AEROSPACE ENGINEERING / ARCHITECTURAL, URBAN AND INTERIOR DESIGN / ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING / BIOENGINEERING / DATA ANALYTICS AND DECISION SCIENCES / DESIGN / ELECTRICAL ENGINEERING / ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY / ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING / INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING / INFORMATION TECHNOLOGY / MANAGEMENT ENGINEERING / MATERIALS ENGINEERING / MATHEMATICAL MODELS AND METHODS IN ENGINEERING / **MECHANICAL ENGINEERING** / PHYSICS / PRESERVATION OF THE ARCHITECTURAL HERITAGE / STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING / URBAN PLANNING, DESIGN AND POLICY

PhD Yearbook | 2022

Dean:
Prof. Andrea Bernasconi

DOCTORAL PROGRAMME IN MECHANICAL ENGINEERING

The PhD Programme in Mechanical Engineering of Politecnico di Milano offers top-level knowledge in one of the most profitable sectors in Italy and Worldwide; it is a key instrument to access leading enterprises and to achieve prominent positions in large international companies devoted to research and development, innovation and design. The primary employment market is composed of leading companies and organizations dedicated to innovation, research and technical development, high-tech SMEs and governmental departments. Our Programme currently ranks 15th in the world according to QS World University Rankings (Mechanical, Aeronautical & Manufacturing Engineering 2021). As for career perspectives, a recent survey (run by Politecnico in 2020) showed that our PhD Candidates are 97% 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 (Mecc PhD 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 28 abstracts belonging to PhDs of the 31st (2), 32nd (2) and 33rd (18) and 34th (6) doctoral cycles (defended in 2021 and 2022) 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 25%.
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 displayed in 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 fibres), 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 physicsbased 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: Cable Dynamics, Characterization of Materials, DBA (Dynamic Bench for Railway Axles),
Dynamic Testing, Dynamic Vehicle, Gear and Power Transmission, Geometrical Metrology, High-Temperature Behaviour of Materials, La.S.T., Manufacturing System, Material Testing, Mechatronics, MI_crolab Micro Machining, Microstructural Investigations and Failure Analysis, Outdoor Testing, Physico-Chemical Bulk and Surface Analyses, Power Electronics and Electrical Drives, Process Metallurgy, Reverse Engineering, Robotics, SIP (Structural Integrity and Prognostics), SITEC Laser, Test rig for the Evaluation of Contact Strip Performances, VAL (Vibroacoustics Lab), VB (Vision Bricks Lab), Virtual Prototyping, Water Jet, Wind Tunnel.

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 H2020, Erasmus Mundus and China Scholarship Council.

We have ongoing agreements with MIT (Progetto Rocca), Shanghai Jiao Tong University (Double PhD), École Centrale de Paris (Cotutelle), Delft University of Technology (Double PhD and Cotutelle), TUM (Cotutelle), ETH Zurich (Cotutelle), RWTH Aachen (Double PhD), Laval University (Double PhD), Qatar University (Double PhD), Northwestern Polytechnical University (Double PhD), Universiteit Antwerpen (double PhD) and the University of Zagreb (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 University of California at Berkeley (US), Imperial College London (UK), Tsinghua University (CN), University of Michigan (US), École Polytechnique Fédérale de Lausanne (CH), Norwegian University of Science and Technology (NTNU), University of Southampton (UK), Technical University of Denmark (DK), Pennsylvania State University (US), Chalmers University of Technology (SE), Virginia Tech (US), Technische Universität Berlin (DE), Warsaw University of Technology (PL), The University of Sheffield (UK), Politècnica de València (ES), Xi'an Jiao Tong University (CN), Tongji University (CN).

ADVISORY BOARD
Roberto Beltrame, CEO and General Director of Microelettrica Scientifica (Knorr-Bremse)
Paolo Braghieri, CEO at GE Capital Interbanca Spa
Lorena Capoccia, CEO and Board Member at Sicme Motori, President at ASSIDAI and Board Member at Praesidium
Paolo Cederle, former CEO at Unicredit Business Integrated Solutions
Lucia Chierchia, Managing Partner at Gellify
Alessio Facondo, Founder and current CEO at RMS Srl, Top management Consulting; previously Head of the Aero-structure Division at Finmeccanica and Chief Operating Officer at SELEXES
Marco Fainello, Managing Director at Add-For Spa and Technical Director at Danisi Engineering
Paolo Manzoni, co-founder of NEGOCO Srl and IOTEAM Srl, founder of PMTSWEB
Paolo Mosa, CEO at Snam Rete Gas
Bartolomeo Pescio, Head of the European Division of Yara International
Andrea Zanella, CEO at Diana Srl

FACULTY BOARD
Prof. Marco Belloli
Prof. Stefano Beretta
Prof. Andrea Bernasconi (Head of the PhD Programme)
Prof. Francesco Braghin
Prof. Stefano Bruni
Prof. Gaetano Cascini
Prof. Federico Cheli
Prof. Alfredo Cigada
Prof. Giorgio Colombo
Prof. Bianca Maria Colosimo
Prof. Roberto Corradi
Prof. Marco Giglio
Prof. Massimiliano Gobbi
Prof. Mario Guagliano
Prof. Nora Lecis
Prof. Stefano Manzoni
Prof. Carlo Mapelli
Prof. Gianpiero Mastinu
Prof. Andrea Matta
Prof. Michele Monno
Prof. Paolo Pennacchi
Prof. Barbara Previtali
Prof. Ferruccio Resta
Prof. Daniele Rocchi
Prof. Edoardo Sabbioni
Prof. Bortolino Saggin
Prof. Tullio Tolio
Prof. Maurizio Vedani

SCHOLARSHIP/EXECUTIVE PHD SPONSORS
BHGE
Boldrocchi
Pirelli
BLM Group
Rold Elettrotecnica
Saes Getters
ST Microelectronics
Inaf - Osservatorio Astronomico di Brera
ENEL Foundation
ITIA-CNR
Thyssenkrupp AG
Clamp
Hirun Europe Srl
IIT (Istituto Italiano di Tecnologia)
ISEO Serrature
GE Power
Impact Innovations
Celada
Pennservice
Monzesi
Salvi
ENI
EURE INOX
Lamborghini
Ferrari S.p.A.
ABB S.p.A.

DEVELOPMENT AND L-PBF PROCESSING OF STRUCTURAL LOW-ALLOY STEELS FOR AUTOMOTIVE APPLICATIONS

Marawan Abdelwahed - Supervisor: Prof. Maurizio Vedani

The laser powder bed fusion (L-PBF) technology has been well recognized among the different manufacturing processes due to the remarkable ability in facilitating the design and the production of light-weight metallic structures with minimal material wastes, highlighting the environmental benefits. The high cost of products represents one of the main drawbacks of L-PBF that hinders the employment of such technology in many industries, especially for those relying on mass-production scale. Hence, the product-cost requires further optimization that is suggested by the development of low-cost feedstock powders produced by water atomization (WA) process as an alternative approach to the standard gas atomization (GA) process. Fig. 1 displays a comparison between both powder morphologies.

Despite the widespread and predominant applications of advanced high strength steels for structural components, the processing of low-alloy steels by L-PBF has not yet reached the same degree of confidence achieved by conventional routes. Consequently, the library of approved Fe-based materials is still confined to stainless steels and maraging grades. Accordingly, the main aspect of the current research is the development and L-PBF processing of several plain-carbon and low-alloy steels starting from WA feedstocks. In particular, the metallurgical features of 10 L-PBF structural steels based on different alloying systems were investigated by characterizing the microstructures (Fig. 2) and evaluating the mechanical properties. Moreover, post-process thermal treatment schedules were designed and applied according to thermodynamic simulations aiming to generate optimal microstructures for enhancing the mechanical behavior.

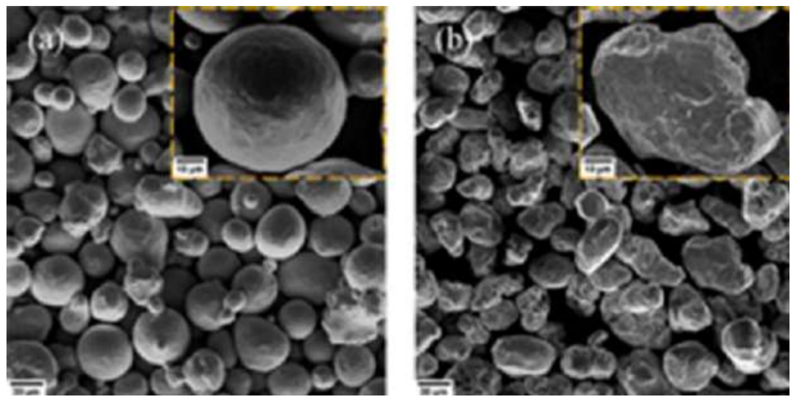

Fig. 1
(a) GA and (b) WA steel powders.

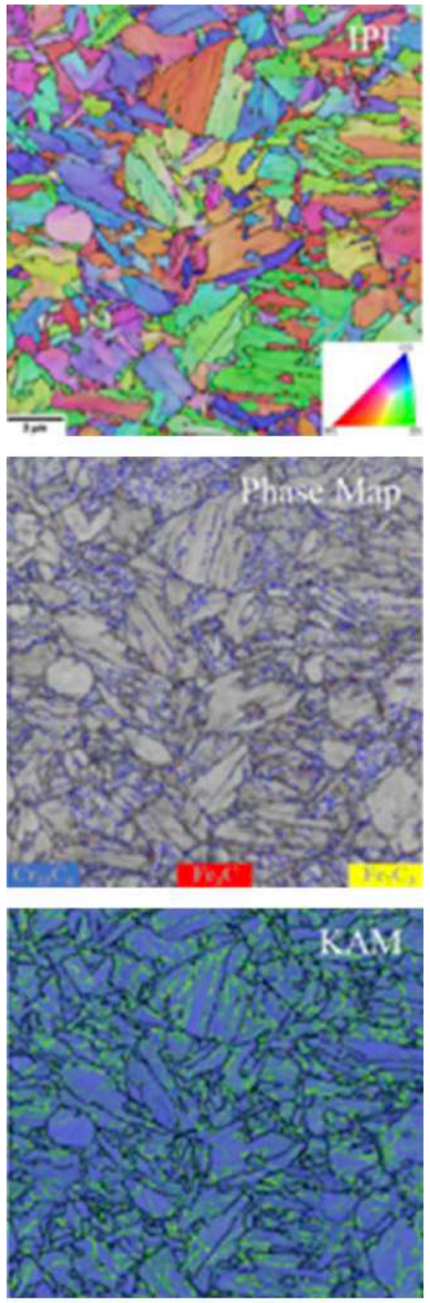

Fig. 2
EBSD analyses of a L-PBF WA steel.

The nature of an atomization process using water jets led to irregular-shaped particles with poor powder characteristics and unavoidably higher oxygen contents. It is possible to overcome the drawbacks of the WA process by applying specific post-atomization treatments on the powder batches, either to improve the particle properties or to reduce the oxygen content. The results showed that the low flowability and packing density of WA particles influenced the densification level during L-PBF, while the pronounced amount of oxygen in powders affected the metallurgy (Fig. 3) of the processed steel components. Depending on the initial alloying elements and the levels of oxygen, oxide-based inclusions having different sizes and compositions are formed in the steel matrix that showed a refinement effect on the microstructure after L-PBF and contributes to the nucleation of other ferrite constituents rather than martensite, leading to a further reduction in the hardenability. Regarding the mechanical properties, the L-PBF WA steels delivered a comparable tensile behavior to the counter components processed from the standard GA powder. Though, the formed oxides played a significant role in reducing the impact toughness of the former alloys. Furthermore, the investigated steels were processed with different microstructures to offer a wide range of tunable properties through the application of post-process thermal treatments, that could also reduce the mechanical anisotropy generated by L-PBF.

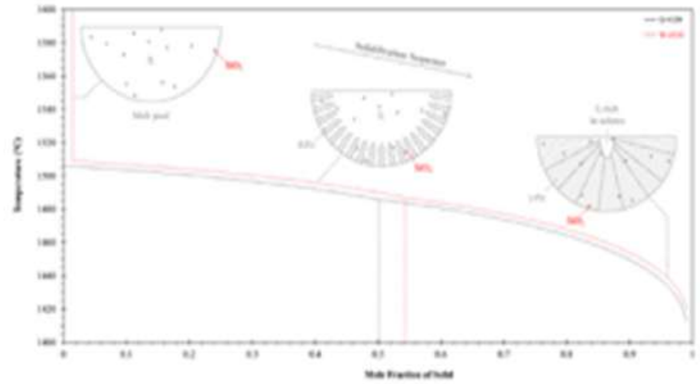

Fig. 3
Scheil-Gulliver solidification model of L-PBF processed 4130 low-alloy steels, starting from GA and WA powders.

The main findings of these studies promoted the WA process to be a potential alternative route for delivering sustainable feedstock materials for L-PBF. In addition, the combined cost-effective approaches of both the suggested powders and the developed steels could shift the potential from prototyping to affordable mass-production goods in favor of light-weight steel structures for the automotive applications.

POWDER DEVELOPMENT OF LEAD-FREE PIEZOCERAMICS MATERIAL FOR ADDITIVE MANUFACTURING TECHNOLOGY

Ruben Beltrami - Supervisor: Prof. Nora Francesca Maria Lecis

In the last decades, 3D printing additive manufacturing has attracted the attention of the scientific and engineering community. In fact, these new technologies have emerged as one of the most interesting technologies for designing and production of innovative materials. Additive manufacturing 3D printing of different types of materials (from metals and plastics to ceramic) has allowed a versatility in design and realization never seen before. Today, 3D printing is one of the most promising technology able to change production paradigms and transform the manufacturing industry. The production process starts from a 3D model CAD design file with the consequent conversion to STL format (stereolitography), which consists in the object slicing into virtual layers printable in 2D, with different techniques, by the 3D printers. Binder Jetting 3D printing is one of the emerging additive manufacturing technologies, in which the object is printed with the aid of a chemical binder and then heat-treated for densification (figure 1). With respect to ceramic materials and more precisely piezoelectrics, additive manufacturing technology offers new possibilities of part designing and thus innovative applications. For instance, just think on the next internet of things (IoT) industrial revolution and the new needs and challenges that we will have to face from the manufacturing point of view. Piezoelectric materials are the basis for a large number of devices including sensors (pressure, force and vibration), accelerometers, actuators and transducers but only few of them are used in applications

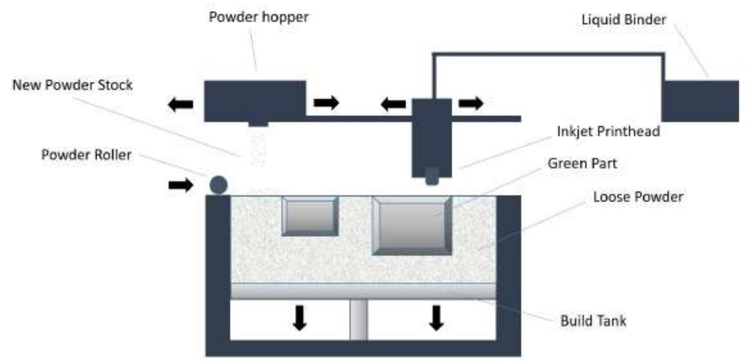

Fig. 1
Binder jetting 3D printing process.

as piezoelectric devices. Nowadays, the most important piezoelectric material applied in the practice is Lead Zirconate Titanate (PZT). In fact, this ferroelectric ceramic material guarantees excellent performances thanks to its high piezoelectric properties and high Curie temperature. Nevertheless, Pb represents a serious hazard for human health leading scientific community to develop alternative lead-free piezoelectric materials. Among the others, Potassium-Sodium Niobate (KNN) system is one of the most promising, due to its high piezoelectric constant and high Curie temperature although its piezoelectric properties are not still comparable with those of PZT. The aim of the PhD project was to study the 3D printing feasibility of lead-free piezo-electric ceramic powder using binder jetting technology. This challenging target was achieved through a dual pathway: lead-free piezoelectric powder synthesis and study of the most important parameters in binder jetting 3D technology. First, $K_{0.5}Na_{0.5}NbO_3$ (KNN) was synthetized by solid-state reaction through mechano-chemical activation and sol-gel method. Second, stainless steel (316L) and alumina (Al_2O_3) were used as powder testing materials for studying binder jetting 3D printer technology and its fundamental parameters. Finally, a KNN sample was 3D printed, poled and tested obtaining a working piezoelectric disc proving the usability of binder jetting technology even for advanced ceramics (figure 2).
Potassium sodium niobates (KNN) was successively 3D printed with binder jetting technology for the first time thanks to the optimized powder synthesized by mechano-chemical and sol-gel method. In particular, in order to increase the sinterability and the piezo characteristics, KNN mechano-chemical powder and sol-gel powder were mixed in different ratio (0 to 20 % wt. of sol-gel). Sol-gel powder with its higher reactivity works as liquid-phase during

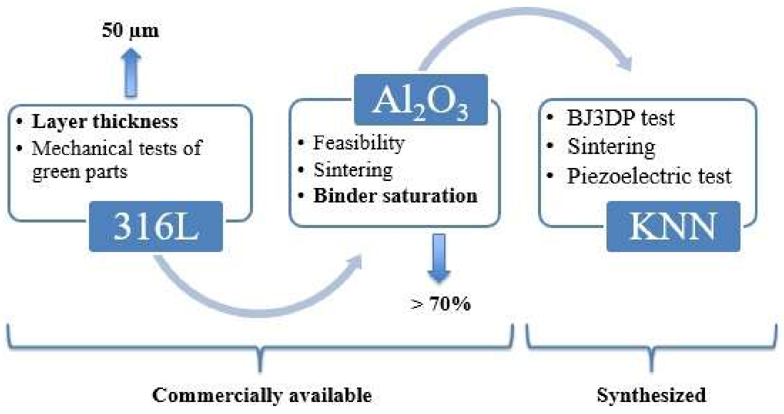

Fig. 2
Experimental steps for KNN binder jetting 3D printing.

sintering making easier densification and improving piezoelectricity. This is a remarkable result because it demonstrates the possibility to use a low melting phase identical to the main material improving both the density and the piezoelectricity. Despite the non-use of pressure techniques to densify the material, KNN discs obtain by only printing and sintering have shown a good relative density (75%) and piezoelectric activity (d33 ~ 73 pC/N). In conclusion, several improvements are still required for wide industrial application, such as improvement of the powder geometry (e.g. spherical powders), optimization and standardization of powder synthesis with enhanced piezoelectric features and adoption of alternative heat treatments (spark plasma sintering or hot isostatic pressing) to obtain reliable and reproducible products.

