role in both the configuration phase and the operative life of manufacturing systems, facilitating the assessment of potential improvement actions and aiding in the selection of optimal strategies. To address this need, this work presents a novel approximate analytical method for performance evaluation of general manufacturing systems. The proposed method is based on a two-level decomposition approach, effectively breaking down the original system into smaller subsystems, which can be analytically solved. The two levels of the decomposition approach are the machine and buffer levels, which respectively model the material flow in each machine and buffer of the system. This decomposition technique provides a general structure, enabling its application to manufacturing systems with specific layouts, material flows, and control policies. To validate the accuracy and versatility of the proposed method, three different manufacturing systems were subjected to analysis. The first was a closed-loop system, where the achievement of material flow conservation within the system was a noteworthy result, unprecedented in existing literature of analytical methods for closed-loops. The second system examined was a multi-product system employing the PHP control policy, while the third was a two-stage system featuring re-entrant flow of parts for double processing. The successful evaluation of these diverse systems showcased the effectiveness and generality of the proposed analytical approach.

FEASIBILITY ASSESSMENT OF A DEPLOYMENT MECHANISM FOR A SPACE TELESCOPE

Pietro Valnegri - Supervisor: Prof. Bortolino Saggin

Co-Supervisor: Prof. Diego Scaccabarozzi

The thesis discusses the feasibility of integrating deployable technology on a telescope to be installed on a satellite platform to perform Earth observations. The objective is to obtain a compact design compatible with the specifications from the platform and the usual profile loads. The advantage of such system is achieving a light and compact structure which could guarantee the needed stiffness during launch and proper positioning and stability during the operative phases. The mechanism has been selected among different viable deployable technologies selecting the most feasible depending on the parameters mostly affecting the telescope performances. A demonstrative breadboard has been assembled validating the models developed for the deployment procedures and verifying the achievement of the required relative positioning accuracy of the mirrors. Mechanical tests have been performed to identify the modes of vibration of the structure and assess the compliance of the mechanism to the qualification loads. Eventually, proposals for future applications of the development have also been identified.

Key-words: Space telescope, Deployable structure, Structural simulation, Dynamic simulation, Mechanical testing, System validation & verification, Structural optimization.

INVESTIGATION OF FAILURE IN FIBER-REINFORCED POLYMER AND APPLICATION TO HYBRID AND DOUBLE-DOUBLE COMPOSITES

Alessandro Vescovini - Supervisor: Prof. Andrea Manes

A composite material is a macroscopic combination of two or more distinct materials with a recognizable interface between them, utilized not only for structural purposes but also in electrical, thermal, and environmental applications. Composites are engineered to strike a balance in properties tailored to specific applications. Typically, composite materials comprise a continuous matrix binding together an array of reinforcing constituents, often resulting in improved properties through load-sharing mechanisms, particularly in structural applications. Composite structures are built from plies stacked with varying orientations, each exhibiting anisotropic mechanical behavior. Understanding the mechanical behavior and the damage mechanisms is essential for developing reliable design methods. Numerical frameworks complement experimental investigations, forming the foundation of engineering development in this field. Despite their attractiveness, composites face challenges, notably in toughness. Composite hybridization, combining different reinforcing phases, has attracted interest for enhancing toughness and reducing costs. Impact resistance, a critical loading scenario for composite materials, has prompted research into hybrid composites. In recent advancements, novel stacking sequences such as Double-Double (DD) and Single-Double (SD) offer simplified manufacturing processes and continuous variation of angle for stiffness and strength requirements. This innovation holds potential for weight reduction and relieving inter-laminar stresses without compromising strength. Fiber reinforced polymers find extensive use in aerospace applications, necessitating research into structural reliability under various loading scenarios such as buckling-induced damage and impacts.

To foster the adoption of composite materials, engineers investigate damage mechanisms and loading effects on composites to improve their damage-bearing capability. In this context, this PhD work had the following objectives: (i) to develop reliable numerical simulations for predicting the response of hybrid composite structures subjected to ballistic impact and determine the material hybridization effect, (ii) to explore the response of hybrid composites with different matrices to low-velocity impacts and understanding the effects of hybridization, (iii) to study the effect of adopting a Double-Double stacking sequence to composite structures, carrying out experimental tests and numerical simulations, and (iv) to simulate the behavior of composite materials subjected to blast loading.

