DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

Chair:
Prof. Bianca M. Colosimo

Within the current global economic scenario, striving to recover from general slowdown and uncertainty, Mechanical Engineering still stands out as one of the leading and driving sectors of industrial manufacturing in Italy. In terms of per-capita manufacturing production, our country ranks 2nd in Europe and 5th on a worldwide scale (Confindustria, Scenari Industriali n.3, June 2012); among major machine tools manufacturing countries, Italy holds a strong 4th position (UCIMU, Annual Report 2011).

In this competitive panorama, and in order to respond to the requests of a challenging sector, the PhD Programme in Mechanical Engineering, organized within the Department of Mechanical Engineering, provides doctoral candidates with a strong scientific training, fostering and refining research and problem-solving abilities with respect to academic and non-academic *milieu*.

Our Doctoral Programme relies on the development of an interdisciplinary and integrated high-level educational offer, by focusing on a comprehensive scientific proposal, from conception to realization. PhD Candidates in Mechanical Engineering at Politecnico di Milano follow a three-year path which includes specific courses and lectures, held by faculty members and foreign professors and experts, in-depth research, laboratories, 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.

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; 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, Rotordynamics, 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 ecc.) and on applied research (e.g. failure and damage analysis, texture analysis, high temperature behaviour, coatings for advanced applications, etc.). The research projects carried out in recent years addressed specifically the following research topics: Steelmaking and Metallurgical Processes, Advanced Materials and Applied Metallurgy.

Methods and tools for product design: two main research topics are addressed in this field: PLM-Product Lifecycle Management, which includes process modelling, engineering knowledge management, product innovation methods, systematic innovation principles and methods, topology optimization systems, and data/process interoperability, and Virtual Prototyping, which includes virtual prototyping for functional and ergonomics product validation, haptic interfaces and interaction, reverse engineering and physics-based modelling and simulation, emotional engineering.

LABORATORIES

One of the key elements of our Doctoral Programme is represented by our laboratories; we feature some of the most unique, active and innovative set-ups in Europe: 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 PhD candidates' mobility abroad, for short-term study and research periods up to 18 months. We promote, draft and activate European and extra-European Joint Degrees, Double PhD Programmes and Joint Doctoral Thesis; our Department is actively involved in EU-based and governmental third-level education agreements such as Erasmus Mundus, Cina Scholarship Council and Brazilian Science Without Borders.
38% of PhD Candidates enrolled in 2012 are foreigners; female presence (Italian and non-Italian) accounts for 23%.
Our international network includes some of the highest-level and best-known universities all over the world, such as MIT, University of California at Berkeley, Imperial College, Delft University of Technology, Technical University of Denmark, Pennsylvania State University, University of Bristol, Technische Universität Darmstadt, University of Bristol, University of Sheffield, Fraunhofer Institut LBF Darmstadt, Universidad Politécnica de Madrid, Tokyo Polytechnic University, Universidad de Concepcion, University of Miami, the University of Western Ontario.

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AN INNOVATIVE METHOD FOR THE DEVELOPMENT OF NUMERICAL MODELS OF HYBRID VEHICLES

Stefano Agostoni - Supervisor: **Federico Cheli**

The need of an environment friendly mobility is nowadays one of the most relevant pull for the development of the automotive market. All cars and more in general vehicles manufactures are developing new vehicles with improved efficiency, reduced fuel consumption and pollutant emissions. Within such panorama the category of Hybrid Electric Vehicles assumes an always greater relevance because of the improvements they offer and their higher feasibility with respect to other technologies actually not ready to substitute the world wide spread conventional Internal Combustion Engine (ICE) vehicles. Because the largest part of activities and researches about hybrid and/or electric systems are focused on standard passenger cars and mainly on small-mid size car for urban environments, the development of alternative powertrain systems for other vehicles categories actually lies in an earlier state of evolution. The reasons for that are the smaller dimensions of markets with respect to the passenger cars market and the difficulties in achieving a good level of social acceptance, which is fundamental for the spread of the hybrid technology, among the users of different categories of vehicles. It is likely to expect a growth of number of applications of hybrid technology also to different vehicles categories as soon as the research and development applied to the cars field would lead to an improvement of the actual state of art.
The analysis of the actual state of the automotive market, starting from an historical overview about the diffusion of the car, represents a fundamental starting point to allow the comprehension of the great change that the field of the mobility has to face nowadays. The main reasons that actually lead to the need of a mobility panorama less dependent from the fossil fuels actually lay in the forecast of a future "oil depletion" and in an increasing attention to the emission of pollutant gasses from the tailpipe of every vehicle. Different technologies are actually available to reach the target of a more sustainable mobility: Battery Electric Vehicles, Fuel Cell Electric Vehicles and Hybrid Electric Vehicles. From the analysis of pros and cons of each of these technologies, the Hybrid Electric Vehicles appear as the most feasible solution for the transition phase that should lead from the actual "oil dependent" state of the automotive field to a new condition in which the electricity will be used to power almost all the vehicles.

The investigation about the actual state of art of Hybrid Electric Vehicles shows different possible layouts of the powertrain. In fact hybrid vehicles can be designed following the series layout (in which the ICE is used only to provide the energy to the electric driveline that moves the vehicle), the parallel layout (in which both the ICE and the Electric Motor can be used to directly power the vehicle's wheels) and more complex layouts (defined as the combination of series and parallel layouts). Besides specific technical aspects that can lead to consider one layout better than others in terms of performances and/or efficiency, the concept of social acceptance of this new technology has to be taken into account to define the most appealing solution of the final customer.
The actual panorama of scientific research about hybrid technology shows how the most of the activities are actually focused on the vehicles belonging to the class of small passenger cars to be used mainly in urban environments. From this consideration and from the observation of the lack of flexible numerical tools able to simulate the behavior of any kind of vehicle powered by any kind of powertrain, come the innovative features proposed by the present activity.

Because of the need to develop a robust method that can be adopted potentially by every vehicle manufactures regardless the kind of vehicle they produce, a modular modeling approach as flexible as possible has been developed. In order to apply this modeling technique the numerical model of every single component of the vehicle (from the driver model, to the gearbox, the battery, etc.) has been developed. In particular the structure chosen for every single model has been designed in order to assure the highest possible flexibility.
The flexibility of this approach has been highlighted assembling the numerical models of the single components and creating the numerical model of five complete vehicles belonging to four novel categories different from standard passenger cars for which the hybrid technology still need to be further developed. The considered vehicles are: a Hybrid Electric Commercial Vehicle similar to the vehicles used to deliver goods within urban areas, a Hybrid Electric Sport Car for which the hybrid powertrain has been designed to improve the vehicle's performances, two Hybrid Scooters with different powertrain layouts (Series and Parallel) and finally a Hybrid Electric Heavy-Duty Truck of the type used in building fields. The development of such models is used to show the advantages achievable by the usage of the innovative proposed modeling approach.
For each single modeled vehicle the corresponding numerical model has been validated on the basis of available experimental data and finally analyzed to find out the benefits achieved by the designed hybrid powertrain. In particular for each different developed model specific operating strategies have been developed according to the operating mission of every vehicle, and the benefits derived from the usage of a hybrid powertrain have been evaluated by numerically calculate the improvements in terms of fuel consumption and/or performances according to the specific requirements of every vehicle's category.
Considering the most relevant and common needs demonstrated by the hybrid vehicle manufacturers involved in any step of the present activity, a specific procedure to better investigate the benefits achievable with the usage of the hybrid powertrain and to find their optimal layout. In particular the developed method is based on three main steps: firstly the sensitivity analysis of the developed model of hybrid vehicle is conducted. A specified set of parameters are continuously changed, thanks to the application of the *Latin Hypercube Sampling* algorithm, at any simulation and for each of these simulations one or more objective functions are evaluated. From the analysis of the obtained results according to the *Spearman rank's* method, the sensitivity of the considered objective function with respect to every single parameter can be evaluated. Secondly the numerical models are optimized through the application of the *Genetic algorithm* exploiting the results of the previously performed sensitivity analysis and the same objective function already introduced. Finally the benefits provided by the optimized hybrid powertrain can be evaluated. Such evaluation is performed following the specific procedure proposed by actual international standards for the calculation of the vehicles fuel consumption. The results provided by this last step of the procedure will be directly comparable with any other similar quantity calculated according to the same standard.

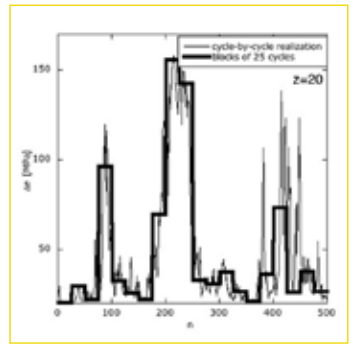
RELIABILITY OF STRUCTURAL COMPONENTS UNDER VARIABLE AMPLITUDE HIGH CYCLE FATIGUE

Alessandra Altamura - Supervisors: **Stefano Beretta, Daniel Straubi**

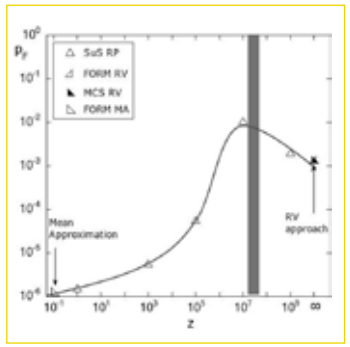
High cycle fatigue refers to the application of more than 103 loading cycles to a structure or to a component. Nucleation and growth of cracks from the free surface or from pre-existing imperfections may be a consequence of the application of cyclic stresses, which usually have a variable amplitude.
An optimized design can be obtained changing over from a safe-life approach to a damage tolerant approach, which ensures a damage without failure during the components' life.
Three key inputs are required: a fatigue crack growth model, a variable amplitude loading model, a reliability evaluation method.

In this thesis a comprehensive model to describe the fatigue crack growth curves and the fatigue threshold for different stress ratio, accounting also for the stochasticity of the crack growth phenomenon, is successfully implemented on the base of experimental tests and verified with full scale tests as well as with a commercial software. The behavior of the experimental fatigue crack growth curves suggests that the stochasticity of the crack growth is mainly controlled by the variation of the threshold, since the threshold variation creates a fanning effect which reproduces the experimental observations. Therefore the stochasticity of the fatigue crack growth can be described simply with only one random variable, the fatigue threshold.
A random variable description of the threshold combined with a proper model for its dependence on the stress ratio, allows an exhaustive description of the fatigue crack growth behavior.
The dependence of the fatigue threshold on the stress ratio can be well fitted using the Nasgro model and considering the cyclic yield strength of the material.
This approach permits to describe the experimental data related to fatigue threshold of small and long cracks. The use of one random variable simplifies the statistical assessment and reduces the approximation in the models.

In previous studies concerning fatigue reliability, the stress is assumed constant or deterministic block sequences are adopted. These sequences are however often not representative of the real service load to which the structure is subjected. In this work in-service stress measurements are used to produce two types of stress sequences. A Markov random processes model of the load is adopted and an innovative method to generate random stress sequences and simulate different service conditions is proposed and applied to the case studied. With this model, the dependence structure is characterized solely by the correlation length. Varying the correlation length of the load permits generating various stress histories representing different mission types.
For the purposes of fatigue crack growth evaluation, it is computationally advantageous to approximate the random load sequence by blocks of cycles with constant amplitude and stress ratio. Such blocks can be defined from the original fatigue load process by dividing the sequence of cycles into blocks of a finite number of cycles.
Figure 1 shows an approximated load sequence built as blocks of length 20 cycles, superimposed on the original random load sequence. The value of stress amplitude at each block is equal to the mid-point value of the original random process at each block and the stress ratio is assumed constant.
The reliability estimation is implemented with the traditional Monte Carlo method, as well as with the Subset simulation method. Additionally a mean approximation (the expected value of the fatigue crack growth rate in respect to the stress process is considered) and a random variable approach for the stress are combined with first order reliability method to explore approximated solutions with faster computational time.
Numerical investigations related to the case study of tubular parts loaded with internal pressure carrying initial semi-elliptical surface flaws are presented in this work. They are used to investigate which factors have the most significant influence in the reliability evaluation, how these factors affect the reliability and when approximated approaches can be applied.
Results show that the initial flaws depth and the stress model are the factors which exert the most significant influence on the reliability evaluation when variable amplitude fatigue loading are applied.
Figure 2 shows the probability of failure as a function of the correlation length of the stress process. The probability of failure varies by several orders of magnitude and reaches the maximum value when it is of the same order of magnitude as the stress process!
Simplified conservative approaches, which assume a fixed initial flaw depth or which do not properly take into account the fatigue crack growth under variable amplitude stress, may lead to an erroneous estimation of the probability of failure. For stress range processes that are ergodic and have limited correlation, the mean approximation of the stress is suitable; for constant stress ranges, the random variable model is applicable; in all other cases, the load block model in combination with the subset simulation provides a practical tool for assessing the reliability.The numerical investigations show also that the failure criteria may exert an influence on the reliability depending on the model adopted for the stress. For the specific case study investigated in this work, unstable crack growth, as represented by the crack driving force failure criteria, has only a limited effect on the reliability. A similar behavior is expected in many structures subject to high-cycle fatigue.
It is therefore recommended to accurately define the distribution of the initial flaws depth, as well as the distribution and the correlation of the stress.
The possibility to apply any approximation should be accurately evaluated, based on experimental evidence and designers should be aware of the error to which the adopted approximation can lead in terms of reliability estimation.