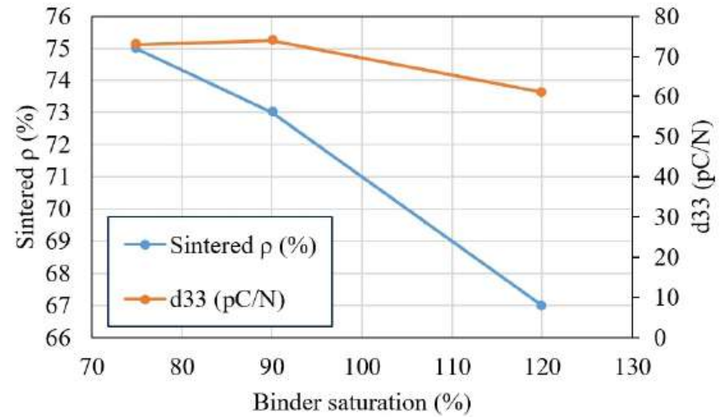

Fig. 3
d33 (pC/V) and sintered density (%) of KNN binder jetted samples at different binder saturation.

EXTENDED STATE ESTIMATION FOR AUTONOMOUS VEHICLE CONTROL

Mattia Bersani - Prof. Francesco Braghin, Prof. Federico Cheli

In 2018, WHO declared that road crashes kill about 1.35 million people worldwide every year, and road traffic injuries are the eighth leading cause of death for all age groups. In 2019, in Italy road fatalities were 3173 with a mortality rate of 5.3 deaths per 100000 inhabitants. Summing up, almost 94% of daily collisions are attributed to driver error, with 31% involving legally intoxicated drivers, and 10% from distracted drivers. Thus, the removal of the human factor from the vehicle control loop allows reducing deaths and injuries on our roads: in this perspective, autonomous driving represents the most promising technology. The National Highway Traffic System Administration (NHTSA) classified the active safety systems based on vehicle automation, ranging from vehicles that do not have any of their control systems automated (level 0) through fully automated vehicles (level 5).

The agency has segmented vehicle automation into levels both to allow discussing this topic with other stakeholders and to clarify the level of automation on which the agency is currently focusing its efforts. Nowadays, autonomous driving represents the mobility of the future. Autonomous vehicles can improve the quality of our life, because of the new job opportunities, the higher productivity due to the more efficient management of the time spent on the vehicle, the higher accessibility for the vulnerable sectors of society, safety improvement, pollution reduction, and, more in general, the possibility of optimizing the management of the transportation systems.

This thesis presents the development of a control architecture suitable for an autonomous level-5 vehicle. As shown in Fig. 1, the two main tasks required for the control unit of an autonomous vehicle are state estimation and motion control. State estimation requires a sensor fusion module to handle the huge amount of data provided by the sensors installed on these vehicles. Processed measurements are used to estimate the state vector of the autonomous vehicle and the one of each obstacle in the surroundings. To provide a consistent reference frame, all the estimates are arranged according to the road. Estimates are the inputs for the motion planner, where they become initial or boundary conditions for the vehicle optimal control problem. The trajectory planner computes the solution to the vehicle control problem, which is sent to the trajectory follower that properly actuates the vehicle. The control unit of an autonomous vehicle implements this loop in real-time.

This thesis presents all the algorithms involved in the figure, dealing in particular with the state estimation process. The understanding of the highly dynamic and uncertain environment in which the vehicle operates represents a crucial task. Various perception sensors are used in this thesis for this scope. Each sensor has been installed on the vehicle in Fig. 2, which represents the platform where all the algorithms have been developed and tested. For what concerns the vehicle state estimation task, two unscented Kalman filters have been developed and compared based on two different setups. The former accounts for a kinematic vehicle model and the measurements given by two GNSS receivers with inertial units; about the latter, self-localization in the road lane is performed by a camera, whilst a dynamic vehicle model developed out of a reverse engineering process on the experimental vehicle provides the state vector prediction. Experimental results show that the algorithm that accounts for the vehicle dynamic behavior is more accurate but less robust with respect to changes in the driving scenario. On the other hand, self-localization given by cameras is not affected by the presence of buildings or trees, but the accuracy depends on the state of degradation of the lateral lines and on the presence of parked vehicles. For what concerns the detection and tracking of the surrounding obstacles, the thesis presents a sensor fusion module which handles the measurements coming from two radars, a rotating lidar, and a camera. Fused measurements are then provided to the tracker, which performs the association with the obstacles tracked during the previous steps. Finally, an unscented Kalman filter handles the transformation of coordinates from the sensors' reference frame to the road and then updates the former state predictions. The hierarchical structure of the developed motion planner is composed of a trajectory planner and a trajectory follower. The trajectory planner provides the solution to the vehicle optimal control problem, which is defined at each time step accounting for the initial and boundary conditions generated by the state estimation routine. The solution is provided by a nonlinear MPC in terms of reference steering angle and vehicle speed to the trajectory follower, which actuates the vehicle basing on two PI control logic. Thanks to the modifications carried on the actuation systems of the vehicle, this thesis presents the test phase of the overall control architecture which runs at 20 Hz on a consumer laptop. The experimental campaigns have been carried in the Monza ENI Circuit, as shown in Fig. 3.

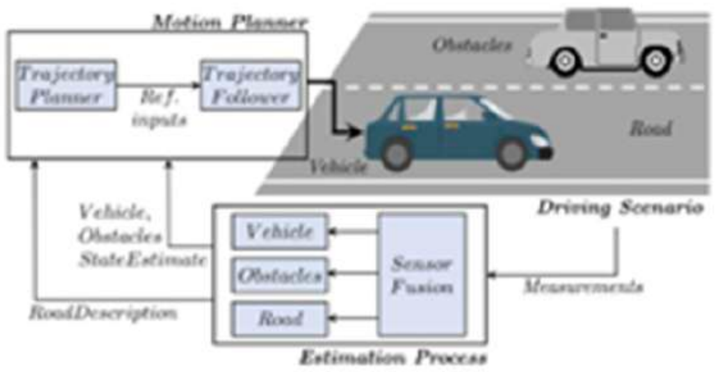

Fig. 1
Representation of the architecture of the control unit developed for autonomous driving.

Fig. 2
The prototype of autonomous vehicle

Fig. 3
The autonomous vehicle drives autonomously along the first chicane of the Monza ENI Circuit.

A BIOINSPIRED APPROACH TO THE LOCOMOTION OF ROBOTS

Giovanni Bianchi - Supervisor: Prof. Simone Cinquemani

The objective of this Ph.D. thesis is the development of innovative methods to address the challenges of underwater locomotion. Most autonomous underwater vehicles (AUVs) are propelled by thrusters, characterized by low energy efficiency and high noise pollution, whereas many fishes are efficient and agile swimmers that outperform AUVs. Therefore, this research is imprinted to create new knowledge about aquatic propulsion by adopting a bioinspired approach. Nature displays a wide variety of swimming strategies, and this thesis is focused on the locomotion of the cownose ray since it is featured by the best combination of efficiency and maneuverability among fishes. Hence, this thesis aims to understand how to put into practice the bioinspiration method and to learn how to transpose a biological solution into an engineering application. The context in which this work is developed is underwater locomotion, and the outcome is the realization of a biomimetic swimming robot inspired by the cownose ray.

An analysis of all the locomotion strategies present in nature has been performed to understand the common physical principles of fish swimming and find out the advantages and drawbacks of each swimming technique. After identifying the rajiform swimming mode of the batoid fishes as one of the most promising in terms of maneuverability and energy efficiency, a kinematic model of the cownose ray fin movement is developed. These fish propel by flapping their large pectoral fins, whose motion is featured by a wave traveling from the fish's head to its tail, pushing water backward gaining thrust thanks to momentum conservation.
Then, a CFD study of fish swimming is carried out to understand the mechanisms of thrust generation and the influence of kinematic parameters on swimming performances. This CFD model solves the coupled equations of fluid dynamics and forward swimming dynamics using an overset mesh consisting of two merged grids: the first encompasses the whole domain and remains still, the second includes a portion of fluid around the fish and moves jointly with it. The motion of the internal mesh surrounding the fish results from the superimposition of two movements: fin deformation, which is imposed as a boundary condition, and forward swimming, which is calculated by the solver. This analysis highlighted that the vortices in the wake form a Reverse Karman Street, with vortices of alternate signs shed by the fin every half flapping period, forming a propulsive jet in the center of the wake. Moreover, fin-tip vortices and leading-edge vortices have been put in evidence. In Figure 1, the vortices in the wake are shown.
The calculation of the energy efficiency of a self-propelled body like a swimming fish is challenging since both thrust and drag act on the same surface, and at the steady state, the net force acting on the fins is zero. Therefore, a novel way to compute the energy efficiency has been proposed to overcome this issue, separating the two contributions.
Several CFD analyses have been carried out varying frequency and wavelength of the fin movement to relate these kinematic parameters to swimming velocity and energy efficiency. Interestingly, the energy efficiency and all the other non-dimensional parameters are not affected by frequency variations, and the forward velocity is proportional to frequency. Conversely, wavelength variations considerably influence the swimming performances as they modify the flow around the fins. Swimming gaits with a greater wavelength allow achieving higher thrust and speed; however, with a smaller wavelength, the locomotion is more efficient.

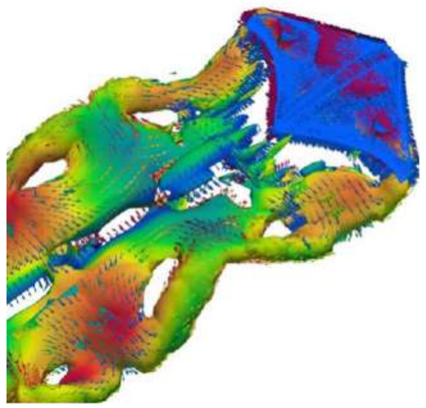

Fig. 1
Vortices in the wake with vorticity vectors

To assess the validity of the principles behind the locomotion strategy of the cownose ray and provide an innovative example of underwater locomotion, a prototype of a biomimetic robot inspired by the cownose ray has been designed and built. This robot recreates the fin deformation using three mechanisms, which are independently actuated so that it is possible to modulate the frequency and the wavelength of the fin movement. The robot dynamics have been analyzed numerically with a multibody simulation, which uses the forces extracted from the previous CFD analyses to compute the required torques for each actuator of the robot.

The first experiments made on this prototype aim to understand the forces involved when the robot moves in a fluid. The reason why also tests with the robot moving in the air have been carried out is that it has been possible to impose a relative speed between the system and the fluid in a wind tunnel, which would not have been possible in a water tank. In the tests, one fin of the robot has been attached to a 6-axes load cell, and forces and moments have been measured. These tests have shown that the locomotion principle of the cownose ray is a good source of inspiration for underwater vehicles and highlighted some limitations of the first version of the robot, such as the need for a smoother external surface.
Nevertheless, they have been overcome in a new version in which the fins and the electronic circuit have been completely redesigned. The fins are entirely made of silicone rubber, a very flexible material with a density similar to water. Hence, the robot can be neutrally buoyant without adding many ballasts, and the mass distribution is well balanced. The final assembly of the robot is presented in Figure 2.

The control logic that keeps the two fins synchronized and the mechanisms in each fin with the correct phase shift has been tested with success.
Some preliminary tests in the water of the robot showed that the realized fins can effectively displace water and generate a force that moves the robot.
As a future development, the robot's control algorithm will be designed and tested.

Fig. 2
Final assembly of the biomimetic robot inspired by the cownose ray.

OBSERVING MOLTEN POOL SURFACE OSCILLATIONS AS A NOVEL APPROACH FOR PENETRATION DEPTH MEASUREMENT IN LASER POWDER BED FUSION

Leonardo Caprio - Supervisor: Prof. Barbara Previtali - Co-Supervisor: Prof. Ali Gokhan Demir

The great potential of Laser Powder Bed Fusion (LPBF) lies in the possibility of observing the manufacturing process in a layerwise fashion to assess the production route. Due to the critical application areas where such technology finds its greatest applications part failure cannot be tolerated and there is need for quality assurance systems. Amongst various stability indicators, geometrical factors related to the melt pool generated by the laser-material interaction have been identified as key elements in determining process drifts and identifying defect formation. However, due to the intrinsic nature of the technology, only top-view observations of the processed layer may be conducted allowing the measurement of geometrical surface parameters. Hence, the in-line measurement of the molten pool penetration depth stands out as an industrially relevant question to provide a complete set of spatially distributed information regarding the melt geometry. Within the present investigation a novel approach to estimate the penetration depth during Laser Powder Bed Fusion is presented.

The aim of the work thus consisted in the development of the sensing principle and the definition of the methodological approach to analyse the phenomena observed and the data acquired. Once the methodological framework was defined, a proof of concept investigation was designed and conducted. The results were analysed and starting from preliminary investigation, validation of the method on different materials was sought. Moreover, the correlation between melt surface oscillations was investigated in conventional LPBF processing conditions. Based on the phenomenological considerations derived from the intial experimental investigations, the use of waveform modulation of the laser emission power was employed modify the melt flow during the LPBF process. Preliminary testing of the monitoring sensor through a coaxial implementation was also explored. The overall scheme of the PhD research is shown in Figure 2. The sensing principle developed in the doctoral research relies on the observation of molten pool surface ripples through the measurement of probe light reflections in the melt area (as shown in Figure 2) which are symptomatic of crests and troughs (according to scientific literature). A phenomenological model representing the molten pool as an equivalent one degree of freedom mechanical system was proposed. High speed imaging with secondary illumination unveiled the melt dynamics during the process and successive image and signal analysis allowed to identify peak oscillation components of the melt surface in the frequency domain. Metallographic cross-sections disclosed the undersurface melt geometry and were used to correlate the oscillation frequencies to the penetration depth. The methodological approach developed is reported schematically in Figure 3.

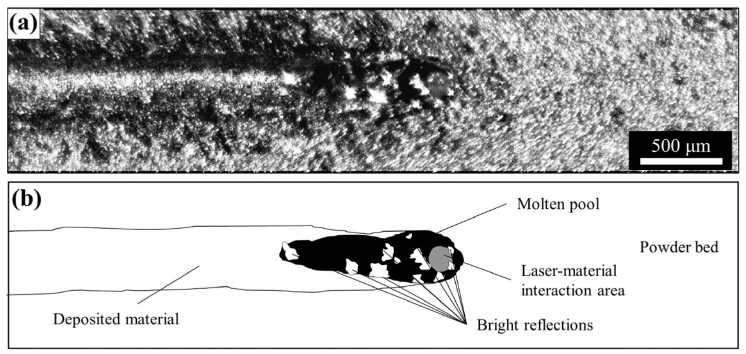

Fig. 2
(a) Frame from a high speed acquisition of the LPBF process and (b) its schematic representation

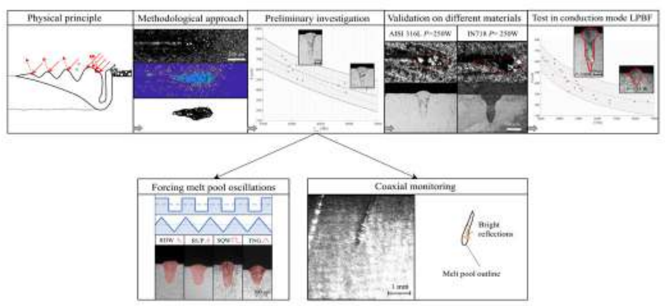

Fig. 1
Schematic overview of the research work conducted.

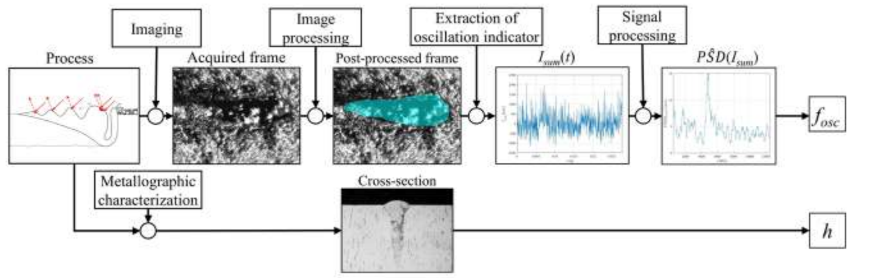

Fig. 3
Methodological approach developed during the doctoral investigation.

Bright reflections on the melt surface could be observed when acquiring high speed frames with a secondary illumination. The methodological framework developed was tested on AISI316L and provided proof of concept demonstration of the methodological framework [1]. In a range of processing conditions from keyhole to conduction mode processing of AISI316L, capillary waves were measured in the range of 3.5 kHz to 9 kHz (as shown in Fig.2). Lower oscillation frequencies corresponded to higher penetration depth. The methodological approach and sensing system were validated on IN718 in off-axis configuration, reporting an analogous trend [2].

The monitoring device was also devised as a sensing tool to verify if waveform modulation of the laser emission power could modify motion in the molten pool. Experimental investigation showed that molten pool surface oscillations corresponded to the waveform frequency and this technique appears to be promising as a process enhancement tool and in reducing top surface roughness of LPBF depositions. Finally, preliminary testing of the sensing device in coaxial configuration was realised demonstrating industrial applicability of the monitoring solution developed.

Overall, the research showed that probe-light illumination of the molten pool can be used to sense the oscillatory motion of the liquid metal during LPBF. Moreover, melt pool surface fluctuations may be employed as an indicator of the sub-surface melt geometry and higher oscillation frequencies correspond to a shallower melt formation. The oscillatory nature of the melt is correlated to the vapour jet formation caused by the laser material interaction coupled to localised variations in the absorptivity. The oscillatory motion may be controlled by imposing waveform modulation of the laser emission power. Coaxial monitoring of the surface oscillations is feasibile and the oscillatory motion may be detected when an off-axis illumination is employed.