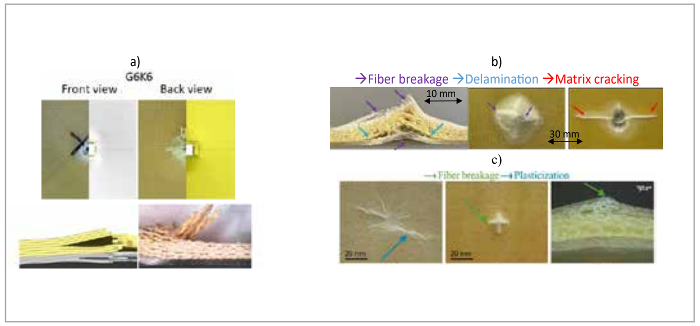

Fig. 1 -Front, back and section view of (a) epoxy based hybrid laminates perforated by ballistic impact, (b) epoxy and (c) polyurethane based hybrid laminates after low velocity impact.

In the research focused on exploring the damage and failure characteristics of glass-aramid hybrid composites under impact loading conditions, both numerical simulations and experimental investigations were conducted. The response to high and low-velocity impacts using thermoset epoxy and polyurethane matrices was investigated. A numerical framework was developed to analyze ballistic impacts on glass-aramid composite panels, effectively predicting inter- and intra-laminar damage and replicating material failure and hybridization effects. Results indicated that stiffer glass fabrics on the impact side and Kevlar on the rear side led to superior ballistic performance, dissipating energy through fiber breakage and strain energy absorption, respectively. Experimental low-velocity impact tests underscored the influence of hybridization, with higher aramid ratios resulting in increased displacement and reduced stiffness. Stacking sequence and symmetry played crucial roles, affecting damage morphology and energy absorption. Delamination was significant at fabric interfaces in hybrid coupons. The comparison between epoxy and polyurethane composites revealed similarities in damage mechanisms but notable differences in extent. Epoxy-based composites exhibited extensive fiber failure and matrix cracking, while polyurethane ones displayed significant plasticization and deformation, with minimal delamination. Polyurethane composites demonstrated greater energy absorption capabilities.
In the study investigating the post-buckling behavior and collapse of Double-Double carbon composite structures, six single-stringer specimens were manufactured using the card-sliding technique with non-crimp fabrics and a Double-Double stacking sequence. Compression loading induced buckling and failure, with focus on the novel stacking sequence and component design's impact. Experimental tests explored post-buckling behavior and collapse, validating numerical models. Some specimens featured tapered cross-sections. Post-buckling exhibited three half-waves under the hat and free edges, with failure primarily due to skin-stringer separation and subsequent collapse. Teflon inserts minimally influenced failure mode and load. FEM simulations demonstrated that hat tapering enhances damage tolerance pre-collapse. The study highlights potential advantages of Double-Double structures, suggesting reduced susceptibility to delamination and promoting intra-laminar failure in composite design.
Finally, a numerical framework for modeling composite materials under blast loading was presented. Two methods are discussed: an efficient uncoupled method for far-field explosions and a coupled method for fluid-structure interaction effects. These methods showcase potential benefits of innovative materials in blast scenarios.

Future work will focus on carrying out low-velocity impacts experimental campaigns on polyurethane and epoxy-based composites with unified testing methods and implementing a validated modeling method to investigate polyurethane based composites. In addition, co-cured structures with Double-Double stacking sequence will be investigated to fully highlight the advantages of adopting DD stacking sequence, and low velocity impact and compression after impact tests will be performed to assess the behavior of this type of composite under various loading condition.

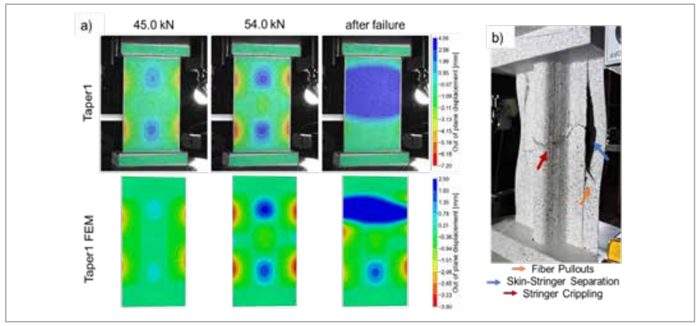

Fig. 2 - (a) Numerical and experimental comparison of the out-of-plane displacement under increasing compression force, (b) failure mode.