1. Approximated stress range sequences built as blocks of 20 cycles, superimposed on the original random sequences



2. Probability of failure pF versus correlation length z of the stress range process: experimental data and trend

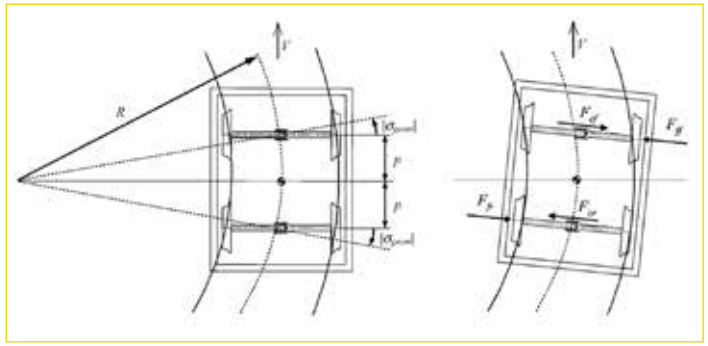
ACTIVE STEERING SYSTEM FOR TRAMCAR BOGIES

Andrea Natale Barbera - Supervisor: **Roberto Corradi**

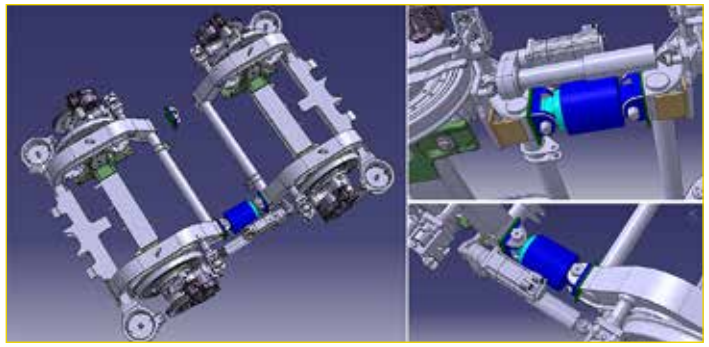
The dynamic behaviour of modern articulated tramcars significantly differs from that of traditional rail vehicles, due to both tramcar and tramway characteristics. In particular, when negotiating the tight curves typical of urban networks, as a consequence of the counter-steering torque associated with the opposite lateral creep forces on the front and the rear axle (see F_{cf} and F_{cr} in Figure 1), tramcar bogies are forced to run with both the front outer wheel and the rear inner wheel in flange contact condition. In this situation, the lateral contact forces on the flanging wheels (see F_{ff} and F_{fr} in Figure 1) balance the counter-steering torque of the creep forces, thus keeping the bogie on the track. Depending on the geometry of the wheel and rail profiles in their actual worn conditions and, as an effect of the deformability of the resilient wheels (if present), flange back contact on the inner side of the rail groove may even occur on the front inner wheel and the rear outer wheel. The running gear curving dynamics will then result in complex distributions of the normal and tangential contact forces on the different coexisting contact patches on each wheel and, in some cases, may lead to high squeal noise levels and to severe wear of both wheel and rail.

Improving bogie curving performance requires the reduction of the contact forces and the even distribution of the lateral forces on the four wheels. Thus, in order to enhance the curving behaviour of conventional tram running gears, the wheelset angle of attack with respect to the track should be remarkably decreased. However, when dealing with such sharp curves as in tramways, the only effective way to make this relative yaw angle tend to zero is that of implementing active steering bogies. Therefore in this thesis an active steering system for a tramcar bogie is developed, which is based on an articulated bogie equipped with an actuator that is used to control the relative rotation between the front and the rear axle (see Figure 2). The goal of this work is to show the benefits of the actively steered bogies over the traditional ones and to demonstrate the feasibility of the proposed active steering system.

The thesis focused on the fundamental aspects included in the task of designing an active steering system, in order to allow the development of an active steering bogie prototype as a conclusion of the entire work. In detail, the state of the art in terms of bogie steering mechanisms was addressed, considering either passive and active solutions. While passive solutions showed a limited effectiveness to enhance the dynamic behaviour of the vehicle, many options being the result of a trade-off between curving performance and vehicle stability, active solutions represented a promising option to improve bogie curving performance, especially for the tight curves typical of urban tramways. Within the possible alternatives, an articulated bogie was proposed, equipped with an active steering system to vary the relative yaw angle between the wheelsets.
Reference was made to an articulated low-floor tramcar, whose main characteristics generally represent the common configuration of many modern urban rail vehicles.
Convenient design should aim at keeping the system complexity to a minimum, hence numerical simulation might be the proper design tool, which allows efficient estimation of achievable curving performance and provides significant information on control and actuation system requirements. Thus, in this thesis, a multibody model was adopted, which was developed to accurately reproduce the dynamic behaviour of a tramcar vehicle. By means of multibody simulation, curving performance of the proposed active steering bogie was assessed, as well as a feed-back control strategy was designed and tested for several curving scenarios, investigating curve radius and running speed effects on the achievable curving performance. Track irregularity effect and a possible active steering system failure were also taken into account in the simulations. The numerical model outlined the benefits introduced by the active steering bogie over the conventional rigid-frame running gears, while showing the feasibility and the reliability of the solution under investigation. A significant decrease of the contact forces was obtained, thus a consequent reduction of the wheel/rail wear is expected.
Finally, the actual stage of development of a prototype of the proposed active steering bogie was illustrated. The prototype final architecture was presented, as well as the final configuration of the active steering system, whose component technical specifications were provided. Since at the actual stage of research the bogie prototype frame is not yet available, the future developments of this work will involve the execution of both lab-tests and line tests of the active steering bogie, to experimentally confirm the expected improved curving performance. Further than demonstrating the achievable benefits in terms of wear and noise reduction, the line test campaign should also highlight the feasibility of the developed active steering solution. The current architecture of the bogie prototype might be reviewed according to standard operation functional and structural requirements, as well as because of fail-safe needs, which are still an open point to cope with in the forthcoming future.



1. Tight curve negotiation of a tramcar bogie: lateral creep forces (F_{cf} and F_{cr}) on the front and rear axle and flange lateral contact forces (F_{ff} and F_{fr}) on the front outer and rear inner wheel.



2. 3-D model of the active steering bogie prototype

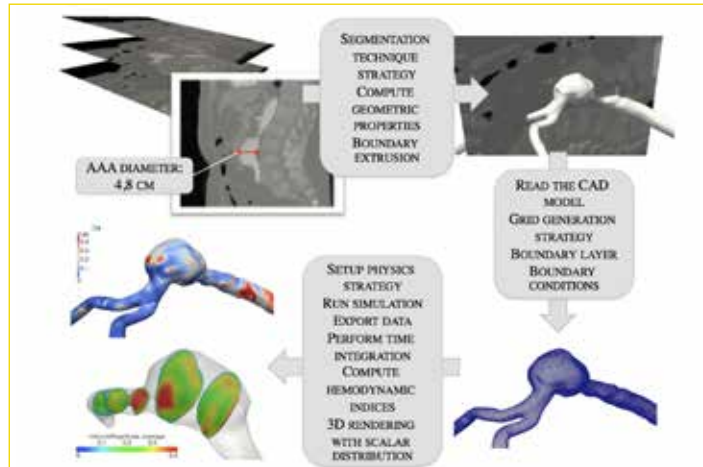
A VIRTUAL AUTOMATED PROCESS TO AID ABDOMINAL AORTA ANEURYSM DIAGNOSIS AND TREATMENT

Simone Bartesaghi - Supervisor: **Giorgio Colombo**

The use of computational tools applied to blood flow in human arteries has increasingly more grown. Nowadays, such tools provide detailed and trustable information on hemodynamic quantities so that researchers are able to investigate a large number of problems, which have been hardly faceable with traditional engineering flow measurement techniques.
On the one hand, during the '80s, a powerful innovative tool to study hemodynamic quantities and indices appeared: the Computational Fluid Dynamics (CFD). On the other hand, the traditional tools - such as magnetic resonance imaging (MRI), Doppler ultrasound and X-ray cine-angiography - keep on being used and allow the investigation in vivo of the blood flow dynamics as well as the highlighting of the differences among hemodynamic quantities between different subjects.
In the last few years several academic works have tested different simulation tools in order to understand the cause behind the rupture of aneurysms. However, these tools have no actual or limited impact on patients' treatment. Due to this, the present work aims at developing a rule-based virtual automated process to aid Abdominal Aorta Aneurysm (AAA) diagnosis, which is useful in consequent treatment.

Thanks to new imaging techniques, it is possible to perform the computations on realistic geometries and on real blood flow conditions. In this way, CFD fully 3D models are decisively improved. Today the CFD approach improves the efficiency of the studies related to local hemodynamic in the biomechanics processes of the vascular bed and allows to test and to validate clinical and surgical procedures. State of the Art tools have been developed to perform patient specific CFD, but usually these tools are not used extensively because of some limitations: lack of CFD experts inside clinics, simulations done outside clinics; CFD simulations done with State of the Art manual approach; high costs/time because of the non automatic approach.
It is easy to understand that clinics need an automatic process to avoid employing CFD experts. On the contrary, CFD in embedded approach can be a direct process from medical imaging to risk indicators, has an automatic workflow, which begins immediately with the CT scan, and is less expensive/time consuming. To do that, it is necessary to define certain features, like geometry (anatomy), CFD modelling, computing, visualization and reporting. CFD and traditional tools have been then integrated.