MODEL-BASED DAMAGE PROGNOSIS OF COMPOSITE LAMINATED STRUCTURES

Demetrio Luigi Maria Cristiani - Supervisor: Prof. Marco Giglio - Co-Supervisor: Prof. Claudio Sbarufatti

The recent advances in materials and manufacturing technology have revolution-ized the field of structural engineering, aiming for increasingly efficient and high-per-formance structures. The workhorse of this revolution is the category of fiber reinforced plastics (FRP), exhibiting superior capabilities in terms of specific stiffness and strength and making them particularly appealing in several structural applica-tions where weight savings are crucial. However, FRP are notably vulnerable to flaws developing from the manufacturing process and service, and unlike metals, are fea-tured by complex and multivariate failure and degradation modes, leading to uncer-tainty in the assessment of current and future material properties. These shortcomings have prevented the fielding of systematic predictive maintenance (PM) strategies for complex, large scale FRP structures, which, at best, rely on resource-in-tensive periodic inspections by non-destructive evaluation (NDE) techniques.
With increasing use of FRP in several industries such as aviation, effective reliabil-ity analysis of composite structures has become imperative in recent years. This de-sideratum may be fulfilled by developing ad-hoc damage prognosis (DP) methods. DP methods attempt to predict the remaining time beyond which the structure is ex-pected not to perform within desired specifications, i.e., the remaining useful life (RUL), by inferring the current state of the system (i.e., structural health monitoring), estimating its future operational environments, and then predicting its RUL. In prac-tice, DP requires the integration of diverse fields of technology and a variety of predic-tive modelling approaches, including the ability to quantify the uncertainty associated with RUL predictions, to enable informed, risk-based maintenance decisions.
The increased ability to sense, acquire and process data has accelerated research and development breakthroughs in the field data-driven (DD) approaches, envisaging a data-centric future for many scientific disciplines, including DP.
In the context of DP of composite structures DD approaches have been strongly encouraged, as a universal structure underlying damage progression models is missing, and the field suffers from ambiguous and inconsistent interpretations. It is however questionable whether the success of DD approaches in domains where data are abundant and physics-based models do not exist should trace the route of DP, being a field where data are typically scarce and scientific knowledge defining how processes evolve is, to some extent, available. The hesitation is even more legitimated by considering that DP requires a predictive effort, and purely DD approaches are unlikely to be predictive, having in-trinsic limitations on the cognitive tasks that they can perform.
The goal of this research is to develop a framework for the DP of FRP structures that merges the partial knowledge of condition monitoring (CM) data from an inte-grated sensors network with the limited predictive abilities of damage progression models, enabling real-time RUL estimates accounting for aleatoric and epistemic un-certainty sources, enabling informed, risk-based maintenance operations.
Bayesian filters (BFs) provide a convenient framework that meets the research goal, where the posterior probability distribution of the system state (i.e., the damage state) is recursively approximated based on a time-growing stream of CM data. Among BFs, the particle filter (PF) is possibly the best candidate, as it can solve the recursive non-linear non-Gaussian state estimation problem without requiring any local linear-ization or any functional approximation.
Solutions are proposed to implement the PF for the DP of FRP structures undergo-ing fatigue degradation, developing approaches meeting the online and real-time op-erational requirements. Local strain measurements are employed as CM data, proving to be adequate and having practical advantages over more complex sensing tech-niques. DD approaches are integrated within the PF to map the relation between the system state space and the CM data, basically solving a pattern recognition problem, reducing the computational expense that structural models would pose during the PF operation. Conversely, the predictive effort is performed by damage progression mod-els. In this regard, a novel state evolution model is postulated for cross ply laminates undergoing fatigue loading, where the interaction between damage modes (transverse cracks and induced delaminations) is acknowledged and multi-damage accumulation laws are proposed, paving the way for future works in the DP of FRP arena.
The proposed framework is tested in various scenarios with increasing complexity. Results demonstrate the feasibility and potential of the proposed approach as a tool able to monitor the fatigue degradation/damage progression while simultaneously providing estimates about the remaining useful life (RUL) of composite structures.

IMAGE-BASED MEASUREMENT TECHNIQUES FOR TEMPERATURE AND THERMAL DAMAGE MONITORING DURING LASER ABLATION FOR TUMOR REMOVAL

Martina De Landro - Supervisor: Prof. Paola Saccomandi

Laser ablation (LA) is a minimally invasive thermal therapy where light is used to induce local necrosis for the malignant cells. LA is suitable for treating lesions in high-risk locations with great precision and minimal invasiveness. Despite the promising features, LA use in clinics has been limited by an inability to assess ablation progress during the treatment. Thermal damage induced may be monitored with two main strategies (see Figure 1), (i) by measuring temperature, then used to predict the damage through mathematical models; (ii) by directly estimating the damage using optic-based technologies. During my Ph.D., I investigated imaging-based techniques combining their use with high-performance systems. From one side, I explored Magnetic Resonance Thermometry Imaging (MRTI), performing a metrological investigation of innovative sequences in the scenario of soft tissues LA. Fiber Bragg Grating (FBG) sensors were chosen to provide accurate (0.1 °C) temperature values of reference. On the other hand, I proposed and validated Hyperspectral Imaging (HSI) technology for thermal damage monitoring using infrared (IR) imaging to provide accurate (2 °C) temperature maps as reference. MRTI represents the clinical standard when temperature monitoring is included in the LA. Besides the potential of providing multi-dimensional temperature maps of the area inside the organ, the current protocols are not ideal for fatty and moving soft tissues. In my work, 2D and 3D echo-planar imaging (EPI) sequences were investigated exploiting optimal accuracy and multipoint temperature measurements provided by FBG sensors. In the first case, the comparison between the FBGs and MRTI measurements allowed the estimation of 2D sequence performances. Firstly, the temperature profiles along a line were extracted (Figure 2a). Then, (i) linear regression (Figure 2c), providing a root mean square error of 0.3 °C for both heating and cooling phases, and (ii) Bland-Altman analysis (Figure 2d), giving 0.1 °C and 1.5/−1.3 °C for mean of difference (MOD) and level of agreement (LOA), were performed. Afterward, FBGs arrays were used to characterize susceptibility artifacts in the 3D EPI sequence. When a power of 2W is set, artifacts appear with a double-lobe shape of negative temperature increase in the sagittal view (Figure 2d). They can be related to susceptibility change following bubble formations. In the study, temperature evolution in 6 MRTI pixels was compared with FBG temperature values, Figure 2d, and temperature error was measured in the susceptibility artifact area (the maximum error is -49.7 °C and 64.4 °C for two different tests). Additionally, the combined use of multiple FBG allowed extracting a 2D thermal map which can potentially integrate and correct the misleading information in MRTI (Figure 2f). Finally, if the 2D EPI demonstrated promising temporal resolution of 1s, the 3D EPI allowed the monitoring of the entire ablated volume minimizing the risk for information loss. More in vivo studies should be performed to identify the optimal protocol for monitoring LA in soft tissues.

On the other hand, HSI is an optic-based technique that guarantees robust data directly linkable to laser-induced damage. As a first step, HS data collected during several in vivo liver LA, were processed to identify spectral indicators of thermal damage. Specifically, the normalized area under the curve (NA) in four spectral regions (see Figure 3c), associated with tissue chromophores, was measured during the treatment and showed consistent variation in the Methemoglobin (MethHb), Deoxyhemoglobin (Hb), and Hemoglobin, Water and Lipid (Hgb, W and L) ranges. Results are reported in Figure 3a-b. After, the HS and IR images were used to develop a deep learning model, peak temperature prediction model (PTPM). PTPM predicts the maximal temperature that has been reached during the overall ablation procedure at that pixel. The Final predicted temperature maps are in Figure 3e. Once the irreversible tissue damage occurs, the PTPM presents much better performance (Figure 3f-g). After the 80 °C steps, the mean relative error is approximately 10% for all three damage classes. In the final step, the linear correlation with the histology scores (Figure 3h) shows rmeasured and rpredicted of 0.90. Therefore, HSI is an attractive cheap solution, and more studies should be made to introduce its actual use in the clinical environment.

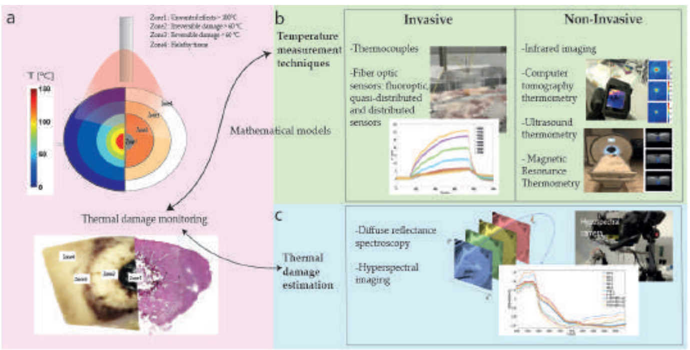

Fig. 1
a) Thermal damage induced in the tissue can be monitored with two main strategies: (b) by indirectly predicting it measuring temperature using either invasive or non-invasive techniques; (c) by directly estimating it using optic-based techniques. Example of data acquired and set-up are also reported for the approaches investigated during my PhD.

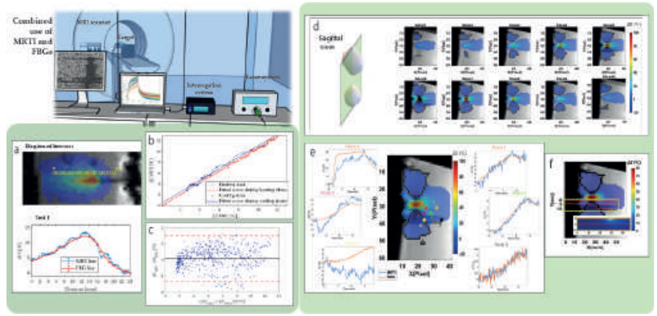

Fig. 2
a) Region of interest in the MRTI images for the analysis and comparison between FBG and MRTI space temperature lines for one test. b) Linear regressions results. c) Bland-Altman analysis results. d) Temperature maps and 3D rendering of susceptibility artifact in gelatine. e) Temperature evolution acquired with FBG (orange) and MRTI (blue) in 6 pixels. f) Temperature map implemented by interpolating the temperature values from the 90 FBGs sensors (bottom image with yellow border). The sensors' positions are also shown in the thermal map (red spots).

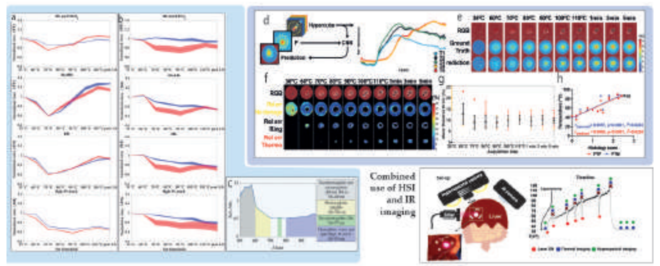

Fig. 3
Hb and HbO2, MetHb, Hb, and Hgb, W and L at different set thresholds for central (a) and boundaries pixels (b) in two tests. c) Spectral ranges considered for the study. d) Dataset and output of the PTPM, and relative reflectance for several pixels associated with specific temperature value (T1 . . . T5) provided by the IR camera. (e) The normal RGBs are shown with ground truth and predicted peak temperature maps in all the acquisition steps. (f) Maps of the Relerr (%) for the three classes. (g) MRE % and its standard deviation in the three areas. (h) Linear regression between histology scores and (1) measured peak temperature values (PTM-blue curve), and (2) predicted peak temperature values (PTP-red curve).

ON THE APPLICATION OF FIBER OPTIC SENSOR FOR REAL TIME STRAIN-BASED DIAGNOSTIC

Ilaria Di Luch - Supervisor: Prof. Marco Giglio - Co-Supervisors: Prof. Claudio Sbarufatti
Prof. Mario Martinelli (DEIB – Dipartimento di Elettronica Informazione e Bioingegneria)

Structural Health Monitoring (SHM) is emerging as a vital strategy to help engineers improve the safety and maintainability of critical structures. Fiber Optic Sensors (FOSs) have been recently used for crack monitoring, detecting ultrasonic acoustic waves in metallic structures. A novel FOS solution for Acoustic Emission (AE) wave monitoring is proposed in this thesis for crack propagation monitoring. The sensor relies on a fiber optic Michelson interferometric architecture associated to a coherent detection scheme, which retrieves the phase information of the received optical signal in a completely passive way. The sensing fiber is organized into multiple loop layouts, bonded on metallic structures in order to increase the phase signal related to the detection of AE. AE measurements carried out with the coherent fiber optic sensor are compared with traditional piezoelectric sensors, proving that this solution represents a promising, alternative for highly sensitive measurements in AE monitoring.

CYBER-PHYSICAL SYSTEM FOR THE CONTROL OF SIZE-REDUCTION PROCESSES TO ENABLE CROSS-SECTORIAL CIRCULAR ECONOMY

Marco Diani - Supervisor: Prof. Marcello Colledani

Circular Economy is indicating the route for a new paradigm in which profits and sustainability are not in conflict, but they cooperate to improve and grow up each other. One of its pillars is to reduce or, if possible, avoid waste, extending products life or restoring functions and materials, preventing incineration and disposal.

In this perspective, the last possible solution is recycling, which aims to recover materials from End-of-Life (EoL) products. Several issues, as variability and market fluctuations, influence its complexity and economic sustainability. In addition, non-optimized processes lead to loss of money and time, in particular due to the rigid monolithic design of the current recycling lines. To overcome these problems, flexible systems are needed, working in feed-forward configuration, increasing the adaptability of recycling lines.

In particular, size-reduction processes (also called shredding or comminution) are fundamental components of recycling systems supporting the recovery and re-use of materials from post-consumer products, under a circular economy perspective. These technologies allow to obtain high liberation degree and suitable size of the material mixture prior to separation and re-use. However, their poor adaptability affects the capability to meet required material properties, thus preventing the systematic re-use of materials in high-added value applications. In addition, shredding processes are fundamental to implement a cross-sectorial approach in recycling. The characteristics of output particles depend on requirements and specifications of high added-value products embedding the recycled material following a demand-driven approach (as in Figure 1).

To overcome these issues, the objective is to maximize the fraction of particles respecting material specifications, minimizing the costs to obtain them through the control of shredding processes exploiting Cyber-Physical Systems (CPS). CPS are systems composed by an hardware and a software part. The hardware part, formed by data gathering systems and actuators, is able to collect and information to the software part, composed by models and metamodels, that elaborates and transforms them into optimized actions for the physical world, both at machine level (to optimize the operational parameters) and at system level (to optimize flows and to avoid possible problems of the line).

While CPS are widely used in manufacturing, few examples of their application in de- and remanufacturing can be found in literature, and no examples are present for size-reduction processes.
To develop and implement a CPS to control shredding, it is fundamental to analyze the parameters impacting on the process itself. In addition to the design parameters, different controllable parameters are present. In particular, the most interesting are the grate size (that can be controlled offline) and the rotational speed and the feed rate (that can be controlled online). Due to this dichotomy between offline and online control, a 2-step approach has been developed, as represented in Figure 2.
The first step is dedicated to the optimization and control of the grate size. The objective is to optimize the dimensional and morphological distribution of particles in output, increasing the liberation of target materials and obtaining particles suitable for following processes (as

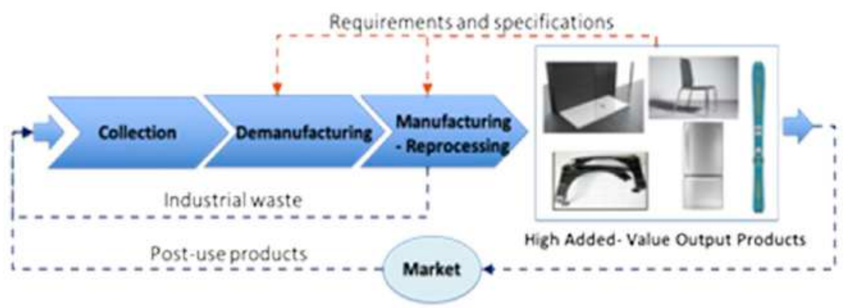

Fig. 1
Demand-driven approach in Circular Economy.

recycling or direct reuse). This step takes as inputs the dimensional distribution of the particles to be shredded and the target output distribution. The output will be the best grate to use in the size reduction process and the throughput expressed in mass per time interval.
The prediction and optimization is based on Population Balance Model discrete in time, describing the evolution of the mass distributions inside and outside the comminution chamber considering the probability of a particle to be broken or to exit from the process after one time unit.
The second step has as objective the minimization of operational costs, in particular due to energy consumption and tool wear. It takes as input the unitary throughput calculated in Step 1 and it gives as results the rotational speed and the throughput expressed in mass per time unit (as seconds or hours) through the minimization of the analytical model describing the behavior of the total cost in function of the rotational speed.
The developed solution has been applied to the specific use case of EoL composite materials, in particular Glass Fibers Reinforced Plastics (GFRP). Recycling of GFRP is typically performed through mechanical processes. The EoL products are shredded to a specific dimension and the fraction respecting the target characteristics is directly reused in new products. To unlock new circular value-chains in which the recycled material is inserted in high-added value products, the maximization of this fraction together with the minimization of the operational costs (to be competitive with the low market price of virgin glass fibers) is fundamental. The proposed solution has been applied to a real industrial case to recycle EoL GFRP sanitary products, leading to the final result that implementing the CPS solution the company would demanufacture and re-use an 81% higher throughput of material at 66% lower cost, also reducing the fraction of non-reusable materials that would be scrapped of about 30%.

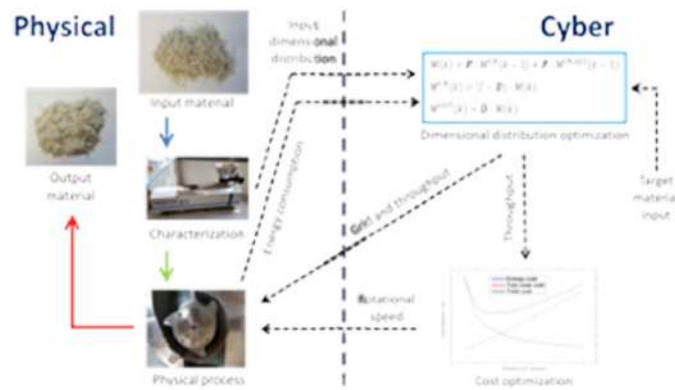

Fig. 2
2-step approach for the control of size-reduction processes.

INVESTIGATION ON METAL COMPOSITE CORRUGATED ENERGY ABSORBERS

Arameh Eyvazian - Supervisor: Prof. Massimiliano Gobbi

The crushing behavior of corrugated metal and metal-composite tubes under quasi-static axial compression is experimentally investigated. Several experiments were carried out to compare the failure mechanism of metalcomposite tubes with that of metallic tubes. The experimental results revealed that the corrugated metal-composite specimens exhibit excellent energy dissipation properties, including a reduced initial peak response and consistent load-displacement diagram. This indicates that the crushing behavior and energy absorption capacity of corrugated metallic tubes can be significantly enhanced by applying a composite filament-wound layer.