DEEP LEARNING ALGORITHMS FOR ROTATING MACHINERY FAULT DIAGNOSIS PH

Daoguang Yang - Supervisor: Prof. Hamid Reza Karimi

Rotating machinery is a key component in many complex mechanical systems, such as vehicles, trains, wind turbines, etc. In the rotating machinery system, gears and bearings are the main components, which would lead to serious accidents if they malfunctioned. Hence, how to quickly and reliably detect the fault states of the bearings and gears in the rotating machinery system is a very challenging topic in modern industry. On the one hand, numerous researchers have employed many signal-processing techniques to extract notable fault features, enabling the identification of potential malfunctions. On the other hand, with the development of artificial intelligence, a growing number of algorithms are being applied to the fault diagnosis of rotating machinery, including shallow learning, deep learning and reinforcement learning. Diagnosis techniques based on signal processing are both interpretable and trustworthy, as their effective utilization demands specialized knowledge in signal processing and rotating machinery. The fault features could be obtained directly with the signal processing techniques, while the artificial intelligence algorithms are different. Artificial intelligence algorithms have the capability to discern distinctions without requiring the specific expertise associated with signal processing techniques. However, the application of these algorithms entails inherent risks due to their black-box nature, even though they often provide highly accurate models.

Fault identification using raw vibration signals, particularly in the time domain, is a complex endeavor when it comes to rotating machinery. Consequently, numerous frameworks have emerged that exhibit increasingly accurate properties in fault identification, leveraging various signal processing techniques like Fourier transform, wavelet transform, and others. However, the presence of significant background noise in signals can pose challenges to effective feature extraction. Additionally, it is crucial for a highly accurate deep-learning model to be trained on a sufficient number of samples. Hence, a novel fault identification model was proposed to address the above problems, residual wide-kernel deep convolutional auto-encoder (RWKDCAE). In this proposed framework, a residual convolutional auto-encoder module was used to pre-train the parameters under the unsupervised learning process, which could improve the performance with limited samples and avoid over-fitting problems. Meanwhile, the wide kernel of the first convolutional layer was applied to improve the feature extraction capability. Consequently, the proposed framework demonstrates exceptional accuracy on both the bearing dataset and gearbox dataset, surpassing the performance of existing state-of-the-art models, particularly in scenarios involving noise and limited sample sizes.

In scenarios where high precision is paramount, prioritizing the enhancement of fault identification accuracy becomes imperative. It is important to recognize that diverse signal types encompass distinct information, such as time-domain or frequency-domain characteristics, and pose varying challenges in extracting meaningful features. Furthermore, within a conventional CNN framework, certain components such as the Rectified Linear Unit (ReLU) activation function, MaxPool layer, and AveragePool layer have inherent drawbacks. For instance, ReLU results in the loss of gradient information by zeroing out negative inputs,

ON THE DEVELOPMENT OF DIGITAL TWIN FOR AIRCRAFT LOAD AND FATIGUE TRACKING AT INDIVIDUAL AND FLEET LEVELS

Xuan Zhou - Supervisor: Prof. Claudio Sbarufatti

The safety of aircraft is critically impacted by fleet aging and structural fatigue, influenced by variations in load history, structural machining, and manufacturing errors. Since the inception of aviation, the philosophy underpinning the assurance of aircraft structural safety has undergone continuous evolution in alignment with advancements in engineering practises. While existing individual aircraft tracking systems acknowledge these disparities, they often underutilize validated models and accumulated service data, leading to challenges in addressing uncertainties in fatigue damage evolution.

The Digital Twin stands as a pivotal core technology and a significant academic frontier in the digital construction of equipment within the aerospace field. In 2010, the United States National Aeronautics and Space Administration (NASA) and the United States Air Force Research Laboratory (AFRL) proposed the concept of the Airframe Digital Twin (ADT) and applied it to the lifecycle management of aerospace structures. This initiative aimed to address operational and maintenance challenges inherent in the intricate aerospace systems of the future.
This thesis proposes a digital twin-based framework for flight load and structural fatigue tracking, aiming to enhance prediction accuracy and elevate aircraft operational safety.
The research is structured into two parts:

In the first part of this thesis, a small, unmanned aircraft is selected as the subject—a particularly suitable choice. Compared to digital twin studies based on specimen- and component-level structures, UAVs exhibit more complex structural forms and loading conditions, introducing a significant amount of uncertainty in measured data and simulation models. This complexity poses novel challenges in constructing structural digital twin models for UAVs and their applications. Furthermore, UAVs share a high degree of similarity with large aircraft but possess lower complexity. This characteristic allows for a more robust testing ground to evaluate the method's applicability in real structures, with results that can be readily extrapolated to large aircraft and other related fields. The reduced-order modelling of fatigue crack growth is then extended to complex crack shapes in complex structures, with a helicopter component adopted to validate the approach.