As a result, it has been possible to perform CFD analysis based on medical imaging and flow data. Compared to traditional tools, CFD methods show more advantages. First of all, they are less expensive, give detailed representations of the velocity vector and pressure fields, allow easier parametric studies based on geometric or flow quantities and above all they are more ethic since they are not performed on patients.
The Computational Fluid Dynamics (CFD) is here the main tool employed to support the decision making process and the final therapy. So, CFD modelling is the main part of the entire workflow, which starts from medical images (DICOM) and ends with the 3D visualization of AAA rupture risk. The automatic workflow for risk evaluation in the AAA disease is entirely based on the domain knowledge. Figure 1 shows the workflow implemented in this thesis. Every task is performed by using automatic procedures. To accomplish these tasks, embedded algorithms are designed to create a link between every part of the workflow; in particular, embedded algorithms work based on rules, information and procedures which are extracted from a detailed systematic analysis of each phase of the workflow; methods and protocols have been designed and developed in order to reach the accuracy required.
For CFD simulations, CAD anatomy reconstruction of the AAA is required. To the purpose, the DICOM data is read, properly segmented and exported to obtain the CFD-ready CAD model. The entire process employs knowledge-based rules. Concerning the next step of CFD simulation, the latter are necessary to implement a correct physics and numerical setup, too. In particular, the mesh study considers a simplified geometric model of arteries and the aneurysm, and analyses 2D and 3D grid topology, the effects of grid refinement, the presence of prismatic boundary layer and the fluid viscosity, eventually. Moreover, it will be considered the influence of fully developed boundary conditions by using a commercial finite volume code. The above-mentioned rules are extracted from the analysis of the influence of the time step size, the number of inner iterations per time step, typology of numerical schemes and fluid rheology. The post-processing and its visualization make numerical data presentable in a portable format, which is easily understandable, since it allows an immediate visual analysis of the velocity gradients, pressure and WSS, as well as characteristic variables which



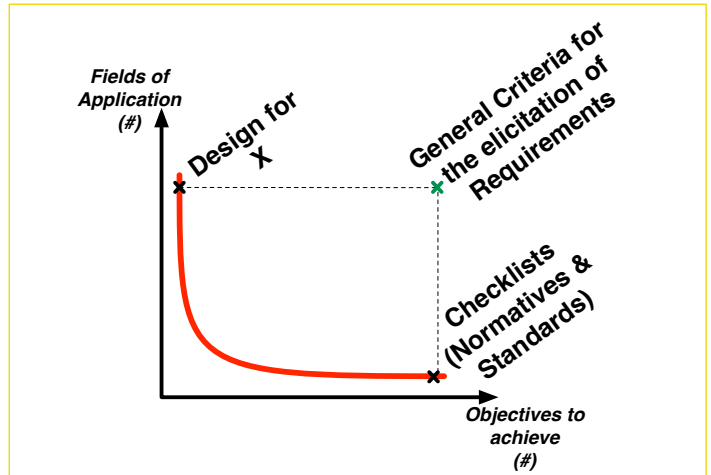
1. Automatic workflow for risk evaluation in Abdominal Aorta Aneurysm (AAA).

indicate possible development of local vortices and helical flows. An automated procedure is able to perform the time integration of transient CFD data, compute hemodynamic indices and generate relative the 3D render visualization. Besides, an overview and further development of this workflow in HPC and cloud computing environment are presented. Findings, application and validation on real patient specific case show the feasibility of the entire workflow in an embedded mode. Rules extracted from the research activity are at the base of the embedded algorithms that drive the entire workflow from DICOM PACS to 3D visualization.
The importance of the research is to define a strategy to automate the process in order to reach an integration between traditional clinical diagnostics tools (imaging) and modern Computer Aided Engineering (CAE) based tools, in this case CFD tools. The latter is the innovative feature of the research. In other words, the integration of medical imaging, geometric modelling, CFD simulations and domain knowledge can be useful to support the making decision process related to medical diagnosis and to aid AAA diagnosis and treatments. As far as the methodological approach concerns, State of the Art tools and methods have been validated and integrated to work in an embedded process.

REQUIREMENTS IDENTIFICATION AND CHARACTERIZATION IN INNOVATION PROCESSES

Niccolò Becattini - Supervisor: **Gaetano Cascini**

The thesis presents a research aimed at identifying new instruments capable to support the engineering design processes by pointing out objectives and requirements to be satisfied by a design proposal, which has to address the emergence of needs from both the industry and the market. This issue is of greater importance in all the circumstances where industries have to face the challenge of competition by innovating their products, processes or services. In this perspective, systematic design methods have emerged as the best alternative to steer the design process with effectiveness and efficiency, thus stopping to miss opportunities that, without the appropriate definition of objectives, will not be taken nor even recognized. Such methods reduce the risks due to wrong choices dramatically impacting on investments and revenues and compromising competitiveness. Knowledge plays a paramount role in the definition of such objectives: means to externalize it from the individual sphere (tacit) to the external world, where it has to be discussed and used and also shared for future reuse (explicit), have a strategic relevance in supporting the design processes.
Existing tools to support the definition of objectives and requirements during the engineering design process are effective in a wide range of cases. However, they are characterized by an apparent contradiction: the ones that support the definition of a wide number of requirements are mostly suited for specific fields of technology (e.g.: standards and checklists) and show lacks in terms of their flexible use in different industrial contexts. On the other hand, methods capable to answer to the exigencies of different domains of technique are mostly tailored to address the satisfaction of an overall objective at a time (e.g.: Design for X guidelines).
The research activity, therefore, has been carried out with the objective of overcoming such dichotomous situation. The author has developed a new set of criteria, having a higher level of abstraction, for the definition of requirements and objectives (Figure 1). They can be contextualized according to diverse situations, thus addressing multiple objectives in a wide range of different applications.
The criteria are organized according to the main drivers suggested by the TRIZ (Russian acronym for Theory of Inventive Problem Solving) theory about the evolution of technical systems: improvement of performances, reduction of side effects and resources consumptions.
The effectiveness and the validity of these criteria has been tested on several test cases concerning both products and industrial processes through experiments tailored to verify specific objectives both in a qualitative and quantitative way. In more details, fourteen different manufacturing technologies have been examined along three different process applications with industrial partners in the field of household appliances and fluid-bed technologies.
The investigation has been also carried out on the definition of requirements for products of different complexity, demonstrating that the criteria dramatically shift the capabilities of individuals in producing more accurate and complete design specifications. Moreover, a further investigation qualitatively explored the capability of the criteria to describe also the needs of customers, through an ex-post characterization of a set of newly appeared product/service requirements as mentioned in scientific and business literature.
The new proposal of criteria for supporting the definition and the characterization of requirements to populate the design specification achieves the objective to be *flexibly* used in different context concerning the development and the innovation of both products and processes. The criteria achieve the objective of producing a design specification capable of exploring the range of potential alternatives at the maximum extent (*completeness*), without neglecting relevant aspects and noting useless ones (*conciseness*). They support considering the collected requirements just once, without introducing ambiguities that could be misleading for driving the design process (*nonredundancy*).
Moreover their use make it possible to build a design specification according to which the different design proposal can be depicted with reference to their capability to generate satisfaction or dissatisfaction according to the objectives (*validity*). Moreover, the criteria satisfy the goal of producing the above results with good *repeatability*, thus releasing from the individual capabilities in externalizing the owned knowledge. Potential improvements concern the *ease of use*, in terms of releasing from the need of carrying out analysis with a facilitator.
At last, for achieving the purpose of easing the use of the criteria, an algorithm to be embedded into a dialogue-based computer interface for supporting the analysis of inventive problems has been developed. It aims at depicting the design space and pointing out non-mutually compatible requirements from which starting the conceptual stages of design. Such an algorithm has been developed in the diverse paths through which the analysis can be carried out, according to the concepts highlighted by the criteria. Tests for validation aim at pointing out the capability of the developed algorithm in supporting the identification of conflicting requirements, as well as in defining the design space so as to support the retrieval of information and knowledge from explicit sources, such as patents, books and whatever codified and retrievable through the world wide web.
The first step of development has defined the overall structure of the algorithm (7 logical blocks and about 150 questioning nodes), also in terms of variables to be investigated and elicited from experts' knowledge, opportunities for their reuse as well as connections among nodes and concepts.
Test produced satisfactory results in terms of support to the problem analysis, even if presenting some lacks in terms of adequate exploration of the design space. The second release of the algorithm (8 logical blocks and more than 200 questioning nodes), addresses the limitations emerged within the first testing session. It includes a new block aimed at widening the boundaries of exploration and providing shortcuts for the investigation of trivial solutions that were not immediately evident at the beginning of the analysis. Satisfactory results have been obtained with both the versions of the algorithm, showing room for extending this kind of computer-aided support also to the synthesis of solution concepts.
Such a research has an impact in both the structuring of more robust design methods and in extending the support of computer-aided systems to the first phases of the development cycles in innovation contexts.



1. Automatic workflow for risk evaluation in Abdominal Aorta Aneurysm (AAA).

TOOLS FOR THE AUTOMATED CONDITION MONITORING OF ROTATING MACHINERY

Pietro Borghesani - Supervisor: **Paolo Pennacchi**

Many mechanical systems are required to operate reliably on various conditions and for long periods. Maintenance is therefore a key issue, not only in case of safety concerns, but also from an economical point of view: breakdowns of the machinery often involve high losses in term of production stoppage, repairing and replacing costs, penalties for late supply/operation.
The developments in electronics and computer science provided maintenance planners with a new opportunity for the design of a new maintenance strategy, the *condition based maintenance* (CBM). In the last decades sensors and digital signal processors have become so cheap that their cost is often negligible when compared to the still expensive mechanical devices and the costs related to breakdowns and operation/ production delay in an increasingly demanding business world (e.g. strict environmental and safety regulations, just-in-time operational strategies).
CBM exploits sensors and signal processors to obtain an assessment of the status of the components, in order to give timely indications for the most economically efficient substitution of the components. Its main aim is to avoid unnecessary maintenance tasks by taking actions only when there is evidence of abnormal behaviours of a component of the mechanical system (e.g. motors, transmissions, bearings, shafts).
The first steps in the field of monitoring of machines were taken where safety issues were crucial; a traditional application is in the field of large turbo-machineries in the power generation sector. In such applications, the automatic signal processing procedures were very simple, usually monitoring energy levels (i.e. vibration r.m.s.) and comparing them with levels provided by ISO standards.
Any other more sophisticated analysis, being even a simple vibration spectrum, has been generally outsourced to experts, called only in case of alarm.
The expert reader would look in the spectral indicators for typical symptoms of damage, in this case mostly due to shaft imbalances, misalignments, foundation resonances or shaft critical speeds, hydrodynamic instabilities.
Therefore in these systems monitoring strategy is split in two parts: a first automated assessment operated in time domain on very simple indicators, and a second root cause analysis operated manually in frequency domain. The last phase consists, almost in every case, in the search for specific damage symptomatic peaks at characteristic frequencies identifying the specific signature of the problem.
The aim to extend this maintenance strategy to more complex systems and distributed systems (e.g. processing plants, production/manufacturing sites, vehicles) involves the necessity to face the unfeasibility of a manual root cause analysis of all the numerous components and often by a complexity and an environmental noise or disturbance, which makes simple magnitude indicators, such as r.m.s., unreliable or inaccurate.
In particular, the obstacles of using simple indicators are:

- The loss of specific information on the single damaged component, which often gives specific symptoms in the signal. This can be solved, partly and only in some cases, by increasing the number of sensors, increasing as well the cost and the complexity of the diagnostic system.
- The possibility of having external disturbance/noise biasing the signal and triggering a series of false alarms.
- A later recognition of dangerous situations, because symptoms of incipient faults would be covered in a broad band analysis by all other sources of vibration and noise.

However the manual analysis seems highly unfeasible, because of the consequent high expenses to afford in order to imply massively highly skilled human resources.
The key solution is offered by a full exploitation of the potential of digital signal processing hardware and software, to obtain a fully automated diagnostic algorithm, tailored on the specific application, but with some degree of adaptability to varying environmental conditions.
Given the large numbers of different types of mechanical systems and components, this thesis does not intend to give a fully comprehensive list of procedures for the diagnostics of all possible components or combination of components. On the contrary, given the fact that most diagnostic signals belongs to two families of processes, both in the framework of cyclostationarity, and that domain transformation from time to angle is often needed, this thesis is aimed at analyzing the most applicable tools for the analysis of those signals.
In particular, a common procedure, shown in Fig. 1, is proposed in this thesis for the automated diagnostic of most machine components.
The steps are analyzed in detail, providing novel techniques to make them more effective and computationally efficient.

1.Process for the automatic diagnostic of rotating machinery

2. Test-rig for the diagnostic of rolling element bearings of a train traction system

Among the proposed novelties the most significant are:

- a new technique is proposed for a fast online calculation of order domain harmonics of the signal, without the need of a resampling of the signal;
- a quantification of the effect of mechanical system transfer function on the domain transformation is provided;
- statistical threshold will be obtained for the identification of damage symptoms in cyclostationary indicators, valid also in case of non-white noise.

All the newly proposed analytical results are tested on numerical and experimental tests. In particular numerous industrial application examples are provided. Among these, a detail description is given for a specific application on diagnostic of rolling element bearings of the traction system of a high speed train, project developed by Politecnico di Milano in the last three years with leading industrial partners. This both works as a significant example of application of a full automated diagnostic process, with some of the techniques discussed in the previous chapters, and provide a guide for the specific application to rolling element bearings, which often represent the system's weakest link in the reliability chain. This discussion will take advantage of the experimental activity performed mainly on a full scale test-rig of a train traction system (Fig. 2), simulating the harsh environmental condition of such application.