In this dissertation, a new developed axially corrugated thin-walled tube has been introduced for improving energy absorption characteristics. The forming process of the corrugations on the tubes has been also described. A comprehensive experimental and numerical analysis have been conducted in order to investigate the effects of various geometrical parameters on crushing behavior of the structure. It can be seen that by the use of such corrugation, there is much more efficient crushing via a more uniform force-displacement diagram while there is also considerable improvement in other crashworthiness characteristics. Subsequently, the experimental data is verified by a finite element simulation on all investigated tubes. An efficient model in axial loading has been obtained which is offering a perfect concertina form. The obtained model deforms through an inversion mode causing an extra frictional force between the inverted part of the tube resulting in a considerable increase in SEA, mean force, and consequently CFE.

Finally, the selected model has been investigated under oblique loading in different crushing angle where it exhibits improved performance. Moreover, The theoretical solution based on experiment and modified simplified super folding element (MSSFE) theory is proposed that depends on the number of plastic hinge line, wall thickness, length of structure and flow stress of material. The comparison between theoretical solution and experiment shows a good agreement with acceptable errors.

MAKE FLOATING WIND TURBINES SEE WAVES - ADVANCES IN FLOATING TURBINE CONTROL AND SCALE MODEL EXPERIMENTS

Alessandro Fontanella - Supervisor: Prof. Marco Belloli

Floating wind is a promising technology for harnessing wind energy in deep waters where conventional bottom-fixed turbines are not cost effective. Two examples of floating turbine are shown in Fig. 1. The price of floating wind energy is still high and technological advancement is needed to make it competitive with other energy sources. The last three years has seen the installation of the first pre-commercial floating farms, and in Europe we currently have 74 MW of floating wind. Europe wants offshore wind to be 25% of its electricity by 2050 and, to reach this target, 150 GW of floating turbines, a third of all offshore wind, must be connected to grid. Turbine control is a key area for reducing the cost of floating wind energy. Waves cause a large fraction of structural loads which can be mitigated by active control. In this way it is possible to extend the fatigue life and reduce the operating and maintenance costs of floating farms. Turbines are currently operated "in the dark", without any real-time information about the sea conditions around the machine. In this work, a new feedforward control methodology that counteracts the negative effects of wave excitation is explored. Radar is used to measure waves in front of the turbine and make this information available to the turbine controller. The real-time preview of the incoming waves is then used to control the wind turbine as shown in Fig. 2. The blade pitch angle is adjusted to produce a rotor-thrust force which ideally cancels the tower loads created by the waves. When the right balance between aerodynamic and wave forces is achieved, the structural loads for the turbine components are lower and this has a positive impact on the turbine fatigue life.

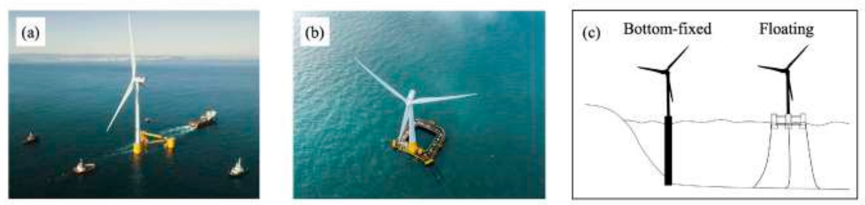

Fig. 1
Two examples of floating wind turbines (a, b) and scheme of the bottom-fixed and floating support structure (c).

Core of the new control methodology is a reduced-order model of the floating turbine, which captures the fundamental dynamics driving the response to wind and waves, but without the complexity of state-of-the-art simulation tools. The model of this work is based on quasi-steady aerodynamics derived from the static characteristics of turbine power and thrust. Hydrodynamic radiation and wave excitation are instead represented by linear-time-invariant parametric models, which are the result of system identification methods.

In recent years, several advanced control strategies for floating wind turbines were conceived, but their diffusion among the research community has been difficult and none of them found any application in the industry so far. One reason behind this difficult progress is the lack of reliable verification and certification methods. Hybrid scale model experiments can provide low-uncertainty validation data, at reasonable cost. Verification of turbine control strategies requires reproducing at small scale the global response of the floating turbine. Experience has shown this is hard to achieve in conventional wave basin tests, where the entire floating turbine is emulated by a scale model. Instead, in hybrid experiments the floating turbine is divided into two subsystems (see Fig. 3): one comprises the floating platform and waves, and the other consists of the turbine rotor and the wind environment. One subdomain is reproduced using a physical scale model and the other by using a real-time numerical simulation. Here, two hybrid experiments, one in a wind tunnel and one in a wave basin are carried out and examined to see the advantages of hybrid tests. A model-based methodology is developed to implement realistic control strategies in hybrid experiments, which are shown to overcome their conventional counterpart as a tool for validation of turbine controls.

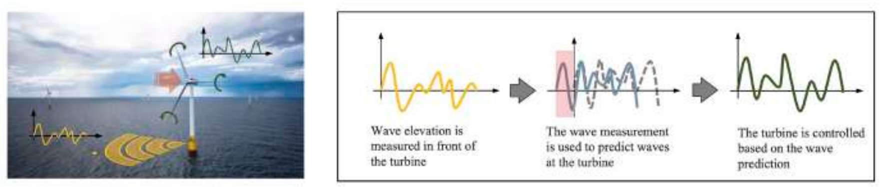

Fig. 2
Scheme of the wave-feedforward control strategy.

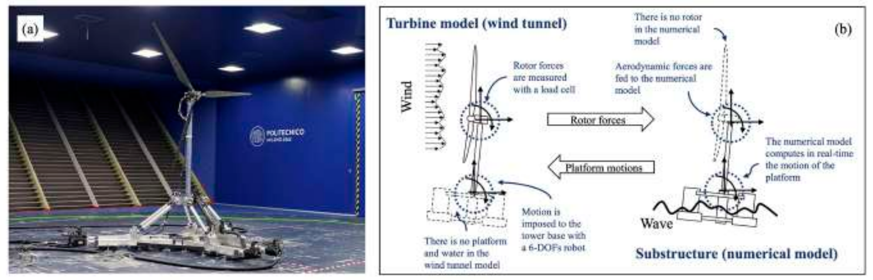

Fig. 3
Picture of the hybrid experiment at Politecnico di Milano wind tunnel (a), and schematic of the working principle (b).

ACTIVE SUSPENSION TECHNOLOGIES OF RAILWAY VEHICLE

Bin Fu - Supervisor: Prof. Stefano Bruni

Active suspension is an advanced concept in vehicle engineering, in which standard suspension components are combined to mechatronic components such as sensors, controllers and actuators, enabling a substantial improvement of vehicle dynamic behaviours with respect to passive suspension.
It provides the solutions to the new demands of higher speed, better ride comfort and lower maintenance cost for the new generation of rail vehicles.

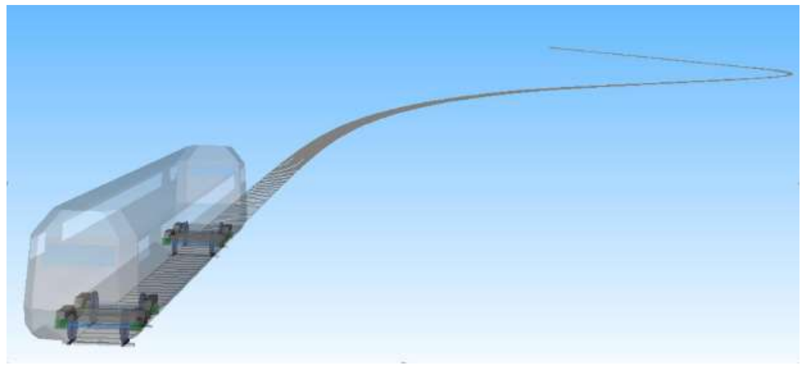

Fig. 1
Rail vehicle model

Tilting train, as a starting point of wide application of active suspension, has proved to be a great success, and more applications of other technologies are only a matter of time.
However, the implementation of active suspension technologies in rail vehicle is very slow and cautious, mainly due to two issues that need to be solved properly: safety and cost-benefit ratio.
The safety issue is concerned as the actuation system may fail in service and cause critical impacts. Therefore, a fault-tolerant design of the active suspension is crucial to ensure the safety even in failure of active suspension.
The cost-benefit ratio decides to which extent the implementation of the technology is worthwhile from the viewpoint of business value, which however is challenging to estimate.
The general motivation of this work is to facilitate the implementation of active suspension technologies in a real vehicle, see a rail vehicle model in Figure 1.
Active steering, as one of the most attractive technologies, is studied from the above-mentioned two aspects, to strengthen the perspectives for application of this technology in real service. In order to evaluate the fault-tolerant capability of the active suspension, a methodology is proposed based on Risk Priority Number (RPN) which is a core concept in the theory of Failure Mode and Effect Analysis.
The thesis proposed a new method in which a vehicle multi-body simulation is performed to assess the impact of typical failure modes of active steering, thus enabling the objective evaluation of the indexes defining the RPN.
Three principles for improving fault tolerance are analysed, including (i) adding passive spring as the backup, (ii) implementing an active suspension architecture with redundant actuators and (iii) reducing the number of actuators through the use of a mechanical linkage.
The evaluation of nine proposed schemes demonstrates that the redundant actuators can provide the overall best fault-tolerant capability in all considered failure modes.
To enable an assessment of the cost-benefit ratio of active steering on a quantitative ground, this thesis builds a wheel wear calculation program based on the KTH wear model. The removed material over wheel surface is simulated with the presence of active steering, based on which, the benefits of active steering in different track layouts are evaluated. Moreover, three control strategies for active steering are compared in terms of wheel wear evolution, see Figure 2 for the removed material over wheel surface. The first two steering schemes show good compromise between performance and ease of implementation.
With the trend of railway vehicle light weighting, car-body structural vibration is posing a new challenge to the vertical ride comfort, which is expected to be solved via mechatronic suspension.
This thesis explores four suspension schemes including active and semi-active technologies in secondary and primary suspensions, with LQG and H∞ controllers. The comparison of four schemes based on a 9-DOF vehicle model is summarized in a four-quadrant diagram, see Figure 3, showing that the full-active secondary suspension is the most effective solution, whilst the semi-active primary suspension can also considerably mitigate the car-body bending mode.
Afterwards, numerical simulation is performed based on a multi-body vehicle model built in SIMPACK and integrated with a finite element model of the car-body to represent car-body flexibility. The results highlight the features of each suspension scheme and show good applicability in a real vehicle.

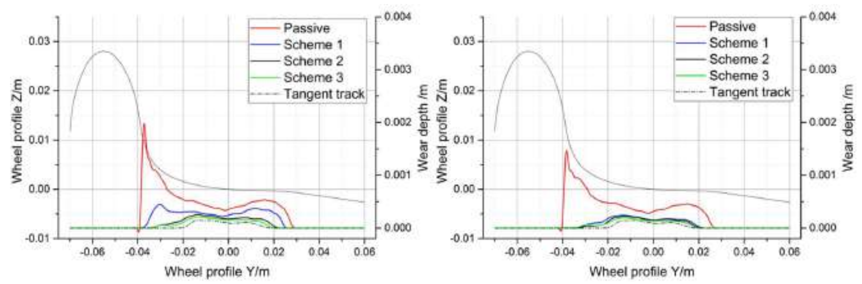

Fig. 2
Removed material in three steering schemes for Outer (left) and Inner(right) wheels

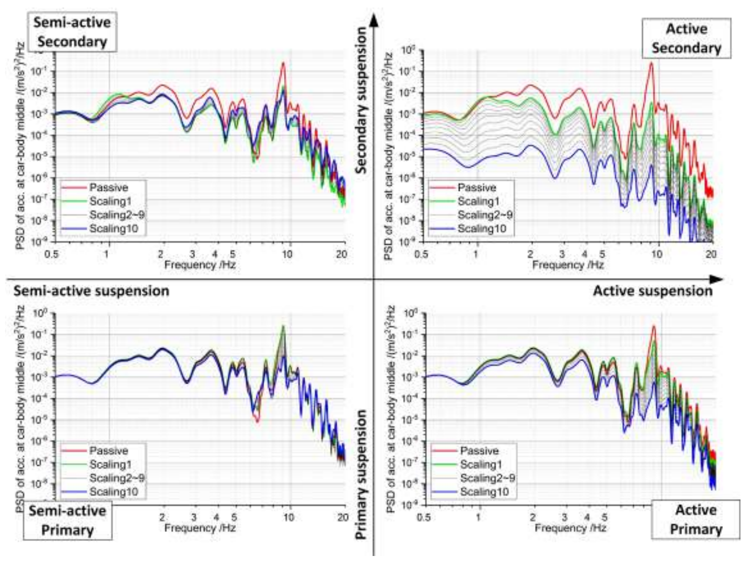

Fig. 3
PSDs of car-body vertical acceleration at car centre, based on 9-DOF vehicle model

MECHANICAL CHARACTERIZATION AND DESIGN OF LATTICE STRUCTURES FOR INNOVATIVE MULTI-FUNCTIONAL APPLICATIONS

Matteo Gavazzoni - Supervisor: Prof. Stefano Foletti- Co- Supervisors: Prof. Stefano Beretta, Prof. Simona Perotto

Lattice structures are periodic cellular materials whose geometry can be designed so as to obtain a unique set of physical and mechanical properties. Their implementation in innovative multi-functional design contexts allows to relax the constraints imposed by the use of common monolithic materials, thus giving extreme advantages. Despite the scientific literature provides a detailed insight about their physical, dynamic and mechanical behaviour, as well as their implementation for a broad range of applications, open points that hinder their diffusion and narrow their potential are still present. The aim of this doctoral research thesis is to fill some of the literature gaps on the knowledge of the effective mechanical behaviour of lattice structures and on the methodologies to design novel metamaterials.
The first part of the current work was dedicated to metallic lattice structures (Figure 1). A preliminary work was conducted on compression testing methods for lattices, given the lack of a comprehensive and general reference standard. The acquired knowledge was then applied in a following work, where the multi-axial strength of an aluminium lattice structure that exhibits a brittle behaviour was described and characterize numerically, focusing also on the effet of as-built defects. Finally, a third work on the experimental characterization of the random fatigue behaviour of a triply periodic minimal surface lattice structure was carried out. This topic represents a totally uncharted territory, yet of great relevance for all the applications where a component is subjected to variable amplitude cyclic loading.
The second part of the research focused on the cyclic behaviour of elastomeric lattices that undergo local instabilities during the deformation process. These metamaterials find important applications mainly in soft-robotics and in small biomedical pneumatic actuators. Although many works can be found in the literature about the static response of soft elastomeric lattices under uniaxial and multi-axial loads, their behaviour under cyclic loads is still unexplored. Experimental tests were performed and numerical models were built to better understand the coupled role of material non-linearities (non-linear hyperelasticity, creep and damaging), geometric non-linearities and manufacturing defects. It was found that the cyclic response is strongly affected by this coupled interactions and may significantly differ from the static one, as shown in the chart in Figure 2, thus highlighting the practical importance of considering the investigated aspects.
Finally, the last part of the thesis work was devoted to improving the state of the art design methods for novel cellular structures. The potentiality offered by lattices in multi-functional design can be extremely increased by the use of topology optimization at the micro-scale to obtain target effective properties, by means of an inverse homogenization technique. Despite this method is well established in the literature, it suffers from the typical problems of topology optimization, such as non-uniqueness of the solution, mesh dependency, checker-board, grey-scale, and staircase effects, together with geometric complexity issues. All these issues can be even exacerbated when performing the optimization at the micro-scale. To overcome these problems an inverse homogenization approach based on a mesh adaptation procedure was extended to a multi-physics environment where both elastic and thermal conductivity effective properties are controlled. In this scheme, an anisotropic mesh is iteratively adapted in the optimization loop, allowing to mitigate some of the typical issues of topology optimization and to obtain clean and smooth geometries, ready to be manufactured with a very contained post-processing. A schematic picture about this part of the research, together with some obtained results, is provided in Figure 3.

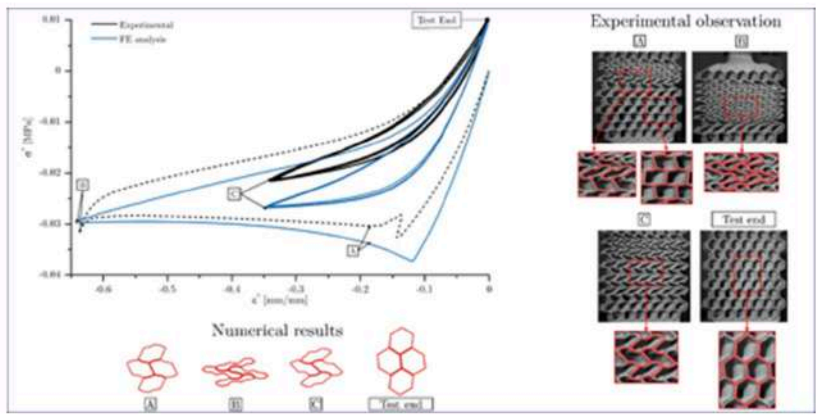

Fig. 2
Cyclic response of an elastomeric 2-dimensional lattice: experimental and numerical stress-strain response and deformed configurations

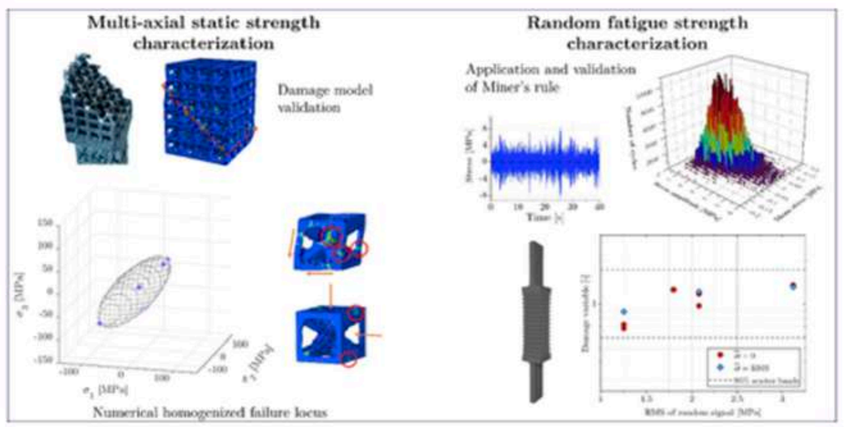

Fig. 1
Characterization of metallic lattice structures: multi-axial static strength numerical determination and random fatigue strength characterization for two alluminum structures

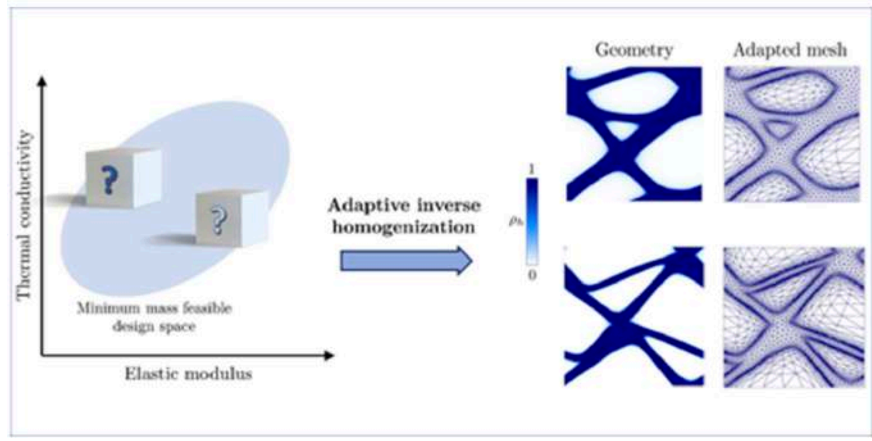

Fig. 3
Adaptive inverse homogenization for 2D thermo-elastic highly performant lattices

THERMAL RESPONSE OF COMPOSITE PCMS: THE EFFECT OF ARRANGEMENT AND COARSENESS OF THE STRUCTURAL PHASE APPLIED TO HYBRID PCMS

Ziwei Li - Supervisor: Prof. Elisabetta Gariboldi

In recent years, improving the efficiency of storage and use of energy has become a more urgent issue due to the growing world energy demand and environmental concerns. The Phase Change Materials (PCMs) that can release or store sensible and latent heat are meeting progressively more interests in the engineering field. Pure PCMs generally have low thermal conductivity, leading to slow thermal storage and, therefore, limited application. Composite PCMs (C-PCMs) can increase and tailor the thermal response of pure PCMs by combining a proper PCM phase and a high conductivity and melting temperature phase.