(1) Introduced a novel service flight load tracking method, leveraging test flight data and load inversion to enhance prediction accuracy. The proposed deep learning-based flight sensor-strain prediction model showcases significant advancements in predicting strain data, particularly in comparison to traditional methods.is dedicated to flight load tracking, with a specific focus on strain measurement and reduced-order simulation.

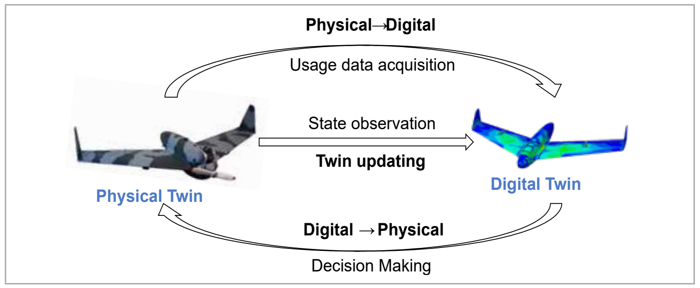

Fig. 1 - The concept of the Digital Twin

(2) Addressed the scale differences between overall UAV loading and structural detail damage. The integration of load tracking, multi-level structural analysis, and probabilistic crack growth models into a UAV digital twin offers a comprehensive solution. The developed methodology demonstrates efficiency and accuracy, paving the way for real-time damage prediction using the digital twin methodology.

(3) Presented a real-time simulation approach for deterministic and probabilistic predictions of crack growth and remaining life in a complex structural component, which is an extension of the reduced-order fatigue crack growth approach in Chapter 3. The combination of SGEBM-FEM coupling, parametric modelling, and reduced-order models significantly reduces computational costs and enhances efficiency for online deployment.

In the second part of the thesis, the exploration of digital twins at the fleet level involves an extensive investigation into methodologies aiming to enhance the efficiency of fatigue tracking. This includes novel approaches to data integration, machine learning algorithms, and advanced analytics. The objective is to provide a comprehensive understanding of the structural health and fatigue status across an entire fleet, paving the way for informed decision-making in maintenance and operational strategies. Additionally, this part of the thesis addresses the scalability of digital twin technologies to accommodate diverse aircraft types and operational contexts, ensuring their adaptability and effectiveness in a broader aviation ecosystem.

(1) Proposed two novel domain adaptive regression algorithms, termed the Online Fuzzy-Set-based (Cluster-based) Joint Distribution Adaptation for Regression, for the structural damage quantification. The two algorithms are utilized to tackle the challenge of insufficient labelled data in online damage quantification, leveraging simulation data and similar structure/damage history within the fleet to enhance online damage quantification accuracy. The two algorithms and the damage quantification framework were then validated with the crack growth in helicopter panels and debonding in composite structures, illustrating its effectiveness across various adaptation scenarios.

(2) Introduced a copula-based approach for enhancing fleet diagnosis and prognosis using digital twins. The proposed method establishes correlations between the damage states of different structures, effectively updating the damage state of uninspected structures based on the inspection results of others. The chapter concludes with suggestions for further validation and exploration of advanced similarity measures.

In conclusion, this thesis establishes a scalable digital twin-based framework for tracking aircraft loads and fatigue at both individual and fleet levels. The incorporation of key technologies and visualization systems positions this framework for application in larger-scale aircraft in the future.

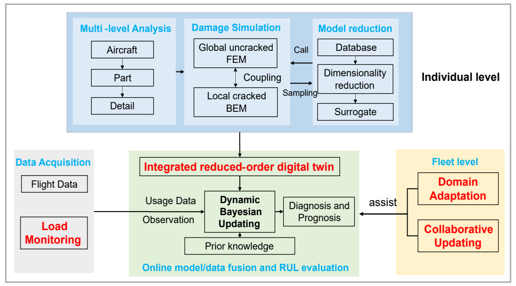

Fig. 2 - Framework and main works of the thesis

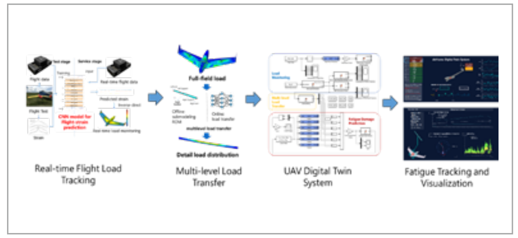

Fig. 3 - Integrate the load tracking, multi-level structural analysis, and probabilistic crack growth models into a UAV digital twin to offer a holistic solution.