SENSOR FUSION AND DATA ANALYSIS FOR STRUCTURAL HEALTH MONITORING

Alessandro Cattaneo - Supervisor: **Alfredo Cigada**

Structural health monitoring (SHM), whether it relates to mechanical, aerospace or civil structures, is a discipline that, after three decades of continuous evolution, offers ready-to-use solutions, which ensure great added value to the structures on which they are adopted and, concurrently, represents a research topic drawing the attention from a great many different fields including data acquisition and processing, statistical and physical modeling, structural dynamics and control system, smart materials. SHM basically consists in implementing a damage detection strategy for a structure in the attempt of preventing failures potentially resulting in life-safety and economic losses. Among the panorama of SHM applications, great interest is shown in the development of solutions specifically conceived for civil structures. As a matter of fact the development of effective SHM strategies would represent an extremely appealing answer to the pressing problem of assessing the actual health conditions of infrastructures that are approaching, or have already gone beyond, the end of their design service life. Even further, in the event that extreme and unexpected weather, as well as landslides and earthquake strikes cause damage to civil structures, SHM could be used for rapid condition screening. This thesis specifically builds on the field of continuative and long-term SHM on large civil structures. A distinctive trait of structures like high rising buildings, bridges, dams, and stadia, to name a few, is represented, especially in presence of audacious architectural projects, by the coexistence of different substructures each of which exhibits its own features. In order to increase the robustness and reliability of SHM strategies conceived for such complex structures, an increasing attention is paid to adopting an approach, called sensor fusion, which consists in integrating data from sensors of various nature. Noticing that a damage, for its own nature, is a local phenomenon, the implementation of a damage detection strategy can basically follow two different approaches. From the one hand, it is possible to assess the presence of a damage by capturing a macroscopic change in the behavior of the entire structure. On the other hand, the onset and ongoing of the damage can be directly inferred by observing a physical phenomenon that locally arises as a consequence of the presence of damage. Among the different techniques contemplated by the SHM community, this work focuses in particular on a couple of them particularly promising to develop a monitoring strategy operating on a whole structure-level. Namely these techniques are operational modal analysis (OMA) and acoustic emission (AE). The former belongs to the group of the so-called vibrating-based approaches and basically consists in assessing the health condition of the structure by continuously monitoring over the long-term period the evolution of structure dynamic behavior as result of the excitation provided by environmental load (i.e. vehicular traffic and wind). The latter aims at capturing short-time, transient events which arise due to the onset or the ongoing of a damage and propagate through the structure as a wave that can be sensed within a certain distance from the source. The sensorization of the structure and the data acquisition and management that are needed when such approaches become part of a SHM strategy pose a variety of challenging issues. With regard to the vibration-based methods, the current work specifically addresses the problems related to the extraction, from the structure measured response, of those parameters providing a synthetic description of its dynamic behavior. These parameters (namely eigenfrequency, non-dimensional damping ratio and modal constants which are referred to as modal parameters) are estimated by mean of over-refined modal identification techniques. The current work goes into depth in the analysis of an OMA algorithm particularly suited for the extraction of modal parameters from structures exhibiting close-in-frequency and highly damped modes as it is the typical case when large civil structures are investigated. The merit of the first part of this work consists in the development of a general purpose Monte Carlo-based simulation method conceived to assess the result intrinsic dispersion and bias effects of a generic OMA algorithm. Spread assessment is clearly a key information towards any attempt to exploit SHM methods based on modal parameter changes; bias assessment, on the other hand, offers a precious information to critically interpret the modal parameters estimates. With regard to the continuative long-term AE-based SHM strategies, the current work deals with the problems arising from the need to size short-transient events over extended period of time. The challenge associated with capturing these events using classical techniques is that very high sampling rates must be used over extended periods of time. The result is that a very large amount of data is collected to capture a phenomenon that rarely occurs. Furthermore, the high energy consumption associated with the required high sampling rates makes the implementation of high-endurance, low-power, embedded AE sensor nodes difficult to achieve. The merit of the second part of this thesis consists in investigating the suitability of a new sampling technique, called compressed sensing (CS), that, by collecting a small amount of compressed measurements, enables to relax the requirements on the sampling rate and memory demands. The CS technique substantially lends itself as a highly promising approach to promote the transition to SHM strategies relying upon wireless sensor networks featuring minimal installation costs. The research activity carried out within the framework of this thesis is supported by an extensive experimental activity. In particular, the Giuseppe Meazza stadium in Milan is used as test case. Such a structure, due to its specificities, offers the opportunity to investigate the suitability of a monitoring solution relying upon both OMA- and AE-based SHM approaches. The Monte Carlo-based simulation framework developed in this work, thanks to its close adherence to reality, allows to study in depth what are the performances of the OMA-based algorithm of interest in extracting the modal parameters of a given structure where is installed a specific measurement setup. Thanks to the developed methodology, the Monte Carlo method allows to test the OMA algorithm on numerical responses exhibiting the presence of those same modes close in frequency and affected by large modal overlap that are featured by the responses collected on a 3rd ring Meazza stadium grandstand where a permanent monitoring system is operating. As practical outcome, the developed methodology has allowed to deeply test the performance of the OMA algorithm used for the analysis of the data gathered on the real structure and tune it for an increased effectiveness of the analysis over the long-term period. The second part of the work, on the other hand, investigates the suitability of a monitoring strategy for the Meazza stadium roof based on the detection of AE events. On the basis of the data gathered during some preliminary tests conceived to assess the transmissibility of AE events through the stadium roof, CS has demonstrated its suitability to size the AE events of interest by exploiting a number of compressed measurements roughly equal to 25% of samples required by conventional sapling techniques. Ultimately, the general purpose methodology developed to assess bias and dispersion intrinsic to a generic OMA algorithm, as well as, the investigations on the innovative compressed sensing technique make this work a valuable contribution to cope with the challenging issues SHM on large civil structures poses.

EFFICIENCY OF GEAR TRANSMISSIONS AND CFD ANALYSIS OF THE LOAD INDEPENDENT POWER LOSSES

Franco Concli - Supervisor: **Carlo Gorla**

Efficiency is becoming an increasingly issue in the design of gear power transmissions. Since it is important to be able to predict the power losses already during the design step and as reliable models for the prediction of some kinds of power losses are still missing, a comprehensive analysis of the power losses in power transmissions has been performed in order to define the weight of the different contribution to the global efficiency and to understand the appropriateness and the effectiveness of the models and tools available in literature for the prediction of the different kind of losses.

From this investigation has emerged that, even if for all the kind of losses improvements are in principle possible, the fields in which more research is needed concerns the load independent power losses. The load dependent power losses have already been deeply investigated and reliable models are available, while other losses, as those determined by the interaction with lubricant, still need further investigation.

For the prediction of the no-load losses of gears only few works are available and each of them covers only few aspects. Furthermore, this source of losses is the only one in which discrete margins of improvement are still possible, while for other sources, like, for instance, frictional losses, thanks to the results of many years of studies, the remaining possibilities of improvement are comparatively lower.

For this reason a specific research program focused mainly on churning, windage and squeezing losses has been conducted.

Since CFD has had remarkable developments in the last years, it was considered an appropriate tool for the prediction of the no-load losses of gears. This, has been done experimentally and by means of CFD (computational fluid dynamics) simulations.

Some specific studies on the three typical phenomena that generate the no-load losses of gears (churning, windage and squeezing) have been performed. This numerical studies are supported by experimental data and show the influence of some operating and geometrical parameters on the losses and prove the CFD-based method to be a powerful tool for this kind of investigation.

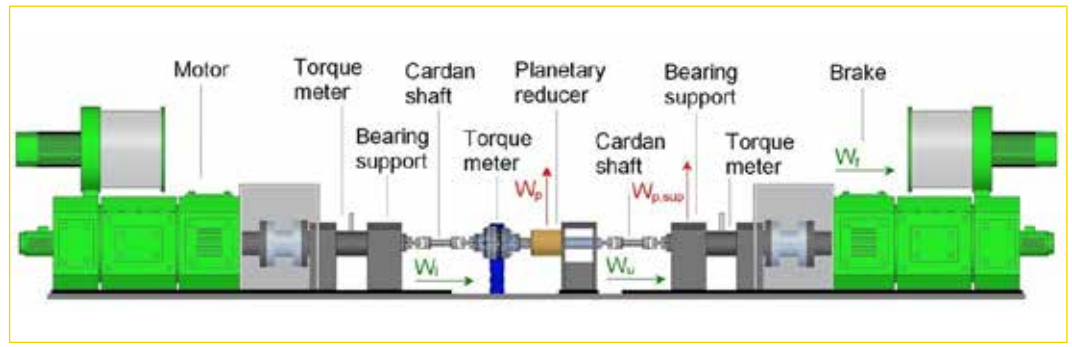
One particular study regards the churning losses of a planetary gearbox and the influence on this losses of lubricant level, lubricant temperature and rotational speed. Moreover the influence of tip diameter, helix angle, face width, lubricant density and viscosity, temperature and rotational speed on the windage power losses has been investigated. Also the influence of operating parameters like temperature and rotational speed on the squeezing losses have been studied.

The weight of the three sources of no-load losses of gears is strongly dependent from the operating conditions and geometrical parameters but, in principle, the squeezing losses are of a lower order of magnitude with respect to the other losses and becomes important only for extremely high rotational speeds and/or for low temperatures. The windage losses can be subdivided in air-windage losses and oil-windage losses. The air-windage losses also becomes important only for high tangential speeds (big gears and/or high rotational speeds) while the oil-windage losses are significant in each operating conditions and for each geometrical configuration.

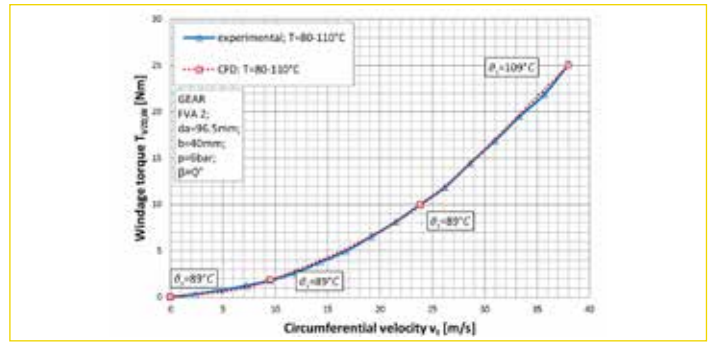
A separate discussion can be made for the churning losses. In this case the presence of a free surface and an air/oil lubricant mixture complicates a lot the phenomena. This losses are comparatively lower than the oil-windage losses and higher than the air-windage losses and are strongly dependent from the amount of lubricant present.

One relevant conclusion is that the experimental tests have fully validated the CFD as a reliable tool to predict the load-independent losses and which can be therefore used to obtain a large amount of results without experimental tests. However, at the present state of the art in terms of computational power, long calculation times are still required. Moreover, in order to simulate the typical phenomena that occurs in a gearbox, some particular techniques should be used and specific tools should be specially developed, in particular to be able to manage the mesh and to correctly describe the motion of the gears.

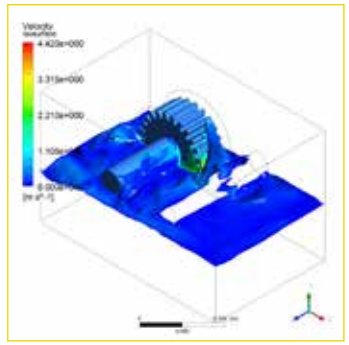
Nevertheless, even if CFD does not still seems to be a tool ready for being used in practical design applications, it has confirmed to be an effective method to partially substitute experimental tests in order to provide data which can lead, in the end, to lean analytical equations which can be easily managed in the design practice.



1. Schematic layout of the test rig



2. Windage power losses: resistant torque vs. circumferential velocity



3. interface between the 2 phases – 500 rpm

CHANNELING RESOURCES FOR INNOVATION IN SUSTAINABLE DESIGN

Walter D'Anna - Supervisor: **Gaetano Cascini**

Over the past decades, environmental issues have been studied with higher interests and efforts, embracing new approaches and concepts. Among these, Life Cycle Assessment and Sustainable Development emerged as a reference direction of study. During this evolution, several tools have been developed for addressing a vast number of challenges that often require a multidisciplinary approach.
In this context, Product Design assumes a central role due to the interconnections between the choices made in this phase and the decisions to be carried out later. Today, managing the effects of these interconnections is certainly favoured by instruments of Product Lifecycle Management (PLM). While these tools are mature enough for detail design tasks, being immediate and easy to use at this stage, the benefits for the early phase of Product Development are certainly more limited. This is true both with respect to the definition of the objectives of a new product proposition, that to its conceptual design development. However, the choices made in these phases strongly limit subsequent decisions, especially when radical shifts have been established (e.g., the reduction of the use of resources by a Factor X).