Paraffin-metallic porous composite PCMs are considered in the present study since they have several positive features. Paraffins are widely applied as PCMs because of their density of energy stored (of about 240 kJ/kg), combined with the possibility of modulating the temperatures at which melting occurs (in the present work, 20°C -110°C range) and material availability. Thus, classical uses for paraffins as PCMs are in the field of building and industrial thermal management systems. Metallic foams with open cell structure and high porosity can be filled by paraffins, obtaining composite PCMs with a significant increase in the overall thermal conductivity with the relatively low decrease of stored energy density.

The main aim of the PhD work is to offer simple methods to predict the thermal response of the above C-PCM, considering different geometrical features of the metallic phase, heat supply and orientation.

The first step has been to study analytical models for thermophysical properties independent of phase distribution for paraffin-porous metallic C-PCM. Firstly, extensive literature data and models analysis have been carried out for temperature-dependence of thermophysical properties of paraffins. Secondly, for paraffins melting in about 280 K-370 K range, optimal analytical descriptions have been proposed for the temperature- and composition-dependence of the heat of fusion and density, specific heat, thermal conductivity, and viscosity in the liquid state. Similarly, literature data and models of thermophysical properties of aluminium and copper have also been reviewed and analysed. In addition, the effective properties of C-PCMs independent of phase distribution, such as density and specific heat, have been calculated.

The second step has been to investigate C-PCM properties affected by the phase distribution, like effective thermal conductivity and permeability. The thesis first focuses on providing a tool to model effective thermal conductivity for paraffin-porous metallic C-PCM. Numerical methods like Lattice-Monte Carlo (LMC) and Direct Simulation (DS) method and analytical models have been set up and compared to predict effective thermal conductivity. In 3D structure, porous structures can be modelled (and in some case produced) as lattices with a regular arrangement of phases, like the simple-cubic (SC) model, face-centred cubic (FCC) model and body-centred cubic (BCC) model. Their effective thermal conductivity has been evaluated by the DS method, considering both different geometrical and material features and compared to available experimental data. The BCC model can be considered to be closer to high-porosity foam. Analytical models have been derived from results of sets of DS for paraffin/Al foams composite. In 2D structure, parameters of lattice and phase size in the LMC method have been optimised to obtain a reliable estimation of effective thermal conductivity with minimal experimental efforts. The LMC method has also been applied to 2- or 3-phase microstructure with experimental validation.

The next step has been to investigate the effects of porous structure coarseness on the thermal response and onset of natural convection in C-PCMs. Starting from this latter, which is analysed on a basic of RD number, the permeability of porous structures modelled as different lattices have been studied. A simplified analytical model derived from the Rayleigh-Darcy number has been proposed to estimate if convection motion exists in the liquid phase of the C-PCM differently oriented with respect to the heat source. The model has been validated by means of literature experiment data.

The last step of the thesis has been devoted to predicting transient thermal performance of composite PCMs, which, by their nature, are materials used to work during thermal cycles in non-steady situations. The thermal response of the material is not characterised by specific properties. Rather the transient thermal response of composite PCMs under simple service condition, is monitored in different points of the complex 3D structure by the DS method. The results showed that composites made by the same phases and volume fractions, and thus with the same effective thermal conductivity, display different thermal response depending on the material coarseness. The coarser structures, specifically under high heat flux, can no more consider the local temperature distribution within phases as homogeneous. This prevents the possibility to model the material as a homogeneous medium, which is a clear advantage in view of the engineering use of the material. Thus, the engineering validity ranges for the one-temperature volume-averaged (1T) method considering composite PCM as a homogenous medium has been investigated by comparing the heat response for paraffin-Al composite provided by it and the DS method considering both geometrical features (side length, porosity of BCC-modelled Al) and boundary conditions (heat input). Local error for the volume fraction of molten PCM (and thus stored energy) has been analytically described.

SURROGATE-BASED PERFORMANCE OPTIMIZATION FOR MANUFACTURING SYSTEMS

Ziwei Lin - Supervisor: Prof. Andrea Matta

The doctoral thesis, titled "Surrogate-Based Performance Optimization for Manufacturing Systems", authored by Ziwei Lin and supervised by Prof. Andrea Matta and Prof. Shichang Du, aims to solve optimization problems with high execution costs of the objective function and/or the constraint functions, such as time-consuming simulation models or physical experiments.

The complexity of manufacturing systems is increasing due to the development of mechanical technology and variable requirements in customer demands. Therefore, analytical methods, such as queuing theory and Markov chains, might have difficulty in providing highly accurate system performance estimates, because very strict system assumptions are usually required. As a consequence, simulation is frequently used to evaluate the systems recently, although it may be slow in execution. On the other side, the development of information technology allows us to capture and store a large amount of data generated in the production process. This makes it possible to evaluate the system performance based on real-time data. In the thesis, information with different fidelities from multiple sources (e.g., analytical methods, simulation models or data from the field) is integrated to improve the efficiency of the optimization method, reducing the number of function evaluations from high-cost sources during the optimization process.

Surrogate-based optimization is efficient for optimization problems involving expensive simulation models. A surrogate model is constructed based on the observed data, which can approximately and quickly predict the values of unobserved points so that promising points can be point out during the optimization. Faced with the three main contents of the surrogate-based optimization framework: the surrogate modeling, the initial design generation and the selection of infill points, three methods are developed in the thesis, as shown in Fig. 1.

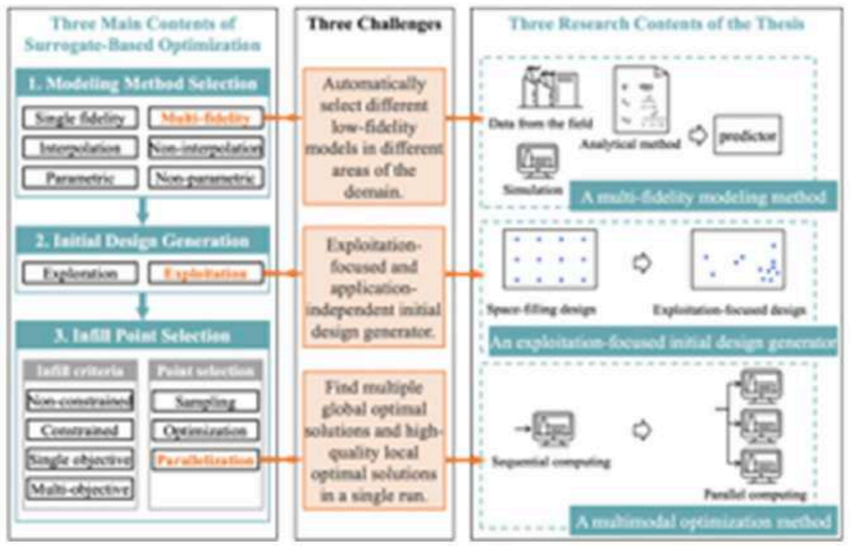

Fig. 1
The three main research contents of the thesis

The first one is a multi-fidelity modeling method, which is called Extended Kernel Regression (EKR). It combines high-fidelity data (e.g., outputs of highly detailed simulation models or data from the field) with multiple low-fidelity models (e.g., analytical methods or coarse simulation models) to improve the prediction accuracy of the constructed surrogate model under sparse data. A data-driven mechanism is embedded to judge and select different low-fidelity models in different areas of the domain. This is to deal with the phenomenon that analytical methods developed under different assumptions might have area-based accuracy. The second one is an exploitation-focused and application-independent initial design generator, which is called Budget Allocation for Quantile Minimization (BAQM). It concentrates the initial design points on promising areas to improve the prediction accuracy of the initial surrogate model in these areas, although it might scarify the accuracy in unpromising areas. Closed-form formulas are derived to iteratively sample the feasible solutions according to the observed data, thus, the developed method is easy to implement. The third one is a partition-based multimodal optimization method, which is called Partition-Based Random Search for Multimodal Optimization (PAR-MMO). It can capture multiple global optimal solutions and high-quality local optimal solutions in a single optimization run, which allows multiple infill points to be find in one iteration and the high-cost model (i.e., the high-fidelity model) can be performed in parallel. Compared to alternative methods in the literature, the developed method will not waste effort to search for local optimal solutions with poor objective function values. A production authorization card system is investigated as the case study and a surrogate-based optimization method, which is composed of the three developed method, is used to optimize the control parameters. The numerical results show that the optimization efficiency can be significantly improved in terms of the simulation budget.

The three developed methods solve the three challenges in the literature and outperform alternative methods in the studied cases. A Matlab toolbox for the EKR method is uploaded to the public repository so the engineers and researchers can implement it easily. The use of the low-fidelity models can help the surrogate-based optimization both in modeling (i.e., in the EKR method) and in initial design (i.e., in the BAQM method). In the proposed method, biased estimates can also provide useful information for the prediction and optimization if they are properly adjusted, thanks to the knowledge in the high-fidelity data. Thus, the huge asset of analytical methods established in the past can be used combining them with simulation output data or, even better, with data collected from the field. The possibility of merging information from multiple sources in a single framework might change the way in which low-fidelity models will be developed, focusing more on shaping the accuracy of the constructed surrogate models. A low-fidelity model, which has a high bias but contains the trend of the system performance, is preferable to a low-fidelity model, which has a low bias but is not highly correlated to the real system performance.

DESIGN, SIMULATION AND TESTING OF A COUPLED PLATE-CAVITY SYSTEM TARGETED FOR VEHICLE INTERIOR NOISE ANALYSIS AND CONTROL

Ling Liu - Supervisor: Prof. Roberto Corradi - Co-supervisor: Prof. Francesco Ripamonti

Nowadays, people are paying more and more attention to the acoustic comfort of vehicles, as well as the health issues caused by noise. The various types of vehicles including automobiles, trains, aircrafts and ships are all being requested for a better acoustic design, where the vehicle interior noise analysis and control are important. Computer-Aided Engineering (CAE) tools are now popularly used for these purposes, but engineers are always doubtful about their reliabilities. Besides, the currently available vibroacoustic methods are still far from satisfactory in terms of capability, accuracy or efficiency, especially for the analyses in mid-frequency range. New methods and codes are continuously developed, but they are hard to find suitable benchmark cases for assessment and validation. Therefore, to facilitate the CAE analysis of vehicle interior noise, this thesis presents a benchmarking and testing tool called Noise-Box. The Noise-Box includes the test equipment and its numerical models, so that it can provide both reference measurements and reference computations. The test equipment, designed as a plate-cavity system that is easy to model and analyse, can perform vibroacoustic tests that can be accurately reproduced by numerical models. Its ability to measure sound transmission loss and test noise control measures is also considered. The numerical models that simulate the test equipment, should accurately predict its behaviour. Three numerical methods are used in order to cover a wide frequency range. While Finite Element Method (FEM) and Statistical Energy Analysis (SEA) are respectively for the low- and high- frequency ranges, Wave Based Method (WBM) is applied and developed for its potential to fill the mid-frequency gap. Commercial software is used for the FEM, and self-developed codes are provided for the SEA and the WBM. Concerning the demand for 2D benchmark cases in developing new numerical techniques, validated 2D models of FEM and WBM are provided for the additional reference results.

To obtain such a tool, this work designs, constructs and characterizes the test equipment, and builds, validates and updates the numerical models. It is a big challenge to reach the agreement between the numerical models and the test system, and this thesis has overcome the difficulties through the following efforts:

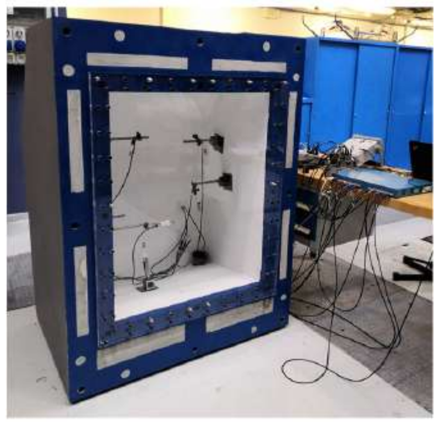

Fig. 1
Noise-Box cavity

Fig. 2
Noise-Box plate-cavity system

(1) When the plate-cavity coupled Noise-Box is designed towards the ideal conditions, its modelling considers the uncertainties in materials, manufacture and assembly. Especially, the plate edge conditions are modelled by elastic restraints to handle the uncertainty, where the stiffnesses can be updated based on test results.
(2) The Noise-Box is comprehensively and accurately characterized through experiments. Experiments are performed to the plate, the cavity and the plate-cavity system, respectively, covering different issues. Particularly, the modal parameters of the three situations are all precisely estimated through Experimental Modal Analysis (EMA), so that they can be the reliable reference for FE model updating, where the plate edge conditions are characterized.
(3) The numerical modelling techniques are strictly verified. Since the FEM results are important reference, both for updating the physical parameters of the real system and for validating the self-developed codes of WBM, the FE modelling techniques are first validated by benchmark cases, removing any doubt in element types, mesh control and boundary conditions. Then, the FE models are updated, and the updated models match well with the test system. Based on the FEM results, the WB models are also validated, during which the efficiency of WBM is demonstrated. The SEA models are built for the Noise-Box system to investigate the structure-borne noise and the airborne noise, respectively, and their validations are based on the open source software "SEAlab".

Finally, with its characteristics well-informed and its matched numerical models prepared, the benchmarking and testing tool Noise-Box, is ready for application. The thesis lastly has an initial test on this tool for structure-borne and airborne noise investigations, where the solutions from the test equipment and the numerical models are presented and compared.

It is considered that this dissertation has the following innovative contributions:
• Proposes a modified weighted residual formulation to WBM, extending the availability of the method for elastically restrained plates;
• Introduces a way to employ EMA for vibroacoustic systems, through which the modal parameters of both plate- and cavity-controlled modes are identified with good accuracy;
• Presents a novel benchmarking and testing tool that can benchmark different techniques for vibroacoustic analysis and test the measures for interior noise control.

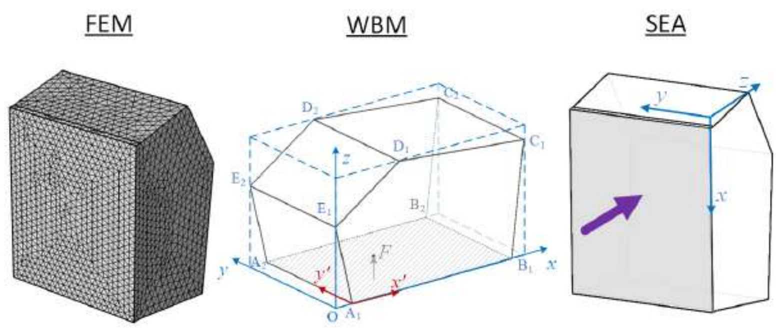

Fig. 3
Noise-Box numerical models

AUTOMATED GENERATION AND EXPLOITATION OF DISCRETE EVENT SIMULATION MODELS FOR DECISION MAKING IN MANUFACTURING

Giovanni Lugaresi - Supervisor: Prof. Andrea Matta

The latest developments in industry have involved the deployment of digital twins for both long- and short-term decision-making, such as supply chain management and production planning and control. The ability to take appropriate decisions online is strongly based on the assumption that digital models are properly aligned with the real system at any time. As modern production environments are frequently subject to disruptions and modifications, the development of digital twins of manufacturing systems cannot rely solely on manual efforts. Industry 4.0 has contributed to the rise of new technologies for data acquisition, storing and communication, allowing for the knowledge of the shop floor status at anytime. If a model could be generated from the available data in a manufacturing system, the development phase may be significantly shortened. However, practical implementations of automated model generation approaches remain scarce. It is also true that automatically built representations may be excessively accurate and describe activities that are not significant for estimating the system performance. Hence, the generation of models with an appropriate level of detail can avoid useless efforts and long computation times, while allowing for easier understanding and re-usability.
This research focuses on the development and adoption of automated model generation techniques for obtaining simulation-based digital models starting from the data logs of manufacturing systems, together with methods to adjust the models toward a desired level of detail.
The properties and parameters of the manufacturing system, such as buffer sizes, are estimated from data through inference algorithms. The system properties are also used in a model tuning approach, which generates an adjusted model starting from the available knowledge and the user requirements in terms of complexity (e.g., number of stations).
imental results prove the effectiveness of the proposed methodology in generating proper digital models that can correctly estimate the performance of a manufacturing system. The model generation and tuning method can positively contribute to real-time simulation. Indeed, its application within an online framework of production planning and control allows for adapting simulation models to the real system, potentially at any time a modification occurs. This way, decisions taken online are guaranteed to be referring to the current state of the factory. Thanks to this research, manufacturing enterprises will be able to reach a higher production flexibility, together with higher responsiveness to technological changes and market-demand fluctuations.
Since complex production systems may suffer from data with multiple part identifiers, the adoption of model generation techniques could result in the wrong finding of the system structure with traditional mining techniques. For instance, this is the case for systems that include assembly or disassembly operations. In this thesis, the problem of discovering manufacturing systems with assembly operations is described. The adoption of the new paradigm of Object Centric Process Mining is proposed to solve this issue. Further, an algorithm for the proper simulation model generation is introduced. The proposed approach has been applied to a test case and a real manufacturing system dataset, in both cases proving its applicability to realistic settings.