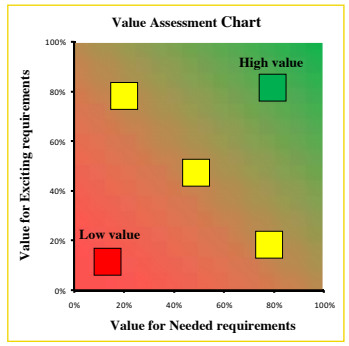
From the analysis of the state of the art in this domain, three main issues emerged: *(i)* how to identify the limitations of a technical system (an artefact consisting of elements that interact in order to satisfy a desire) in the definition of new scenarios; *(ii)* how to integrate the analysis of products and processes characteristics; *(iii)* how to map the ultimate impact of the design, in terms of benefits perceived by the users.
The thesis describes the three main results of the research activities that have addressed these issues. These results share a common thread and are shaped into a tool, namely the SUSTAINability map, a method, called Environmental-Process Value Analysis (E-PVA), and a prototype approach. The common thread is represented by the channelling of environmental resources towards elements that effectively deliver benefits in the customer's quality of life. While the SUSTAINability map is designed to be used at the strategic level, E-PVA is conceived for the operational level. The prototype approach is intended as a novelty item that allows a better understanding of effects produced in the customer's life by choices made in the design phase.
The SUSTAINability map supports the systematic identification of innovation opportunities for achieving the satisfaction of a certain need in a sustainable environment, by considering resources exploitation. In order to assess the limits and potential of technical systems, the systematic identification of opportunities for innovation sprouts from the Laws of Engineering System Evolution of classical TRIZ, the Theory of Inventive Problem Solving. These laws govern the technical systems' paths of evolution at abstract and general level.
The Environmental - Process Value Analysis (E-PVA), is a business re-engineering activity that takes into account both environmental impacts and benefits of the current business process, so as to identify directions of improvement on the basis of the concept of value. The method consists of three main phases: defining the business process and the associated environmental impact, understanding how the phases of the business model generate satisfaction and interpreting results. Specifically, the environmental impact can be calculated through the application of the Life Cycle Assessment, both in normal or simplified form, or by means of other evaluation methods.
The definition of the impact of each phase of the business model on customer satisfaction considers customer requirements. Their potential effect on satisfaction or dissatisfaction of customers is determined by the introduction of the Kano model of customer satisfaction, while it is asked to determine the relative contribution of each phase in achieving the expected performance of each customer requirement.
Once impacts and effects on satisfaction and dissatisfaction have been defined, for each phase of the business process, two main indicators can be calculated: Value for Exciting requirements and Value for Needed requirements that are calculated according to the following formulas:

$$Value\ for\ Exciting\ requirements_{\ j} = \frac{Phase\ Customer\ Satisfaction_j}{Environmental\ impacts_j}$$

and

$$Value\ for\ Needed\ requirements_{\ j} = \frac{Phase\ Customer\ Dissatisfaction_j}{Environmental\ impacts_j}$$

These parameters represent the suitability of the resources employed along the phases in achieving customer satisfaction through unexpected properties of the product or the service (VE) and in fulfilling the basic requirements, so as to avoid customer discontent (VN).
These parameters communicate in relative terms the potential contribution of each phase and they can be represented in a two axis diagram. The interpretation of the diagram allows the identification of directions that are to be considered as a priority, based on the concept of value. Figure 1 reports a generic Value assessment chart. A phase that was in the top right corner of the diagram would be characterized by a high value compared to the other phases and, therefore, does not require immediate improvements. Instead, priorities of intervention are represented by phases characterized by low values, i.e., those in the bottom left area.
It is worth underlying how the Value Assessment chart provides comparisons means between phases of the business process, while numerical values are not of interest.
It is important to note that the same method described above may also involve considerations on costs and social impacts, thus integrating the three traditional pillars of Sustainability.
At last, the prototype approach is integrated in the conceptual design phase in order to propose requirements priorities pursuant to final benefits, identified by the introduction of the Quality of Life concept. The benefits in this case are no longer evaluated as a list of requirements, but by the effects that are produced on the quality of life (i.e. the well-being of the customer). By the application of this approach, it is possible to reduce the detachment between Product Policy and Product Development activities, making the development team more aware and responsible about its choices.

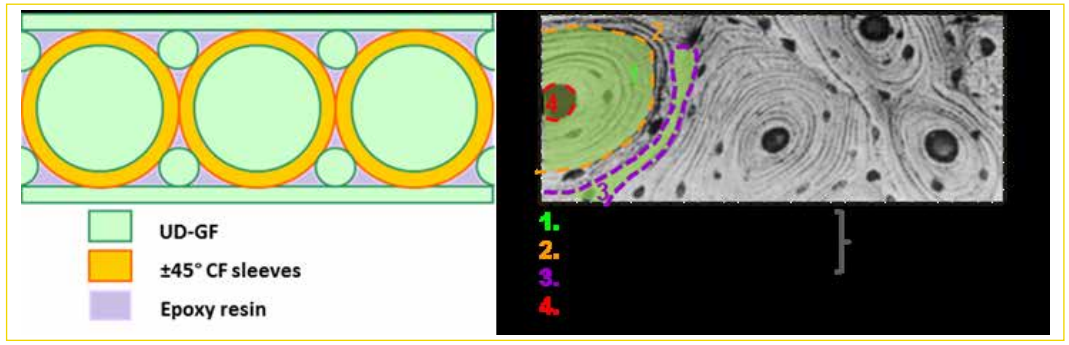


1. E-PVA results could easily be interpreted using the Value assessment chart that reports, relative indications of the potential contribution of each phase to satisfaction or dissatisfaction

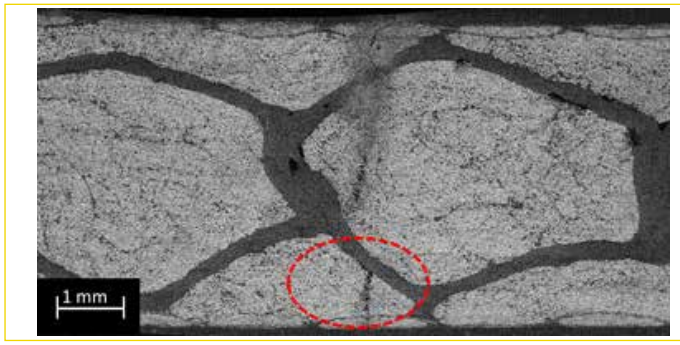
BIO-INSPIRED COMPOSITE MATERIALS: FROM HUMAN BONE TO BONE-LIKE COMPOSITES

Flavia Libonati - Supervisor: **Laura Vergani**

Biomimetics is an engineering design approach to create new structures, by reproducing characteristics found in nature. Indeed, in nature it is possible to find many smart solutions, which can be mimicked to build new materials, with potential applications to various engineering fields. Research in biomimetics has led to the development of a large number of innovative materials and technological solutions, such as gecko-like adhesives, self-cleaning materials, lightweight wood-like composites, and new bio-inspired nanocomposites. Nature is the largest producer of composite materials: wood, bone, nacre, all of them are examples of composite materials. These materials are characterized by a hierarchical structure, consisting of a highly controlled organization at different levels, with characteristic structural dimensions at each level, ranging from the nanometer to the macroscopic length scale. This results in a complex architecture, which provides the material with multifunctional properties. In some biocomposites, such as bone and nacre, also known as bone-like materials or biominerals, the controlled growth and the specific size of their constituents, resulting from the biomineralization process, play a crucial role in determining the mechanical performance of the whole composite; thus, there is an increasing interest among researchers to understand the mechanisms behind the controlled biomineralization. Among those biocomposites, an intriguing material is the human bone, a composite of collagen and hydroxyapatite. Bone is considered as a biomineral, due to the high content of calcium-phosphate minerals, which make it hard and stiff. However, a common characteristic of bone is the incredible toughness, in spite of its brittle mineral components; in fact, bone toughness is about three to five orders of magnitude more than that of the mineral it is made of. Until now, no conventional man-made composite material has reached such an amplification in toughness, compared to the raw components; for this reason bone is considered as a biomimetic model material. The reasons of the toughness and ductility of this materials have to be seek in the hierarchical organization. The key mechanisms, which make it a quasi-ductile and damage-tolerant material, with an increased toughness, are different and simultaneously act at various length scales. Hence, to understand the effects of the hierarchy on the mechanical response of bone, and the structure-property relationship, it is worthwhile to use a multi-scale approach. In this work, after a study of the bone hierarchical structure, an atomistic approach is used to get an insight into the mechanical properties of the bone building blocks, the collagen organic fibers and the hydroxyapatite (HAP) mineral crystals. Full atomistic simulations are carried out to get information about the mechanical behavior of the bone basic components, their interactions and the size effect on their mechanical performance, and in particular on the fracture behavior of the brittle mineral components. A systematic variation of the crystal size allows one to identify a critical size, below which the material becomes flaw tolerant, approaching a constant level of strength, regardless the presence of the defect. The concept of size-driven flaw tolerance is very common for natural materials, confirming the importance of characteristic size in smart natural systems. A further study of bone nanocomposites, made of HAP crystals and collagen fibers, is carried out, by performing molecular dynamics simulations, to get an insight into the mechanical behavior and the failure mechanisms of such systems. At the meantime, a biomimetic approach is used to create a new material, with the aim of replicating some of the toughening mechanisms operating in bone and harnessing them in engineering materials. Hence, by observing the bone structure, selected structural features of bone, the osteons, characteristic of the secondary Haversian structure of bone at the micro-scale, are implemented in a new glass-carbon/epoxy synthetic composite, which could replicate the toughening mechanisms of crack deflection and twisting (Fig. 1). The osteon-like structure is chosen for the simple geometry and the for the role played in enhancing the toughness, by deflecting and twisting the crack. Conventional structural materials, widely used in the field of composites, such as glass fibers, carbon fibers and epoxy matrix, are chosen for the new structural materials. The initial design is simplified to make it feasible, with respect to the available manufacturing processes. The material, manually laminated at the Technical University of Clausthal, is characterized, by performing experimental tests (i.e. tensile, compression, three point bending, fracture toughness), according to ASTM standards. Also, microscopic analyses are performed to get an insight into the fracture process (Fig. 2). Moreover, in order to assess if the bio-inspired composite could really offer improved mechanical properties, compared to existing structural materials, a classical laminate, with the same type and amount of fibers and resin of the osteon-like composite, is created and tested, to allow a direct comparison. The new concept of bio-inspired material is not meant to be a mere copy of what is found in nature, but instead it should provide a smart solution for engineering problems. Until now, it is only a first solution, which could be optimized, by adding reinforcing nano-structural elements with proper shapes and characteristic sizes, as suggested by the results of the atomistic simulations. This work was carried out jointly at the Laboratory of Atomistic and Molecular Modeling of Massachusetts Institute of Technology, under the supervision of Prof. Markus J. Buehler, and the Department of Mechanical Engineering of Politecnico di Milano, under the supervision of Prof. Laura Vergani.



1. Comparison between the structure of the osteon laminate (left) and the microstructure of cortical bone (right)



2. SEM image (100X) showing the fracture process in a cross-section of a specimen of the bone-inspired material: crack deflection, from the intra-osteon to the inter-osteon region

UNCERTAINTY ESTIMATION AND REDUCTION IN DIGITAL IMAGE CORRELATION MEASUREMENTS

Paolo Mazzoleni - Supervisor: **Emanuele Zappa**

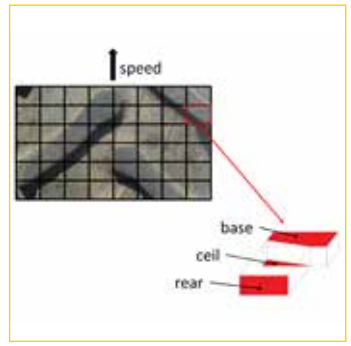
Digital image correlation, DIC, refers to a class of non-contacting measurement technologies that acquire images of an object, store them in digital format and perform image analysis to extract two- or three-dimensional full-field motion and deformation measurements evaluating the gray intensity changes of the object surface among the acquired images.
Thanks to its characteristics of contact-less, handiness, flexibility and density of measurable points, the technique is wider and wider exploited; firstly proposed in the early '80s, it has undergone a great development in the last decade, pushed by the synergic improve of vision hardware and computing power performances, both in terms of analysis algorithms and fields of application. Nowadays DIC-based testing activities spans from micro-electro-mechanical-systems to full-scale civil structures testing, in a variety of temperature ranges (that can easily overcome the melting limit of many metal alloys), materials (from nano-reinforced mortars through composite multilayer material to organic tissues) and dynamic capabilities (static, dynamic and blasting tests).
Out of the main critical issues still associated to digital image correlation applications highlighted in the most recent scientific literature, this work faces the problems linked to the probably most important metrological parameter for a measurement system: the associated measurement uncertainty, i.e. a synthetic index of the attended dispersion of the probability function describing the measured quantity.
On one hand, the full field measurement capabilities of the most modern DIC systems has to face a resulting measurement uncertainty that can not yet compete with the ones of traditional pointwise state of the art approaches (e.g. electrical resistance or fiber optics strain gauges based measurements), and this is generally a problem in case brittle material testing and elastic strain evaluation, where the resulting signal to noise ratio may not be sufficient. On the other hand, the quantification of the uncertainty associated to DIC strain measurements is by itself a non-trivial aspect: no theories exist able to quantify the main uncertainty contributions and return a reliable estimation of resulting strain data dispersion.
The first aspect, i.e. the problem of uncertainty minimization in digital image correlation measurements, is faced in this work from two different points of view is order to propose solutions able to reduce the expected data dispersion.
In the first part, image blurring is proposed, studied, tuned and successively validated as an effective pre-processing procedure on the acquired data able to reduce the measurement uncertainty: high spatial frequency components in the acquired images are proven, in this work, to be misinterpreted by state of the art DIC analysis algorithm and consequently low pass image filtering is proposed, implemented and verified as an effective method to remove these components and improve the resulting codes performances. The theoretical study of the problem is carried out on synthetic (i.e. numerically generated) images, where the effects of image blurring on the resulting measurement uncertainty is tested on more and more complex simulated displacement and strain fields (from constant displacements, i.e. a rigid motion of the measurement surface to cubic displacements, that is parabolic strains profiles).
The stability of the obtained results is consequently proven adding noise to the acquired data, varying the main DIC analysis parameters and the characteristic of the numerically built speckle patterns (i.e. the characteristic textured surfaces required for DIC analyses, particularly in terms of predominant frequency content of the gray value distribution of the measurement surface).
Successively, experimental tests are carried out in order to verify the validity of the implemented simulation strategy and confirm the obtained results. In detail, both rigid motion tests (where the uniform in plane displacements are imposed to the measurement surface by mean of a coordinate measuring machine) and uniform deformation and more complex strain fields tests (with a finite element model of the loaded structure, locally validate by means of strain gauges measurements, providing the reference strain fields) are carried out. A Gaussian low pass filtering of standard deviation equal to 0.75 pixels is doubtless identified as an effectively image preprocessing operation able to minimize the resulting measurement uncertainty.
In the second part of the work, an innovative technique for surface texturization, "toner transfer", is proposed. Highly contrasted randomness in the surface intensity colours (generally referred to as "speckle pattern") is required by the digital image correlation approach for the displacement and strain fields estimation; this is achieved, with the proposed methodology, transferring a numerically designed and printed speckle pattern on the final measurement surface by means of a thermo-mechanical process. Toner transfer is proven to be a cheap, fast and repetitive technology, able to generate, with respect to the traditionally exploited techniques, higher quality textures (i.e. speckle patterns able to increase the resulting measurement resolution and decrease the associated uncertainty). Furthermore, its flexibility in terms of tested materials, sizes, and geometries as long as its suitability in high temperature measurement setups is presented and verified. With toner transfer, the resulting speckle pattern is numerically generated, thus allowing the optimization of its design aimed to the reduction of the resulting measurement uncertainty. A "quality parameter" of the resulting pattern, the "mean intensity gradient", largely accepted in the scientific literature, is numerically maximized varying the main characteristics of the speckle pattern design (speckle size, average distance and amount of introduced randomness). The capability of the optimized speckle pattern to reduce the resulting measurement uncertainty, in particular in case of high noise level or low intensity gradients in the acquired images, is experimentally proven.
The last part of the work deals with the second of the previously mentioned problems associated to uncertainty in digital image correlation: its quantification in relation to strain measurements, a non trivial, but fundamental, aspect due to the large number of variables, both in the test setup and in the processing software, strongly influencing this parameter in digital image correlation applications. An innovative fast procedure to estimate "on the field" this metrological parameter in case of 2D analyses, taking into account all the major uncertainty sources, is proposed and applied. The technique relies on the generation of known controlled fictitious strain field by means of out of plane camera-specimen rigid motion, misinterpreted with a two dimensional approach as an in plane imposed deformations. The theoretically imposed fictitious strain fields are retrieved using two different version of a pose estimation algorithm (previously developed for simple camera placement): the initial position of the specimen with respect to the camera is computed relying on the information extracted from the calibration grid while the final one is estimated iteratively roto-translating in a 3D volume the flat measurement surface trying to minimize the resulting re-projecting discrepancy between simulated and measured in plane displacement fields. The strain fields resulting from the described procedure are compared with the ones measured by the DIC algorithm in order to quantify the expected data variability for the given measurement setup.

ON THE MODELLING OF DEFORMABLE TYRE ON DEFORMABLE SOIL FOR TREAD PATTERN DESIGN OPTIMIZATION

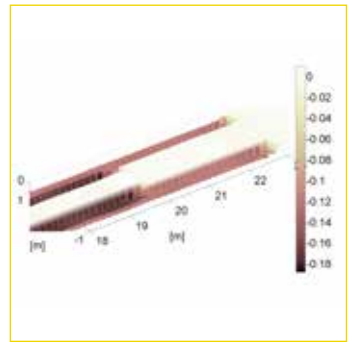
Silvia Negrini - Supervisor: **Francesco Braghin**

Tyres of off-road vehicles, in particular of agricultural tractors, should satisfy many different requirements; moreover their performance is significantly affected by soil conditions, which can highly vary as a function of humidity and temperature.
First, the tyres passage should not overly degrade soil conditions, indeed soil strain and compaction due to tyres passage affect soil by decreasing water infiltration and water holding capacity, increasing runoff and erosion, leading to a rise in crop production problems, thereby decreasing crop yields and profitability of farming systems. Moreover, when plastic flow occurs, although soil is not compacted, the strain may decrease the connectivity of pores in the soil, thereby decreasing the water infiltration rate.
Secondly, the tyres should provide a limited level of vibrations, since the vibrations transmitted by the tyre impact on ride comfort, and the exposure to significant levels of acceleration for a long time affects the efficiency and the alertness of the operators leading also to unsafe situations.
Finally the tyres should guarantee good traction performance, indeed variations of the normal contact forces due to vertical tyre displacements result in variations of the traction force provided by the tyres which influences the quality of tillage and other operations.
Hence the aim of this thesis is to state a model able to predict the impact of tyre structure and tyre tread pattern, depending on soil characteristics, on these achievements.
To this purpose in this thesis two tyre-soil interaction models have been proposed, based on different modelling techniques.
The first one that has been discussed is a plane model, since it considers only the forces and displacement in vertical and longitudinal directions, and represents the soil as a grid whose nodes can move vertically, whereas the second one is a multi-body particles model, based on Chrono::Engine multibody library, describing the soil as a pebbles bulk.
The plane model can be outlined as composed by two sub-models interacting with one another: the first one models the tyre structure and tread pattern geometry whereas the second one represents the soil.
The tyre model allows to take into account the effect of the tread pattern design, so that the excitation of the vertical dynamics associated with lugs geometry can be included.
The tread pattern shape is taken into account by means of four different surfaces, associated respectively to the lug tip (base surface), to the front and rear sides of the lug (front and rear surfaces), and to the surface between the lugs (ceil surface).
Thus the tread pattern is subdivided in a grid of elements, which are itself associated to the areas covered by of each one of the four surfaces, as shown in Figure 1.
Moreover the tyre model considers the tyre structure through the eigenfrequencies and eigenvalues resulting from the analysis of an impulsive response of a real agricultural tyre.
The soil model represents the soil as a plane surface, whose nodes can be displaced vertically under the tyres load, reacting with shear and normal stresses.
The shear and normal responses of the soil have been characterized by two tests: respectively the direct shear test, performed to measure the shear resistance of a soil under pressure, and the cone penetrometer test, allowing to measure the normal resistance of the soil to the sinkage of a conic pin.
Through those tests it has been possible to set the parameters of the numerical model of the tyre-soil interaction, based on Matlab language.
This model has been validated by comparison with the experimental results of a traction test, measuring the traction force provided by a tractor depending on the wheels slip, and allows to achieve reliable results on traction force, comfort and soil sinkage.
For instance Figure 2 shows the soil deformation after the tractor passage; the tyres tracts are visible in the soil and it is possible to notice the sinkage increases corresponding to the rear tyres, due to the load distribution.

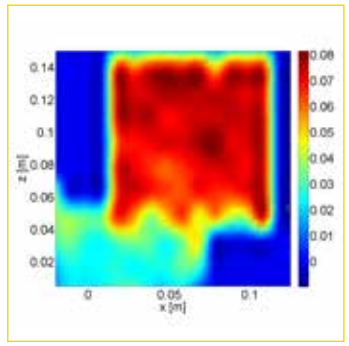
Finally, a multi-body particles model has been stated to simulate the subsoil dynamics. This model is based on a multi-body C++ library, called Chrono::Engine, representing bodies interaction by means of differential variational inequalities theory.
The main advantages presented by this model are the possibility of considering the soil displacement and stress distribution in subsoil layers and the capability to introduce in the formulation the three-dimensionality of the problem, allowing to consider the lateral forces involved in more complex manoeuvres than forward ride, although at the moment the focus is pointed on the soil dynamics.
In order to set the soil parameters for future tyre-soil interaction simulations, a direct shear test has been modelled. This test provides the shear resistance of a soil sample placed in a box, whose upper part is moved at constant speed with respect to the lower one.
For instance Figure 3 shows the pebbles velocity modulus in the middle section of the box. It is possible to notice the pebbles in the upper part of the box moving at higher speed than the ones in the lower part.
The proposed models are aimed to provide a tool for tread pattern design, in order to reduce experimental tests for tyre optimization, however they can provide also viability simulations depending on soil properties.