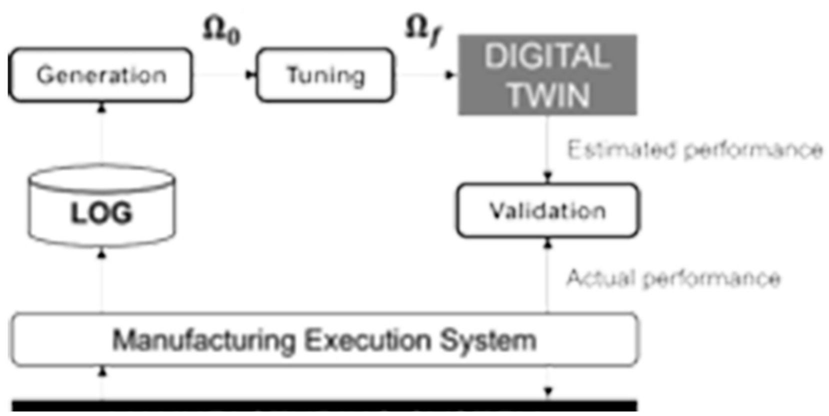

Fig. 1
Model Generation Framework Summary.

In addition, a lab-scale environment has been built with the aim to test decision-making frameworks based on digital twins within a realistic data infrastructure. The lab-scale models allow to reproduce material flows and the production control logic of real factory environments. Further, a software architecture aligned with industrial standards has been developed to allow for the lab- physical-digital integration. The laboratory has been used to set a real-time rescheduling problem on a Flexible Manufacturing System (FMS) model. The test involves simulation models aligned with the current system state for the online identification and implementation of a production scheduling rule that decreases the expected makespan. The results testify that the proposed lab-scale models can be used successfully to test production planning and control approaches.

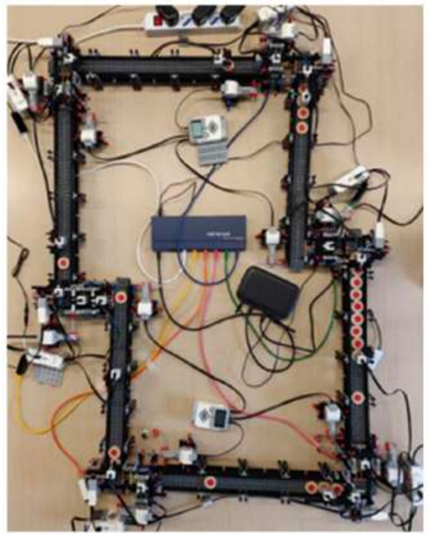

Fig. 3
Example of Lab-scale Model built with LEGO® components.

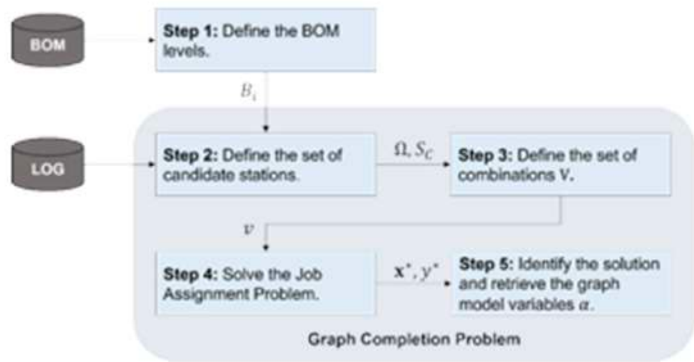

Fig. 2
Procedure for Model Generation in Case of Event Logs with Multiple Part Identifiers.

DESIGN OF COMPOSITE STRUCTURE WITH NANOPARTICLES TO IMPROVE IMPACT RESISTANCE

Dayou Ma - Supervisor: Prof. Andrea Manes - Co-Supervisor: Prof. Marco Giglio

Nanoparticles, showing capabilities to improve the mechanical performance and provide multifunctional properties, can be regarded as the ideal reinforcements for composite materials. The combination of composite materials and nanoparticles would widen the potential applications of composites in industrial fields, especially when extreme loading conditions are considered. However, their size poses several challenges. Modelling the effect of nanoparticles in composites materials requires investigations at different scales. In order to comprehensively understand the effect of nanoparticles on the physical and mechanical properties of composite materials, a multiscale virtual design approach may be an efficient methodology in a numerical framework.

Aim of this thesis was to investigate the effect of nanoparticles, with a special focus on the mechanical properties, while also considering their electrical conductivity, and to develop virtual design methodologies for further applications of nanocomposites under complex loading conditions, like impact cases. Based on experimental activities, the thesis developed numerical methodologies in a multiscale framework, as presented in Figure 1, to study the effect of nanoparticles on polymers and woven composites by modelling the mechanical and electrical behaviours of nanocomposites and related neat composites. Three main research lines were followed in the thesis: nanoparticles in polymer materials, nanoparticles in woven composites and multifunctional properties of nanocomposites.

In order to understand the effect of nanoparticles on the mechanical behaviour of materials, neat and nanoparticle-reinforced polymer were initially considered. The numerical investigation was firstly focused on tensile and fracture behaviours of neat polymer, while the capabilities related meshfree modelling methodologies were compared. It was verified that Mode-I fracture properties are mainly driven by tensile properties. However, further numerical work uncovered the existence of different damage and competing failure mechanisms through comparing nanoparticle-reinforced polymers with neat polymers, and it was found that the bridging of carbon nanotubes can increase the fracture resistance, while defects caused by nanoparticles may affect tensile properties. Based on these achievements, a modified peridynamic method was then proposed with constrained material points to replicate the effect of nanoparticles in polymer materials instead of creating their real geometries. This approach bridges different scales in the modelling process and allows to achieve efficient but very realistic mechanical simulations at macroscale.

Subsequently, the reinforcement of nanoparticles on fibre-reinforced composites were investigated, and reliable numerical modelling strategies, validated by experiments, were developed. Considering various scenarios during the service of composites (including impact events), a characterization of the mechanical properties under static and dynamic (high strain rates) conditions is needed. However, large variability in the manufacturing process would require a specific test campaign. In order to reduce experimental efforts,

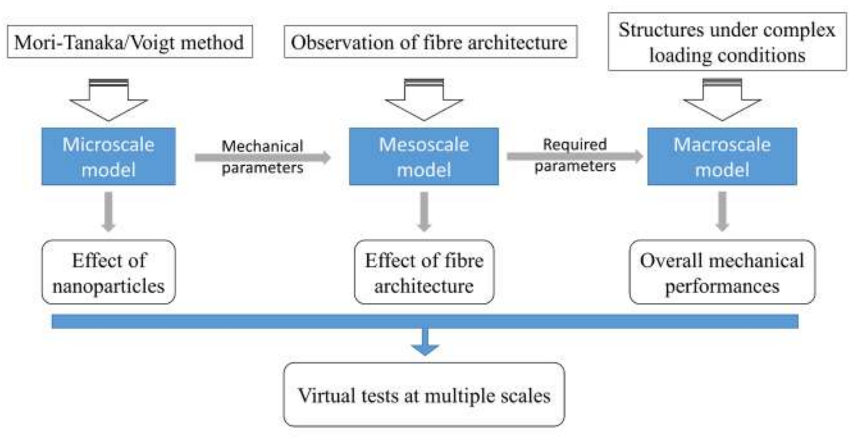

Fig. 1
Multiscale modelling strategy for nanoparticle-reinforced composite materials

a numerical modelling approach, able to assist in defining the mechanical properties of a generic composite starting from the data of the constituents under various strain rates, was developed for woven composites. The method was validated in a relevant environment, exploiting the material data in replicating ballistic tests with respects to the residual velocity and damage morphology. Furthermore, uncertainties in the fibre architecture were also investigated on neat woven composites by means of a multiscale modelling. Resulting from both works on neat woven composites, a numerical method coupled with a theoretical model was developed for the reproduction of the behaviour of nanoparticle-reinforced woven composites under low-velocity impacts. Moreover, the electric conductivity, provided by tunnelling effects from carbon nanotubes, attracted attentions in experiments. This effect can be potentially applied for structural health monitoring. Through measuring the electric conductivity during the tensile and fracture tests, the presence of damage/cracks on the samples was correlated with the changes in conductivity. In addition, considering that the quantification of nanoparticle distributions inside materials remains a challenge in the field of nanocomposites, the electric properties were inversely used to determine the distribution of nanoparticles.

In conclusion, the thesis explored the effect of nanoparticles on the mechanical and multifunctional properties of composite materials enriched with nanoparticles. A comprehensive investigation was carried out including both experimental and numerical works, as shown in Figure 2, considering multiple scales and the uncertainty of materials. Furthermore, the related numerical works paves the way for the development and boost of design by analysis methods of such kinds of materials even in a very harsh and extreme loading environment.

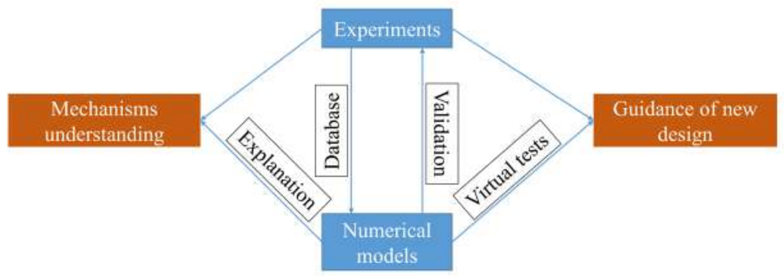

Fig. 2
Experimental and numerical activities in thesis work

PARAMETRIC REDUCED ORDER MODELS FOR IMPERFECT STRUCTURES WITH GEOMETRIC NONLINEARITIES

Jacopo Marconi - Supervisor: Prof. Francesco Braghin - Co-Supervisor: Prof. Paolo Tiso (ETH Zürich)

In common engineering applications, design and analysis of complex systems is bounded to undergo a phase of numerical studies, which are fundamental to fill the gap between preliminary results, usually based on simplified analytical models, and reality. Structural dynamics is normally studied with the aid of the Finite Element Method (FEM), which consists in accurately reproducing the geometry of a real structure through the union of small elements, each one pertaining a portion of material of the whole structure. The more the model is complex and the more the model is rich of geometrical details, the more elements are required; this usually leads to models counting hundreds of thousands or even millions of unknowns, whose numerical analysis can be extremely expensive in terms of computational resources and times. For these reasons, since the very origin of FEM (and even more then, when computational resources were much more limited than the ones available today), there have always been a struggle to develop strategies to reduce the complexity of the problem. First examples are to be found in the so-called modal analysis, where the full solution of the system is sought in terms of a weighted sum of a relatively low number of system eigenvectors (usually in the order of tents); this way, simulation times are greatly reduced. Modal analysis and its derivative methods, however, provide a solution only to problems featuring a dynamics which can be considered to be linear. When a structure undergoes a displacement which is relatively large with respect to its characteristic dimensions, usually the hypothesis of small deformations does not hold anymore: we talk in these cases of geometric nonlinearities and one has to resort to nonlinear dynamic analysis. The numerical complexity of the latter, however, is further increased by the fact some quantities (such as elastic internal forces and stiffness matrix) are now displacement-dependent and need to be evaluated at each analysis step/iteration of the adopted numerical scheme. For practical interest applications, this usually exponentially increases the computational times associated to the single analysis, often already demanding in the case of linear dynamics. Moreover, several phenomena that can be found in nonlinear dynamics and that have no counterpart in linear dynamics require specific numerical tools to be studied; the latter, however, usually can handle only a very limited number of unknowns.

For these reasons, the development of NonLinear Reduced Order Models (NL-ROM, or ROM in short), is a research topic which gained ever increasing momentum over the last decades. Several solutions are already available in literature, which will be briefly addressed throughout the present dissertation. A theme that almost every method shares, however, is the fact that the construction of the ROM itself is usually an expensive process which, in fact, may hinder the efficiency of the method. A way to amortize these offline construction times is thus to have the ROM to be parametric (pROM), that is, valid over a set of one or more parameters rather than for a single instance of the structure. This way the pROM can built once and used multiple times, so that the attainable overall speedups can be very high.

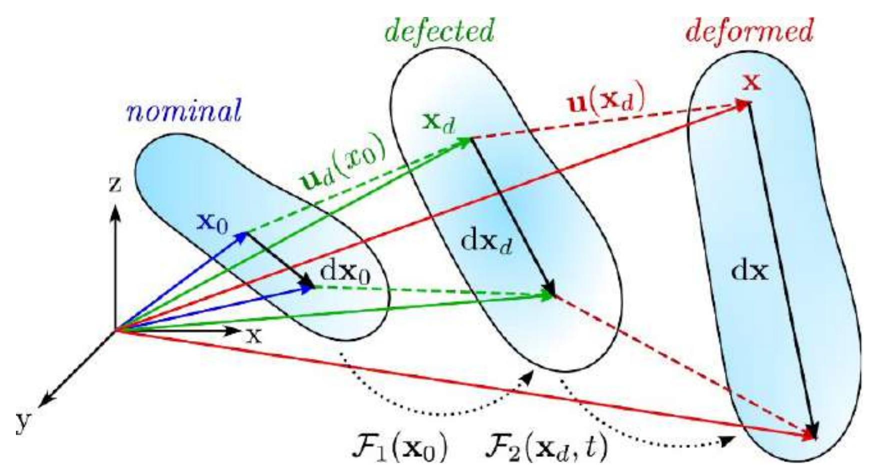

Fig. 1
Two-step deformation scheme.

In the present dissertation, after introducing some rudiments of nonlinear FEM and of a class of ROMs, some nonlinear pROMs for the analysis of structures affected by the presence of defects are developed and discussed. Indeed, in many engineering applications it is important to assess the performances of a system not only in the nominal-blueprint case, when the geometry is "perfect", but also in the case in which small imperfections are present. Notable examples are the micro electro-mechanical system (MEMS) industry, where the characteristics of the sensors are directly related to the imperfections of the production process, and the aerospace field, where the presence of lightweight and slender structures undergoing high-amplitude vibrations usually triggers nonlinear responses strongly affected by the imperfect geometry of the real components.

The proposed methods rely upon the parametrization of a two-steps deformation scheme, depicted in Fig. 1, where first transformation corresponds to an imposed defect of the nominal structure. Following, the nonlinear internal forces of the structure can be approximated to retrieve a polynomial formulation, enabling the use of tensors for the fast online evaluation of the model. The small size of the model, the parametrization and the tensorial formulation for the internal forces all contribute to provide significant speedups of the analyses, in time and frequency domain, compared to the full order model. Usually, the speedups exceed a factor 100x. In Fig. 2, the results for a straight beam, clamped at both ends, with an imperfection in the form of an arc, are shown. A detailed assessment of the different versions of the Defect-parametric ROM (DpROM) are discussed and compared on several examples, with particular emphasis on MEMS applications.

Possible future developments and applications will see the use of DpROM together with statistical methods, such as Monte Carlo analysis, to predict the distribution of the performances of structures and devices.

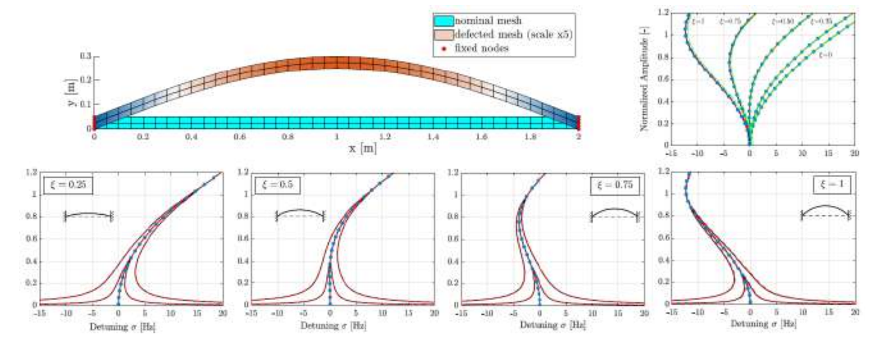

Fig. 2
Straight beam transformed with a shallow arc defect. The frequency responses correctly capture the transition from hardening to softening behavior.

ON THE ROLE OF KINETIC POWER ON THE CUTTING CAPABILITY OF THE ABRASIVE WATERJETS

Francesco Perotti - Supervisor: Prof. Michele Monno -
Co-Supervisor: Prof. Massimiliano Pietro Giovanni Annoni

Contemporary abrasive waterjet (AWJ) cutting processes mostly rely on empirical model of the cutting quality, in terms of the most important process parameters, avoiding any in-line closed-loop control strategy. However, the increasing development of the Industry 4.0 has been representing a driver of change in different manufacturing sectors, like the AWJ technology. In this framework, the physical signals, coming from the process, could represents a valuable set of information for the development of in-line monitoring and diagnostics of the cutting process, which is considered as a cold mechanical material removal process. However, the performance of the cutting, is evaluated on the manufactured part, by measuring its geometrical features. Predictive models of the cutting quality has been developed through the correlation between some control factors of the process and the experimental data. To this purpose, the development of an in-line monitoring strategy of the jet power would improve the supervision of the process with a better control on the cutting quality.
The material removal theory in abrasive waterjet cutting has identified the kinetic power of the abrasive particles flow, as the physical quantity which influence the abrasive waterjet cutting capability. Hence, it would be extremely important to monitor and control this quantity during cutting operations. However, a lack of a systematically investigation of the influence of the jet power on the spatial profile of the cutting kerf was found.
This thesis work concerns an experimental investigation about the influence of the kinetic power of the abrasive particles flow in the abrasive waterjet (AWJ) cutting process, with application to the effect on the spatial profile of the cutting kerf. Results have strengthened the material removal theory in AWJ, highlighting how the jet power could be considered as a reference energetic parameter which explain different aspects of the AWJ cutting performance, like the kerf width variability along the cutting depth. Said results may be useful for the fundamental comprehension of the material removal process, specifically the understating of the taper angle, is fundamental since it represents a geometrical defect, which is considered a detrimental effect on the quality of the part. The mechanical power of the abrasive water, i-e., the jet power, was found to be a fundamental quantity which explains the temperature distribution during the cutting process. An experimental study of the monitoring of the temperature distribution has been proposed in the present thesis. Results showed how the thermal field resembled the well-known case of a distributed heat source, which plausibly arose through the transfer of a fraction of the jet power as thermal power to the workpiece, because of the continuously friction of the abrasive particles with the target material The second part of the thesis work has been focused on the development of an in-line measure strategy of the jet power, during the abrasive waterjet firing stage, exploiting the vibrations emission from the cutting head. The operational vibration can effectively be exploited as the monitored variable for closing the control loops of the water pump and the abrasive feeder, thus improving the process stability, as well as allowing the process tracking. With respect to the previous state of the art, the present approach does not entail the presence of sensors on the workpiece. This feature is expected to make the setup more robust and compatible with day-to-day operations of a real production environment.