1. Tread pattern geometry modeling



2. Simulation results: tractor tracks in the soil



3. Particles velocity modulus in the soil bulk

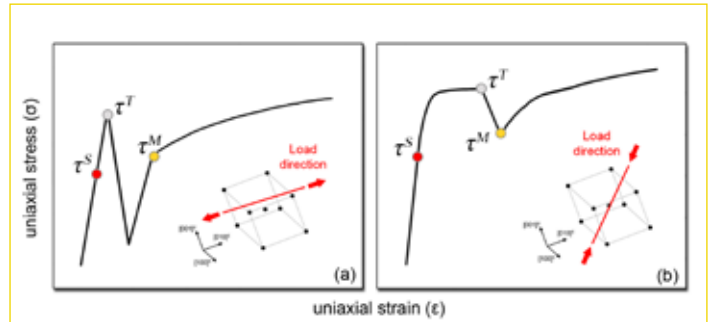
EXPERIMENTAL CHARACTERIZATION OF MICROSTRUCTURAL DAMAGE MECHANISMS

Luca Patriarca - Supervisors: **Stefano Beretta, Huseyin Sehitoglu**

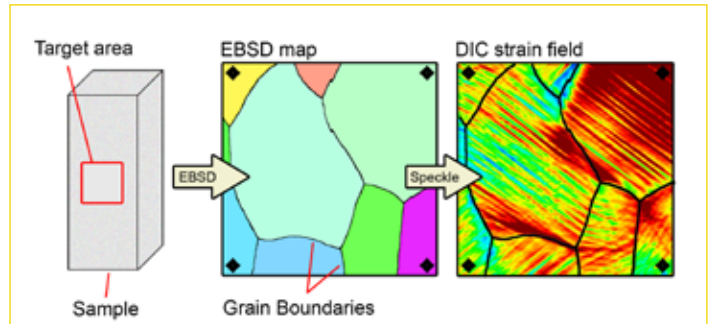
This work presents an experimental approach to investigate the material behavior at the micro-scale of two important alloys (FeCr and γ-TiAl) for structural applications. Local strain fields at multiple length scales are measured using an advanced optical technique. Local strain heterogeneities arises as a consequence of the local microstructure and deformation mechanisms. This work aims to gain further insights into the relation between the mechanical behavior of metals at the micro-scale with the observed mechanical behavior on the meso and macro scales. The main findings presented here provide valuable information into the deformation mechanisms activated in bcc metals (slip and twinning), which can be utilized by researchers as the basis of analytical models to be developed in the next future. The work is divided into three main parts. In the first part, tension and compression experiments were conducted on multiple single crystal orientations of body-centered cubic Fe-47.8Cr single crystals. The critical resolved shear stress magnitudes for slip, twin nucleation and twin migration were established (see Figure 1). The results show that the nucleation of slip (indicated with τS) always precedes twinning which nucleates with an associated load drop at an higher critical resolved shear stress (τT). Following twin nucleation, twin migration proceeds at a critical resolved shear stress (τM) that is lower than the initiation stress. The experimental results of the nucleation stresses indicate that the Schmid law holds to a first approximation for the slip and twin nucleation cases, but to a lesser extent for twin migration particularly when considerable slip strains preceded twinning. The critical resolved shear stresses were determined experimentally using digital image correlation in conjunction with electron back scattering diffraction. The digital image correlation enabled pinpointing the precise stress on the stress-strain curves where twins or slip were activated. The crystal orientations were obtained using electron back scattering diffraction and used to determine the activated twin and slip systems through trace analysis. The results presented in the first part of this thesis provide a considerable contribution in understanding the micro-mechanical behavior of bcc alloys.

In the second part of the present work slip transmission through grain boundaries is investigated. The full slip dislocation blockage, or the partial slip dislocation transmission processes at grain interfaces provide a significant contribution at the material strengthening. The study focuses on the link from the deformation mechanisms at the micro-scale to the global mechanical behavior (macro-scale). Strain fields across grain boundaries were measured using advanced digital image correlation techniques (Figure 2). In conjunction with strain measurements, grain orientations from electron back-scattered diffraction (Figure 2) were used to establish the dislocation reactions at each boundary, providing the corresponding residual Burgers vectors due to slip transmission across the interfaces. A close correlation was found between the magnitude of the residual Burgers vector and the local strain change across the boundary. When the residual Burgers vector magnitude (with respect to the lattice spacing) exceeds 1.0, the high strains on one side of the boundary are paired with low strains across the boundary. When the residual Burgers vector approaches zero, the strain fields vary smoothly across the boundary. The FeCr bcc alloy exhibits single slip per grain making the measurements and dislocation reactions rather straightforward. The work points to the need to incorporate details of slip dislocation-grain boundary interaction (slip transmission) in modeling research.

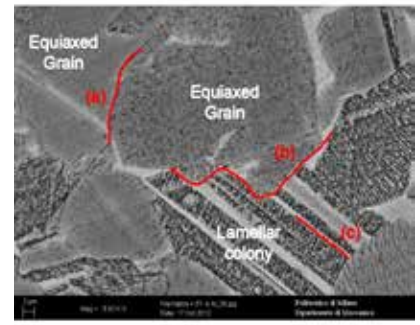
In the last part of the work, a γ-TiAl alloy manufactured with electron beam melting technology is examined. The electron beam melting technology enables to avoid typical manufacturing defects. It follows that experiments carried out on this material provide several insights into the microstructural damage mechanisms leading to crack initiation. Classical experimental methodologies for the fatigue characterization were conducted adopting plain fatigue specimens, fatigue specimens with an initial artificial defect, and crack propagation specimens. Preliminary considerations from these experiments indicate that the interfaces between lamellar-lamellar grains, and lamellar-equiaxed grains act as potential crack initiation sites (Figure 3). Taking into account the typical lamellar grain size, the fatigue resistance of the duplex γ-TiAl alloy can be predicted. Further investigations on the influence of the microstructure were obtained using residual strain fields via high resolution digital image correlation in combination with high resolution images of the local microstructure after etching.



1. Schematic of the possible stress-strain curves for crystal orientations displaying twinning. For each stress-strain curve the CRSSs for slip nucleation (τS), twin nucleation (τT) and twin migration (τM) are determined. Case (a) represents crystal hardening governed by twin-twin interactions, while in Case (b) large slip activity precedes twin nucleation and twin-slip interactions dominate the hardening



2. Experimental methodology for the experiments on the FeCr polycrystal samples. A target sample surface is polished and analyzed with Electron Back-Scattered Diffraction in order to define the grain orientations. Successively, strain fields from Digital Image Correlation are used in conjunction with grain boundary information in order to study the strain transmission/blockage process



3. Potential crack initiation sites due to the microstructure for a γ-TiAl alloy: a) interface between two equiaxed grains; b) interface between an equiaxed grain and a lamellar colony; c) decohesion between lamella phases or micro-cracking induced by slip blockage at lamellae interfaces

TIME BUFFER: A CONTINUOUS APPROXIMATION FOR SIMULATION OPTIMIZATION OF DISCRETE EVENT SYSTEMS

Giulia Pedrielli - Supervisor: **Andrea Matta**

This work focuses on the optimization of stochastic Discrete Event Systems (DES's). The state of a DES changes only when events happen, whereas no modifications happen between consecutive events. As a result, the system dynamics is fully characterized by the sequence of events, which defines the system sample path. Stochastic DES's are such that given and sequence of known input the system sample path is a stochastic process instead of a deterministic sequence of events.

The optimization of stochastic Discrete Event Systems (DES's) is a critical and difficult task to be addressed. Indeed, besides the search for the optimal system configuration, it requires the assessment of the system performance. In other words, both an optimization problem and a simulation problem need to be solved. In the literature, this framework is referred to as Simulation-Optimization. Traditionally, the simulation-optimization architecture is made of two decoupled modules: an optimization module (generative module), solving the optimization problem and a simulation module (evaluative module), solving the simulation problem. These two modules work iteratively until the optimal solution is found or a predefined stopping condition is met. The optimization module does not contain the description of the system dynamics. The simulation module, instead, can evaluate the system performance since it embeds the description (explicit or implicit) of the system behavior; however, as no optimization procedure is contained within this module, it cannot optimize the system configuration. Hence, in the scope of simulation optimization, both modules are required.

Mathematical Programming Representation (MPR) can be applied to avoid this decoupled architecture. Indeed, if the dynamics of the system can be represented by means of a set of constraints, they can be embedded in the optimization model. As a result, the DES is optimized and simulated at the same time.

This thesis proposes an integrated simulation-optimization framework based on the use of mathematical programming for both configuration generation (i.e., to solve the optimization problem) and system performance assessment (i.e., to solve the simulation problem). Specifically, LP models for simulation-optimization, developed based on the Time Buffer (TB) concept, are proposed. The TB is a continuous approximation to replace the integer decision variables defined in the original optimization problem. In general, to approximate a discrete variable with a TB, it must be possible to formally describe its effects on the events characterizing the system dynamics.

Herein, the time buffer framework is formalized, describing the tractable classes of Discrete Event Systems and optimization problems. The approach steams from the description of the simulation-optimization problem, i.e., (1) the objective of the optimization, (2) the constraints on the decision variables, (3) the description of the system behavioral rules. Afterwards, the IP mathematical model for simulation optimization can be developed and the TB-based LP counterpart can be derived. The solution of the TB models provides a good approximate integer solution to the optimization problem and robust bounds on the exact solution, i.e., upper and lower limit defining the interval where the optimal solution lays. The time buffer concept has been applied for approximating the buffer capacity in an open flow line to solve the Buffer Allocation Problem and for approximating the number of pallets in a loop line to solve the Pallet Allocation Problem. In particular, this thesis represents the first contribution in the modeling of closed queuing networks adopting the TB approach.

Three main results can summarize the brought research activity:

R1. Development of the Time Buffer Framework for the simulation-optimization of DES's. This work has presented the main properties of the class of DES's and optimization problems in order to generate TB models. Moreover, the proposed approach has been characterized providing the main guidelines to derive and solve approximate models for simulation-optimization starting from the description of the dynamics of the system and the optimization problem (simulation-optimization problem setting).

R2. Application of the Time Buffer Framework for the solution of (1) the Buffer Allocation Problem (BAP) for multiple stage open queuing networks and (2) the Pallet Allocation Problem for closed queuing networks with finite buffer capacities, laying the prerequisites for the simulation-optimization of multiple loop systems. This application led to the development of two optimization algorithms to solve the respective problems.

R3. Solution of the developed models and proof of structural results exploiting the set of tools coming from the Mathematical Programming Representation framework and the theory of convergence.

This work was partially funded by the European research project Virtual Factory Framework (grant agreement No.: NMP2-LA-2010-228595). In the scope of the project, the developed simulation- optimization application has been integrated within the Virtual Factory (VF) platform forming, with other connected tools, a first proposal of a comprehensive suite for the factory design. As a result, besides the presented scientific results this thesis represents a contribution towards the answer to a relevant industrial issue: the presence of a collaborative platform supporting the design of virtual factories.

The design platform was tested on a real industrial case provided by the System Engineering Department of COMAU SpA Power Train division, one of the most important technology providers for FIAT automotive. The positive feedbacks received from COMAU fostered further extensions to the platform on which we are working at the present moment.

Three main future research directions were outlined:

F1. Time Buffer framework extension. The general approach has to be further detailed and the whole framework extended both in terms of the class of optimization problems that can be managed and the class of discrete event systems that can be represented. The idea is to provide a definition of the time buffer as a mean to connect events affecting a DES. In this way a large class of discrete decision variables can be modeled based on their effects on the event sequence. This approach seems promising as it acts on the sequence of events that is among the most general ways to model a DES.

F2. Definition of convergence requirements. The convergence study has to be extended to the closed queuing networks case with the purpose of understanding the convergence property of the time buffer models in general. As ultimate end, this activity should lead to the definition of the properties that the class of systems and optimization problems need to satisfy in order to guarantee the convergence of the time buffer models.

F3. Computational efficiency. Increase the efficiency to solve the LP approximate models exploiting the derived properties. The proximity of the approximate integer solution and the one obtained running OptQuest (i.e., the optimization tool provided together with the commercial simulation software for Discrete Event Systems Arena), suggests that a branch and bound based search method, starting from the generated solution and the computed bounds, could reach the optimum requiring less time than other commercial applications do. However, to make this two-stage optimization appealing the computational time required to solve time buffer models needs to be decreased.

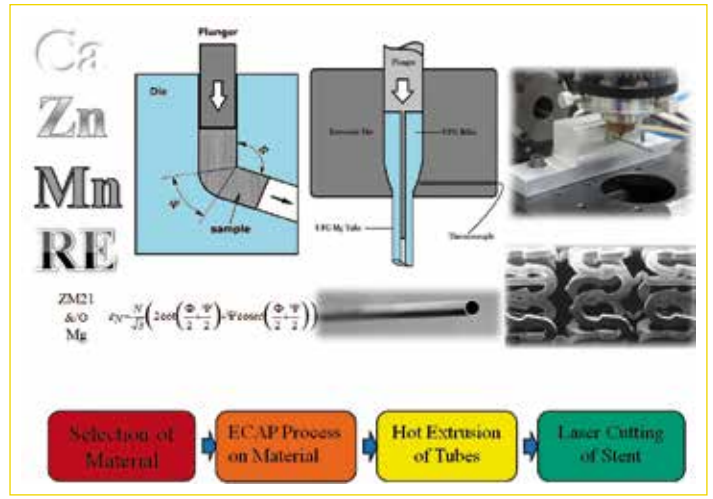
The results obtained in this thesis, despite the specific systems and optimization problems, considered, lay the foundations of a general framework for DES's optimization, hence oriented to a broader class of both discrete event systems and optimization problems.