ON APPROXIMATE SOLUTIONS FOR IMPROVED PRACTICABILITY IN ACOUSTIC AND ELASTIC CLOAKING

Davide Enrico Quadrelli - Supervisor: Prof. Francesco Braghin

Cloaking refers to the idea of making an object invisible with respect to probing incident radiation. This is achieved by surrounding such object with an opportunely designed coating (called cloak, from Harry Potter's well-known cloak of invisibility) that forces waves to "bend" around the target in such a way that not only they are not reflected back, but also the wavefronts are reconstructed past the obstacle as if it were not there, eliminating shadows. The last decade has seen a constant growth of this research field in all the physical realms of wave propagation, fuelled by the simultaneous development of metamaterials, i.e. composites that unlock the possibility to achieve unconventional applications. The first part of this work deals with acoustic cloaking, whose chief application field is in avoiding detection of submarines by sonar systems. In order to bend waves in the desired fashion, inhomogeneity and anisotropy of wave propagation speed is required for the fluid material that implements the cloak, and this, in the setting of acoustics, traduces in the requirement to engineer a composite showing inertial and/or elastic anisotropic equivalent properties, while maintaining the dynamic behaviour of a fluid (only longitudinal waves allowed). The exact prescription of the spatial distribution of material properties can be computed using the so-called Transformation Theory, where the metric change coefficients introduced in the wave equation by an appropriate coordinate transformation are reinterpreted as material properties. This approach is in general easy to apply only for simple cases, as for example cloaking of circular or cylindrical objects, where the map can be handled in spherical/cylindrical coordinates. Here we discuss the use of elliptical coordinates to define quasi-symmetric transformations that make possible the design of invisibility devices for elliptically shaped obstacles comprising anisotropy in the elastic tensor only, avoiding in this way the increased complexity of non-scalar densities. This is done at the cost of introducing some approximating assumption that partially reduces the performance. The focus is put on elliptical shapes in part because typical submarine cross sections are not exactly circular, exhibiting a major and minor axis. Composites with fluid-like behaviour that simultaneously exhibit anisotropic elasticity are also known as pentamode materials and can be realized by engineering a microstructured lattice of trusses that meet at very tiny joints, embedded in a soft matrix. The final geometry is obtained by structural optimization driven by long-wavelength homogenization, computed based on the dispersion relation of said artificial lattices (Figure 1).

Figure 1: Unit cell adopted to implement the required pentamode material properties (left). Manufactured cloak (right).

The use of the introduced method thus allows for the numerical and practical experimental validation of a non-axisymmetric cloak that is used for scattering reduction in the underwater environment.
In the second part, the attention turns to elastic cloaking. In this case, the goal is to render an obstacle "invisible" from the perspective of elastic incident waves propagating in solid materials. Following the same approach used for the acoustic case, perfect cloaking for both longitudinal and transverse waves is in theory achievable only assuming to employ materials characterized by exotic constitutive behaviours, e.g. elastic solids showing the Willis coupling, with possible non-symmetric stress. In order to avoid such complexities, we firstly decouple the Navier equations for isotropic media in two scalar wave equations for displacement potentials, and then apply the formalism of conformal mapping to such equations aiming at designing carpet cloaks that employ only isotropic materials characterized by a slow (adiabatic) gradient of density. In doing that, we can clearly underline the approximation that need to be introduced by neglecting in the equations the terms related to said slow variation of density, providing the designer with an estimate for the degree of non-ideality implied in his design. Numerical tests show that cloaking is achieved for both in plane and out of plane motion. Special attention is also given to surface waves: as an example of application, it is numerically shown that a Rayleigh wave propagating at the interface between a solid and vacuum can overcome a defect of the surface without any mode conversion to a bulk wave (i.e. without losing energy in the interior of the material) when said defect is surrounded by the cloak (Figure 2).
A common thread links the two parts of this thesis, i.e. finding approximate solutions to the cloaking problem, with the goal of improving feasibility and practicability: in the acoustic case, the quasi.symmetric transformations allow for use of pure pentamode materials without any anisotropy in the inertial properties, and without any spatial variation in elasticity, while in the elastic case, the conformal mapping allows to obtain cloaks with isotropic elastic materials, avoiding impractical constitutive models like those characterizing Willis materials.

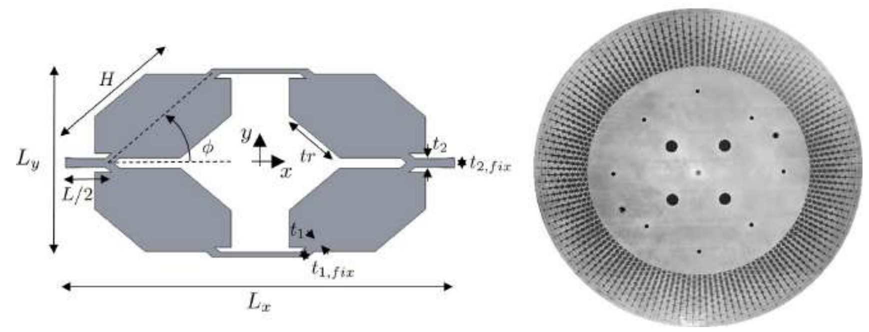

Fig. 1
Unit cell adopted to implement the required pentamode material properties (left). Manufactured cloak (right).

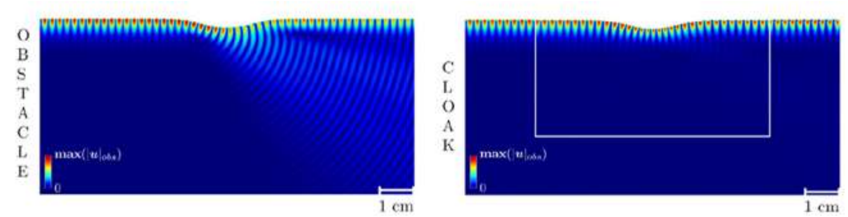

Fig. 2
Elastic cloaking for a Rayleigh wave.

OPTIMIZATION OF SET-UP CONDITIONS FOR STABILITY OF THE CENTERLESS GRINDING PROCESS USING PHYSICS-ENHANCED MACHINE LEARNING TECHNIQUES

Hossein Safarzadeh - Supervisor: Prof. Michele Monno - Co-Supervisor: Dr. Marco Leonesio (CNR)

This research presents novel methodologies and analytical tools for the set-up, monitoring and control of plunge centerless grinding aimed at workpiece roundness improvement. Firstly, an original rounding stability analysis has been developed, which considers the nonlinearity associated to wheel-workpiece detachment under large waviness. The loss of contact is approximated by a harmonic linearization, in the frequency domain, by a Double Input Describing Function (DIDF). The stability analysis shows the effects of clipping and structural compliance: both clearly produce a waviness with a quasi-integer number of lobes. Our approach removes the need of additional hypotheses, sometime found in the literature. Under increasing lobes amplitude, clipping reduces waviness growth rate until a limit cycle is reached.
Then it shown that, it is not always convenient to have a fixed setup angle. Based on simulation results it is suggested to consider the raw workpiece profile before selection these parameters accordingly to the type of raw workpiece roundness error (odd or even lobed). It was found that changing the setup angles from an initial appropriate point to a final point results in better simulated and experimented roundness. This changing was simulated with two methods, continuous and multistep but the best results was achieved by first one. Furthermore, a new support blade design for through feed centerless grinding is presented for application of above-mentioned method.
New modeling approaches have been developed, to predict process outcomes and allow parameters optimization. In deterministic models, uncertainties affecting the various parameters are not explicitly considered. Complexity in centerless grinding models arises from phenomena like contact length dependency on local compliance, contact force and type of grinding wheel, unpredicted material properties of the grinding wheel and workpiece, precision of the manual setup done by the operator, wheel wear and nature of wheel wear. In order to improve the overall model prediction accuracy and allow automated continuous learning, several Machine Learning techniques have been investigated: a Bayesian regularized neural network, an SVR model and a GPR model. To exploit the prior knowledge embedded in physical models, hybrid models are proposed, where neural network, SVR and GPR models are fed by the nominal process parameters enriched with the roundness predicted by the first principal model. Those hybrid models result in an improved prediction capability.
Then an innovative method based on a convolution neural network approach is presented for grinding wheel wear monitoring in plunge centerless grinding. In this approach instead of utilization of manual features extraction in traditional methods, the presented technique incorporates automatic signal processing and pattern classification in one model, to achieve a novel wheel condition monitoring system. To do so, thirty different combination of signal processors and CNNs were studied, and their classification accuracy were measured and the best combination for the dataset in this study was found.
Seeking a more robust solution for process parameters set-up, a completely new perspective has been investigated, consisting in the possibility of varying some geometrical parameters (stepwise) within the single workpiece cycle. This activity leaded to the deposit of two patents. First one is about new mechanism of height variation by numeric control system and later one patents a new technique to prevent instability due to rounding mechanism in plunge centerless grinding thanks to first patent. It is based on a piece-wise variation of the WP height during the process. Each height variation divides the process into two (or more) different stages; thus, the overall process is called multistage. The height variation disrupts the self-exciting geometrical loop that is the origin of the rounding instability, thus avoiding the formation of lobes around the WP. Even though the technique can be generalized for an arbitrary number of stages, we will show that two stages are enough to satisfy stability requirements.

DEVELOPMENT OF METHODOLOGIES TO SUPPORT SUSTAINABLE BEHAVIOR THROUGH VIRTUAL AND AUGMENTED REALITY

Giulia Wally Scurati - Supervisor: Prof. Francesco Ferrise

Sustainable development is nowadays a major concern, requiring to reach a series of urgent environmental, social, and economic targets. To achieve them, technical and legislative interventions are not sufficient: there is a need for individual, collective, and systemic change rooted in human behavior.
As consumers, communities, in our institutional and professional roles, we all contribute to sustainability-related issues, and we should participate in their resolution.
In this situation, the role of design and engineering disciplines and practitioners is becoming increasingly important.
By developing artifacts, interfaces, and environments, designers and engineers shape the contexts where people take actions and make decisions and inevitably affect users' behavior.
This can have a great impact on resources' consumption, conservation, and distribution. Hence, it implies great responsibility and power, as acknowledged by the field of Design for Sustainable Behavior (DfSB).
However, the study of human behavior is not a typical subject in technical fields and education. DfSB researchers have accomplished a great effort to take this knowledge from psychology to design and engineering, leading to the creation of several design tools. Nevertheless, the integration of DfSB approaches in the industries is not immediate and trivial. Designing for behavior change merges two extremely complex subjects: human behavior and product development. The former is hard to define, including deliberate choices and habits that we mindlessly replicate, both affected by several variables and difficult to predict. The latter includes a set of tasks, stages, specific technical and legislative
standards, it is influenced by the market, and conducted under time pressure. Involving sustainability objectives in the equation makes it even more challenging, implying multiple interrelated social, environmental, and economic problems. Augmented and Virtual Reality (AR and VR) can support designers, researchers, and organizations facing this complexity.
AR adds information and stimuli into existing contexts, environments and artifacts. It is a tool to directly affect users' interaction with the surroundings, their actions and choices. An example is the development of eco-driving systems, providing feedback to users that make them realize the consumption of resources due to their driving style and persuade them to change it to reduce their environmental impact. Feedback can involve different sensory modalities: a possibility is using haptic stimuli (Figure 1).
VR allows creating new hypothetical scenarios, replicating and manipulating present or future ones. It is a tool to create awareness and make people experience desired, or undesirable situations, related to sustainability issues. An example is showing consumers the effects of their choices, (e.g., plastic waste due to bottled water consumption), displaying collective and long-term consequences (Figure 2).
Both these technologies have a great potential to affect human behavior.
They can also support product development activities from concept design to testing and validation of new solutions, improving decision-making processes and collaboration. To reach these objectives it is possible to use a variety of approaches (e.g., visualization, persuasive techniques, serious games).
Serious games allow representing particularly complex systems and situations, merging entrepreneurial and engineering activities with sustainable development, and integrating different perspectives. An example is their use to make practitioners aware of the use of conflict minerals (extracted in conflict areas). A game can effectively represent risks and opportunities related to strategic and operational decisions from a sustainability perspective, managing unpredictability (Figure 3).
This thesis regards the development of methodologies for designers to support sustainable
behavior through AR and VR, contributing to enable change in design and companies'
practices, as well as in users and society.
A variety of approaches are explored, providing directions for their use in specific situations, and suggesting how AR and VR technologies could be integrated depending on the context, user, and objective.

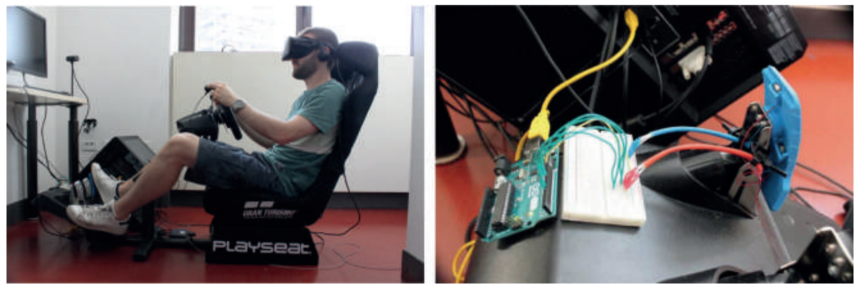

Fig. 1
Experimental set up (right) and eco-driving haptic pedal (left).

Fig. 2
Representation of individual and collective plastic bottles consumption over time in a VR environment.

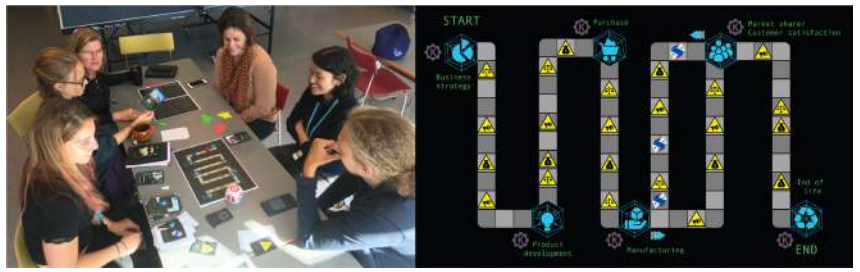

Fig. 3
A serious game regarding conflict minerals developed for an aerospace company.

COMPUTATIONAL STUDIES FOR ARTIFICIALLY SIMULATING HUMAN COLLABORATION IN DESIGN TEAMS

Harshika Singh - Supervisor: Prof. Gaetano Cascini -
External Co- supervisor: Dr. Christopher McComb (The Pennsylvania State University)

Collaborative teams are getting more and more popular. There is a current need to understand how the complex and dynamic system formed by collaborative teams behave when system parameters are changed to see their impact on project outcomes. Research in the past has focused on studying the single elements of the collaborative design like design task, design team structure, design tools and design process (idea generation and idea selection). Understanding the complete system of the design team collaboration is challenging to the researchers as it increases complexity. Therefore, the purpose of this research is to increase the understanding of a collaborative system composed of teams, task and its collaboration environment through an agent-based model called MILANO (Model of Influence, Learning, and Norms in Organizations).

This computational model is implemented using the Python programming language. MILANO is developed to mimic design team collaboration of the real world, hence it serves as a platform to study and simulate different scenarios of team dynamics that are challenging to control in a laboratory setting. The model is composed of agents that are analogous to humans in design teams who work on a design task by collaboratively generating and selecting solutions. Similar to the real world, the selected solutions are proposed to the controller agent (equivalent to a leader or manager to a problem-solving team), who provides feedback to the team. The research is broadly composed of three parts that fulfil the main purpose of the study. The first one is related to the common scenario where certain individuals who have high social influence (referred to as influencers) than others in the team, affect individual thinking during idea generation and selection. This is further investigated by varying the nature of the design task and the size of the team. The second part is related to the team compositions of experience and novices and their impact on the design outcome when changing the nature of the task. The last bit of the work is related to studying the impact of the collaboration environment (i.e., virtual vs face-to-face team collaboration) on the design outcome for various test cases (like teams with an experienced agent, half of the team with high self-efficacy, all agents with same self-efficacy and all agents with same self-efficacy working on a complex design task).

Though most of the model formation is based on the past literature and theories, it also has some assumptions and at times needed logical validation. These assumptions were validated through empirical studies conducted in the real world. The empirical results also provide insights into the relationship between model parameters and verified the logics behind its foundation. Although, agent-based modelling is an effective approach for simulating collaborative design teams, the validation of the entire model difficult, especially if there are plenty of parameters to control in a real-world setting. Therefore, continuously validating and verifying the model rationale by means of empirical studies, adds to the strength of the model and its results.

The extracted simulation results of the design task outcome were measured in terms of quality, exploration and other team performance parameters like the contribution of team agents. Broadly speaking, the model simulation results showed how varying the parameters of the collaboration design affects the outcomes of a design project. For example, different influencer- team composition has a significant difference in the generated solution quality of their team members. Moreover, having an experienced agent in a team of all novices can increase the quality of the solutions while reducing the variety. Likewise, having half of the team members as more influential, could results in a better outcome when the team collaboration is virtual. From the results, it is clear that a type of team that is effective in one situation might not perform well in other situations. Besides, studying the social, cognitive and environmental factors that were unaccounted for in the past literature, this research introduces a novel way to stimulate learning in agents and metrics for measuring design outcomes related to artificial creativity. Most of the research findings conform to the literature, this suggests that MILANO could be used to study collaboration in design teams can provide meaningful insights into team formation and management. These findings could be useful in determining appropriate team and task management strategies to obtain near-optimal project outcomes in organizations during the early design phase. In academia, the model that artificially simulates human collaboration could be used as a faster approach to gain insights into different design team collaboration scenarios.

DYNAMIC CHARACTERIZATION OF NORMAL-CONDUCTING MAGNETS FOR PARTICLE ACCELERATORS

Stefano Sorti - Supervisor: Prof. Francesco Braghin

Magnets are one of the most important components in particle accelerators. They provide a mean to control the flow of particles, called beam, by changing its direction and its profile. Different designs, technologies and operating principles are employed for magnets, depending on the task to fulfill. This work focuses on normal-conducting magnets operated in pulsed mode. This category of magnets typically requires to handle non-linear, hysteric materials, coupled with eddy currents, due to the time-varying field. Simulations are mostly unable to reach the accuracy levels required for accelerators, therefore magnetic measurements are required. The result is that normal-conducting magnets are ultimately regarded as black boxes inside particle accelerators.

This thesis wants to pave the way to a novel paradigm for these devices. Simulations and measurements should not be considered as two consequent steps in magnet development, but they can, and should, cooperate in returning a complete description of the magnet. Within this principle, this work develops both measuring instruments and numerical tools for characterizing normal-conducting magnets. The first part of this work focuses on magnetic measurements. A novel magnetomechanical model for induction coils is developed and employed in the design of a measurement system. This model allows unprecedented control over the mechanical properties of the device, to achieve the desired level of accuracy even in critical conditions, while pushing the capabilities of the device to its limits. These aspects allowed the design, construction and operation of a novel measurement bench, which is specifically devoted to the task of characterizing normal-conducting magnets. The second part is instead devoted to numerical methods. A physical model, based on integral formulation, is developed, together with model-order reductions and modelupdating methods for data-driven corrections. According to the author's best knowledge, this approach is a novelty for particle accelerator magnets. The ultimate goal of the research initiated by this thesis would be the construction of a digital twin for normal-conducting magnets. This twin would guarantee strong reliability thanks to the underlying physical model, while providing high accuracy by data corrections.

MANUFACTURING DATA INTEGRATION IN MACHINE TOOLS TOWARD THEIR ON-FIELD-IMPLEMENTATION IN THE ERA OF INDUSTRY 4.0

Francesco Sortino - Supervisor: Prof. Massimiliano Pietro Giovanni Annoni

Industry 4.0 is nowadays a concept rooted in global manufacturing realities and the permeation of these technologies is reaching small and medium-sized enterprises (SMEs), which in Europe are the primary source of industrial gross domestic product. Data and the interconnection between production resources are the basis of this new manufacturing paradigm, but research and enterprises are still far from expressing its full potential. Several initiatives to support these models have been promoted by European member States aiming at models of connected shop floors and technologies such as Cyber Physical Systems (CPS).

Real shop floors are still far from the models of connected factories reported in literature, as a fragmentation of the process data hinders horizontal interconnections. This is mainly due to the presence of legacy machinery, not always up-to-date and therefore not always able to display structured data through numerical controls. In addition, Original Equipment Manufacturers (OEMs) have only recently begun to adhere to shared communication standards. Individual companies struggle to have skills in selecting the data to be collected and in how to use it. Cyber Physical Systems have recently been introduced as a mean for leveraging process data at the manufacturing level, but their implementation is hardly scalable for SMEs realities, unless plug and play tools are provided.

This study analyzes the methods of accessing production data exploring the main technologies available for the development of CPS. Subsequently, the theme of factory interconnection is investigated using an executive approach, i.e. guided by the development of industry-driven projects that support and allow research to be advanced. The main data exchange protocols for process control and monitoring applications are analyzed and their use is subsequently oriented on the basis of the intended application for the collected data. Three research questions guide this work, starting with the provision of data and the ways to make this accessible even on legacy machinery. Subsequently, industrial applications are analyzed, which allow an improvement in the production strategy through the consumption of process data, reducing times and conforming the dialogue through unique channels for multiple manufacturing entities. Finally, the work focuses on the formulation of new service models, that are intended as the creation of added value from the usage of data both to improve production strategies and provide insights on the result of the production process before it is concluded. Results are reported on methodologies, applications and code examples for the implementation of process data-based tools for the improvement of manufacturing processes.

INVESTIGATION ON THE MECHANICAL BEHAVIOR OF ALUMINOSILICATE GLASS UNDER DIFFERENT LOADING CONDITIONS

Zhen Wang - Supervisor: Prof. Andrea Manes

Glass has been used by humans for centuries, not only as functional parts, but also for load-carrying structures, such as facades of buildings, windshields of airplanes and touch screen of electronic devices. New challenges have been introduced in designing glass components used for load bearing elements, especially for some extreme loading conditions. Glass usually possesses high compression strength but relatively low tensile strength, thus tensile fracture is a main threat to glass structures in service. Glass is a brittle material that fails in a sudden manner with large scatter in its failure strengths and a highly stochastic fracture behavior. These unique mechanical properties of glass are caused by the presence of microscopic surface flaws. To overcome this problem, the apparent tensile strength of glass can be improved considerably by ion-exchange process, during which residual stress was built in glass sheets.

Aim of this thesis was to investigate the mechanical behavior of aluminosilicate glass under different loading conditions based on both experimental tests and numerical simulations. Various experiments under both quasi-static and dynamic loading conditions were conducted to obtain the mechanical response of aluminosilicate glass. Developing reliable numerical modelling techniques able to deal with the brittle fracture, stochastic strength, and dynamic fragmentation of glass, is considered as an important challenge for fracture assessment of brittle materials.

The effect of surface defects on mechanical behavior of aluminosilicate glass is studied and numerical methods used to model the stochastic fracture, size effect and pre-stress strengthening effect are proposed. The stochastic fracture strength of glass specimens is mainly caused by the discrete surface defects. Experimental results show that the average flexural strength decreases with the increase of the specimen size. Also, chemically strengthened glass (CSG) has much better mechanical properties compared to annealed glass (AG) due to the residual surface compression stress in CSG. Weak elements can be introduced into numerical models to represent the discrete surface defects. The dynamic relaxation technique was utilized to build the residual stress in numerical models. The discrete fracture strength, size effect as well as the complex fracture behavior of glass specimens could be reproduced very well via Monte Carlo simulations of the proposed numerical models.

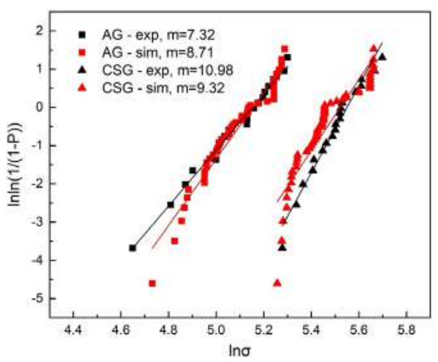

Fig. 1
Stochastic fracture strength of annealed and chemically strengthened glass

The mechanical response and fracture mechanism of glass structures under complex loading conditions including biaxial flexure, low-velocity drop weight impact and ballistic impact are revealed. The calibrated FEM-SPH models are utilized for structural analysis. During the loading process, a gradient strain distribution is built for the Ball-On-Ring (BOR) specimens. Once the peak fracture force is reached, radial cracks formed along the radius of the BOR specimen initiating from the center point. The low-velocity drop weight impact tests demonstrate an obvious dynamic strengthening effect. With the increase of the loading speed, the peak force also increases remarkably. The radial crack density is much higher compared to the quasi-static BOR tests and circular cracks appear. The dynamic responses of glass tiles subjected to ballistic impact with identical weight flat, conical and spherical-nosed steel bullets are investigated. It is found that the residual velocity of projectiles and the fragmentation behavior of glass are strongly affected by the shape of the projectile nose. Glass tiles show a better ballistic resistance performance for flat-nosed bullets than for conical and lastly spherical-nosed bullets.

The finite element coupled to smoothed particle hydrodynamics (FEM-SPH) method, together with other emerging numerical methods including discrete element method (DEM) and Peridynamics (PD) are evaluated and compared for their capabilities to mimic the mechanical response of aluminosilicate glass under various loading conditions. The material parameters for these models are calibrated by uniaxial compression and Brazilian tension tests on a material coupon. As far as the static three-point bending test is concerned, all three methods can provide reasonable numerical results compared to experiments. According to the ballistic impact simulation results, the FEM-SPH method with the JH-2 model captured the projectile residual velocity best. The reproduced glass tile fracture and fragmentation behavior is also very good. The PD method can also provide good predictions of the projectile residual velocity and glass tile ballistic response with a proper value GS for the fracture energy release rate for compression, which governs the maximum compression strength of the elements. The DEM has the largest discrepancy with experimental measurements and observations. This is due to the low packing density property and rotation of discrete element spheres after the breakage of bonds.

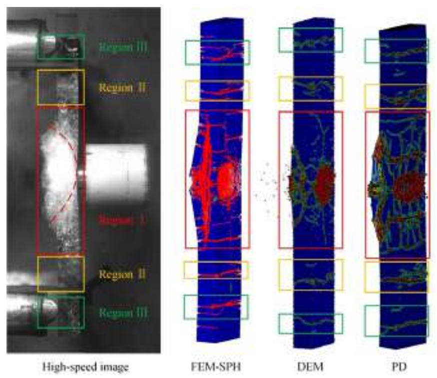

Fig. 2
A detailed comparison of the glass tile's fracture modes reproduced by different numerical methods

In conclusion, the thesis conducted a comprehensive investigation on the mechanical behavior of aluminosilicate glass under different loading conditions. Hybrid experimental and numerical studies were presented considering both the microscopic surface flaws and residual stress in glass structures. High-speed cameras and 3D-DIC technique were utilized for better understanding the fracture mechanism of this material. Furthermore, the related numerical works paves the way for the development and boost of design by analysis methods of such kinds of brittle materials even in a very harsh and extreme loading environment.

FAULT DIAGNOSIS AND CONDITION MONITORING OF ROLLING ELEMENT BEARINGS ON TRAIN POWERTRAIN

Lang Xu - Supervisor: Prof. Paolo Pennacchi - Co-supervisor: Prof. Steven Chatterton

Rolling element bearings (REBs) are critical and vulnerable components in the train traction system. The state of the bearings has a great effect on the comfort and safety of the train. At present, the maintenance of the REBs on the train is still arranged according to certain time intervals or several circles. If bearings are still available to work at the time of maintenance, unnecessary maintenance would increase the cost. If bearings are failed before the time of maintenance, the unexpected malfunction would cause great economic loss even catastrophic accidents. Therefore, the fault diagnosis and condition monitoring (CM) of REBs is very important to the safe and economic running of the train.
The diagnosis of early-stage defects of REBs using vibration signals is a very difficult task since bearing fault signals are usually very weak and submerged by shaft rotating signals, gear meshing signals, and strong background noise, etc. Therefore, usually, there are two important steps for bearing fault diagnosis, namely, weak bearing fault signal extraction and fault type identification. Squared envelope spectrum (SES) has been widely recognized as an easy and effective method. But the prerequisite of the success of the SES-based methods is to well extract the signal component caused by the repetitive contact of the defect and bearing components. To get a better solution to the weak fault signal extraction task, an optimal frequency band selection method has been proposed based on bandpass filtering and SES kurtosis. In this method, several frequency bandwidths that vary from 1.5 times to 4.5 times the fault frequency are determined in advance, see figure 1. Meanwhile, the SES kurtosis of the bandpass filtered signal is evaluated in a frequency range that is centered at the first two harmonics of the fault frequency with a width of 3 times the shaft rotation. Then the frequency band with the maximum SES kurtosis value is selected as the optimal frequency band for bearing fault diagnosis.
Even though the aforementioned optimal frequency selection and SES-based method is a useful REBs fault diagnosis method, it needs to know the fault type in advance. Moreover, the two parameters bandwidth and center frequency both have a significant effect on the bandpass filtering result. Also considering the capability limitation of bandpass filtering, therefore, a new bearing fault diagnosis method combining singular value decomposition (SVD) and SES has been proposed. In this method, only one parameter that is the number of rows of the Hankel matrix needs to be determined. The fault signal can be well separated by SVD using an elaborately selected row number of the Hankel matrix. The composite SES is made up of the four SESs of the sub-signal groups selected for four fault types based on SES kurtosis, which can identify the fault type without knowing the fault type in advance.
The final objective of bearing condition monitoring is to evaluate the health state and to estimate the remaining useful life (RUL) of the bearings. It is a particularly challenging task since

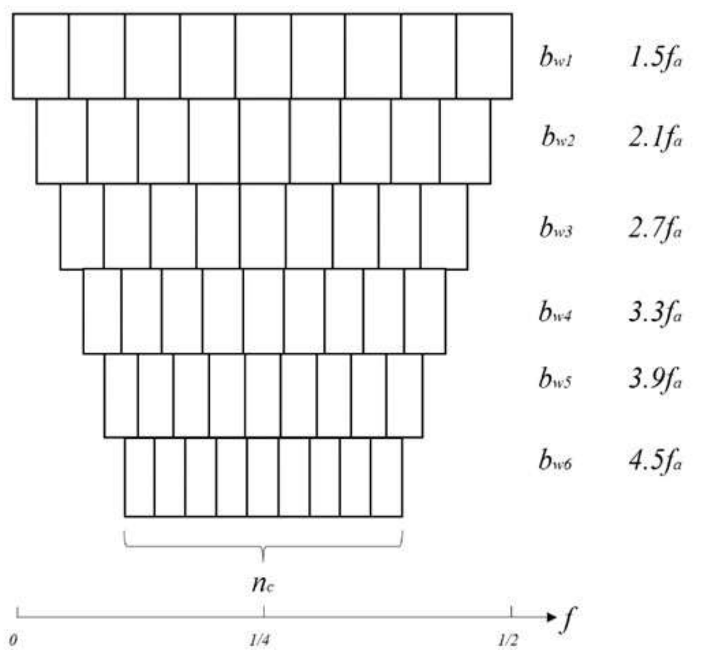

Fig. 1
Schematic diagram of the filter-bank analysis

bearing degradation is a very complex process. Most of the existing health indices (HIs) pursue the property of monotonicity, but generally, there are no obvious boundaries between different health states of bearings. Hence, it is quite difficult to give an objective and independent estimation of the health states, especially in real applications under different operating conditions and in the presence of noise. Furthermore, it is also difficult to set the failure threshold for a given health index when it is employed in different applications. Therefore, a new health index called 'MAC2PSD' has been proposed, based on the moving average cross-correlation (MAC2) of the power spectral density (PSD) of the vibration signals, see figure 2. MAC2PSD can track health conditions and discriminate clearly between the different health states. The MAC2PSD can also be used to estimate the remaining useful life by using its values during the defect-propagation phase. The effectiveness of MAC2PSD is tested employing two different cases of bearing run-to-failure experimental data, from two different test rigs. Additionally, the capability to avoid false positives is evaluated by employing bearing vibration data measured on a locomotive in commercial service.
Since the tachometer on the locomotive train malfunctioned during a period, a great mass of vibration signal needs to be order tracked for following condition monitoring. Therefore, a new tacholess order tracking (TOT) method has been proposed that combines the inverse short-time Fourier transform (ISTFT) with SVD. The target component closely related to the shaft rotation frequency is selected and roughly filtered in the time-frequency domain directly. Hence, the ISTFT is adopted to reverse the target component into the time domain and SVD is used to refine the roughly filtered target component. Finally, the phase of the refined signal is extracted to resample the original signal. The proposed TOT method performs well applied to real vibration signals collected from the test rig of a high-speed train traction system.

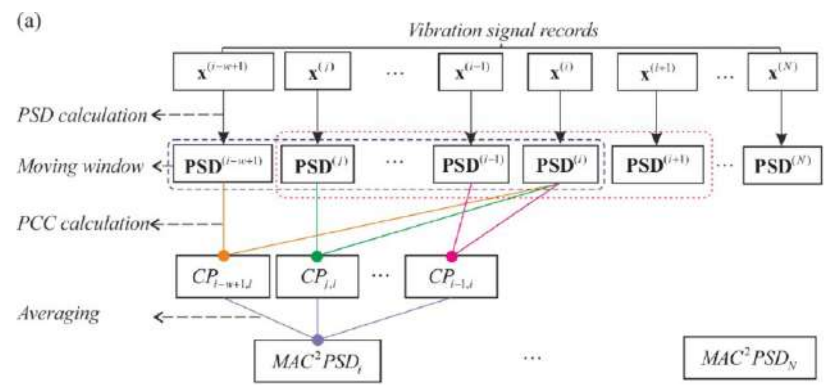

Fig. 2
The schematic diagram of MAC2PSD calculation

RESOURCE ALLOCATION PROBLEMS IN MANUFACTURING SYSTEMS USING WHITE-BOX-SIMULATION-BASED CUT GENERATION APPROACH

Mengyi Zhang - Supervisor: Prof. Andrea Matta

The optimization, including design, control, and operational management, of manufacturing systems is very relevant from a practical point of view and challenging from a scientific perspective. The design, control and operational management parameters generally influence the system intricately, and changing the parameters can improve some performance indicators, but diminish other ones or increase the cost in the meantime. Thus, the parameters should be carefully chosen to deal with the trade-off among performance indicators and cost, so that the manufacturers can improve productivity, reduce cost and gain profit optimally and eventually improve their competitiveness.
This thesis solves a wide set of optimization problems in multi-stage high-volume manufacturing systems with blocking mechanisms, namely the resource allocation problem (RAP). RAPs are constrained optimization problems, with the objective of minimizing the cost respect to target system performances or optimizing a performance measure respect to a given budget. Both performance measures and cost are monotonically increasing on the decision variables, namely amount of resources allocated to different parts of the system. Thus, the optimal solution locates on the feasibility boundary, and it represents difficult cases of constrained optimization.
Even though having drawn great attention in the literature, the algorithm design of RAPs is remaining a difficult task. Due to the complex system architecture and the various sources of uncertainty, performance evaluation of manufacturing systems is usually conducted with black-box functions, either analytical approaches or simulation. Consequently, approximate algorithms dominate the literature of optimization of manufacturing systems, and the only few exact methods cannot be applied to deal with large systems. This thesis proposes sample-path exact algorithms to solve RAPs. Despite the variety of problems solved, all the proposed algorithms belong to a common framework.
The RAPs are first formulated with Mathematical Programming (MP) models integrating the simulation as the performance evaluation method under the state-of-theart framework Discrete Event Optimization (DEO). A new solution method is proposed to deal with the computational issue and solve the models efficiently. Specifically, Benders decomposition is applied to the DEO models, resulting in two submodels. The two submodels represent simulation and the optimization, respectively. Following the Benders decomposition procedure, the two submodels compose an iterative procedure, where i) the simulation generates Benders cuts and ii) the optimization of the RAPs is solved as MP. A Benders cut partitions a subset of the solution region of the RAP as infeasible, so that the feasibility boundary is gradually defined with the cuts added. Furthermore, this work proposes simulation-based cut generation approach, with the white-box MP representation of the simulation. The proposed algorithms are applied to throughput improvement via downtime reduction, buffer allocation problem, integer resource allocation problems with performance constraints and joint buffer and pallet allocation. Numerical analysis shows that the proposed approaches outperform the state-of-the-art heuristics or black-box optimization algorithms in terms of the quality of the solutions and computational efficiency. Furthermore, the real cases are also studied with the proposed approaches, showing that the proposed algorithms can solve real cases within reasonable time and provide suggestions to improve the current systems.