PRODUCING HIGH STRENGTH MG BIO-DEGRADABLE STENT BY USING ULTRA FINE GRAIN SIZED ZM21ALLOY AND PURE MG

Ge Qiang - Supervisor: **Maurizio Vedani**

Magnesium and its alloys are considered as the ideal candidate material for biodegradable stent application because of their biocompatibility and low corrosion resistance in human body. However, the mechanical properties and corrosion resistance are still needed to be improved. Strategies to improve these aspects include changing the alloy composition, tailoring the microstructure to improve the mechanical properties and intrinsic corrosion resistance, adopting surface coatings to temporarily insulating the bulk metallic structure were proposed by all researchers working in this field in order to deal with the balance between biocompatibility, corrosion resistance and mechanical properties. The objective of this study is to develop a non-toxic material system from preliminary composition selection and subsequent microstructure tailoring by Equal Channel Angular Pressing(ECAP) to further enhance the mechanical properties and corrosion resistance, additional surface coating to elongate the device service time is possible to adopt when it is necessary.

The adopted experimental procedures are shown in the Figure 1 which includes the phases of material selection according to biocompatibility of alloying elements, hot deformation investigations to optimize the deformation conditions for the manufacturing of stent precursors, microstructure tailoring by using ECAP processing to obtain Ultra Fine Grain(UFG) material with improved mechanical properties and corrosion resistance, forming the stent precursors into small size tubes by hot extrusion and stent net cutting by laser.
The alloy ZM21 with highest ductility and lowest content of toxic elements was selected for the subsequent experimental procedures. An investigation was carried out on properties and processing of ZM21 ultra-fine grained Mg alloy as a possible candidate material for the manufacturing of improved biodegradable Mg stents.
ECAP process was applied to achieve a significant grain refining in the sub-micrometer grain-size range. Processing was performed according to a two-step strategy aimed at achieving a first refining of the structure at 200°C and then reaching the UFG grain size range by still lowering the processing temperature down to 150°C. A homogeneous equiaxed grain structure featuring sub-micrometer grain size in the range of 500 nm was successfully achieved.
The mechanical characterization revealed a significant improvement of properties of the ECAP treated billets over the starting coarse grained ZM21 alloy. The 0.2% yield strength rose from 180 MPa to 340 MPa after 150°C ECAP processing, still keeping a fairly high tensile ductility.
The UFG ZM21 alloy billets were then used for the extrusion of stent precursors at 150°C having the form of small tubes (D=4 mm, d= 2.5 mm). The grain size after extrusion was kept in the sub-micrometer range owing to low-temperature processing and the contribution of dynamic recrystallization. Consistently, hardness improved from 50 HVn of the coarse grained alloy to 74.8 HVn of the UFG extruded tubes.
The stent net was then obtained by using fiber laser cutting starting from the above UFG precursors. No significant modification of the microstructure was detected close to the laser cut surfaces, thus demonstrating that processing of biodegradable Mg stent having an ultrafine-grained microstructure is feasible and that obtained products feature promising properties.



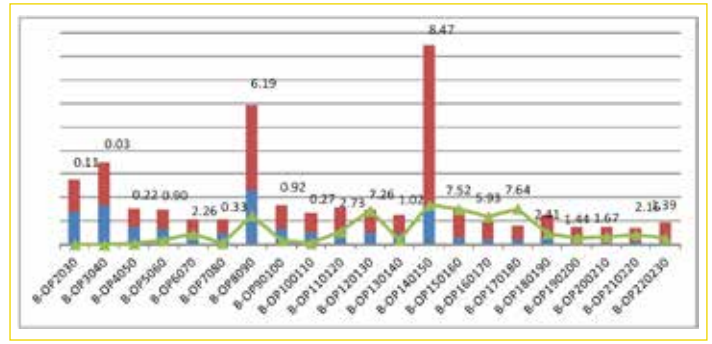
1. Manufacturing procedures of high strength ZM21 magnesium stent

PERFORMANCE EVALUATION OF COMPLEX MANUFACTURING SYSTEMS: AN APPROACH BASED ON FORMAL METHODS AND APPROXIMATE ANALYTICAL MODELS

Andrea Ratti - Supervisor: **Tullio Tolio**

A production system is the set of technological resources that is capable to transform raw parts into a finished products in terms of time, location and shape. In such a system, the interactions between the resources make the behavior of the system quite complex to evaluate and to understand by the designers. For these reasons, the managers of the companies need proper tools and methods to quantitatively support the planning, control and performance improvement of the systems, throughout all the factory life-cycle phases, from early design, up to reconfigurations.
One of the most critical task along the process of design of production systems, is the evaluation of the performance. The goal is to provide the designer a measure of the productivity of a system like production volumes, utilization of the resources, average flow times and work in progress. Usually this task is carried out with the creation of a proper model, i.e. a meaningful simplification of the reality that can be used for a specific design purpose, that is usually a simulation or an analytical model.
Analytical methods are developed with the goal of describing the dynamic behavior of the system in terms of the solution of a set of equation, used to express the relations existing among the different variables. Concerning manufacturing systems, the variables are related with the stochastic processes that afflict the resources, like the failure and the repair of the machines, the processing times, the flow of parts, the blocking of the system, etc. Thanks to this formulation, analytical methods are usually very fast in terms of computational effort. This aspect is useful and desired during the early stages of manufacturing systems design because facilitate the reduction of the number of possible alternative system configurations.
However, the mathematical formulation of such a problem is a cognitive-intensive activity. This means that an extension of the model capabilities requires a big effort. Moreover, the designers need to understand what is happening inside the system, that means recognize the structure of the plant, the behavior of the resources, the relevant features and the numerical parameters, i.e. processing times and reliability. The information of this potential system configuration can be either about the structure or numerical. The structure include all the information about how the resources of the system are connected and how they operate, i.e. layout of the plant, type of machines, kind of operations performed, etc. The numerical include all the quantitative information about the system, i.e. reliability of the machines, processing times, bill of material, etc. At a first glance, such a system appears to be a chaotic composition of technological devices. This means that it takes a lot of time to an expert to figure out what is happening inside the system, i.e. determine the flow of parts, which operations are done by the machines, which are the resources of the system, how the reliability of the machines works, etc. Once the designers have figured out how the system works, they need to determine what is relevant and what is irrelevant from modeling purpose, that is, again, an hard activity.
Here, in this thesis, a new framework is presented, that is composed by an analytical methodology for manufacturing systems performance evaluation based on automatic model generation, obtained from a structured description of the manufacturing system, for aiding the designer both in the configuration and reconfiguration phases. This thesis makes contributions to performance evaluation of manufacturing systems and automatic performance evaluation model generation fields.
The proposed methodology consists of two main elements
The first element is the definition and analysis of manufacturing system structures by means of a new formal method. This new formal method, written using the specification language Alloy, provides a new general way to describe production system, through a series of native primitives of the domain of manufacturing systems. All the possible machines, buffers and structure configurations that can be found in a complex production system, i.e. assembly/disassembly, split/merge, parallel, loop, rework, etc. When a production system is described by means of this new formal language, it is possible to execute an automatic analysis and recognize automatically its relevant structures. Within this framework all the elements and the requirements that are needed to perform the automatic model generation, both in terms of methodologies and practical implementations, are defined.
The second element is the creation of general analytical model for the performance evaluation of manufacturing system, composed by a new analytical model of a two-machine continuous flow system with finite buffer capacity, multiple up and down states. The model provides a way to analyze a wide range of two-machine systems, including for example systems with phase-type failure and repair time distributions and series/parallel machines. The two elements are then used together to build the model of the system. The exact solution of the two-machine line is used as a building block for the analysis of larger systems, using decomposition techniques. The two-machine lines are automatically configured according to the automatically recognized structures from the formal method, and to the numerical parameters from the plant, fitting phase-type distributions. In the thesis, the decomposition techniques used, are already available in the literature.

The framework is validated on a real case production line, dedicated to the machining of components for the automotive sector, integrating all the elements of the framework. The model of the system is created automatically using the empirical distributions available from the plant. The new formal method is validated on a real case production system, dedicated to the assembly of electrical components and on a set of some didactic examples. Moreover, the two-machine line model is used for the investigation of the effect of phase-type distribution approximation on the performance of the system, both in terms of productivity and of average buffer inventory.

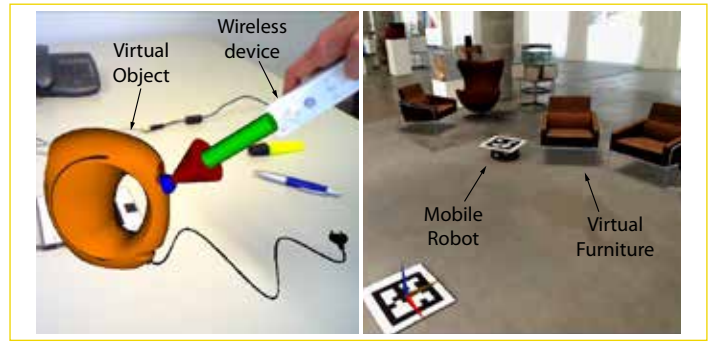


1. Plot of average inventory level obtained from the analytical model on a real production example

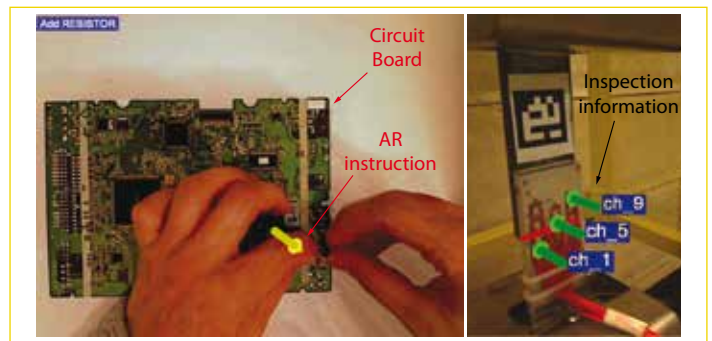
LOW-COST AUGMENTED REALITY FOR INDUSTRIAL PROBLEMS

Guido Maria Re - Supervisor: **Umberto Cugini**

Many technological supports have been proposed and integrated in industrial activities so far. Their purpose is to increase the working performances, in order to speed up the accomplishing time and decrease the costs of an operation. Among them, Augmented Reality (AR) has been proposed, which is an emerging technology that allows to visualize and to interact with virtual objects in the real world. The exploitation of AR in the industrial working field can provide several advantages because it is able to display digital information directly in the working environment. These pieces of information can be data, instructions or alerts that are represented in a textual or graphical manner, otherwise virtual objects in general.
Currently, the majority of the applications for AR in Industry have never left the laboratories where they have been developed. Their purpose was just to check the feasibility of AR in Industry and their use in a real industrial context is indeed difficult. Moreover, the technologies used during the development of the applications were usually limited to fulfil the industrial demands or too much expensive.
This work proposes the use of the technology embedded in low-cost devices, coming from the mass market, as substitute or completion for traditional technologies used for AR. Since these devices are cheap, their use for an AR application is easy to afford for industrial companies and consequently their integration in industrial activities should be an acceptable investment. These low-cost devices are also good candidates for AR purposes because they usually embed robust, cutting-edge technologies and they are easy to find.
Unfortunately, it is not possible to directly integrate these technologies in applications for Industry because they have been designed for different purposes. Thus, the algorithms to manage these technologies have been modified in order to make them working in the new industrial context. During the modification, different needs about the user and the environment wherein he is working have been taken into account.
The low-cost technologies that have been taken into account and adapted to fulfil new tasks are three. The first one is a wireless hand-held device for video gaming and a solution to track its position in space has been implemented by using the infra-red sensors which it is equipped with. The second one is a mobile robot designed for households and its mobility has been exploited to create a hybrid tracking solution for wide environments. The robot has been used to increase the working area of a marker-based tracking system. Thus, it is possible to estimate the camera position without structuring the environment. The last one is a planar image tracking system that has been extended to work also with circuit boards. In this way it is possible to recognize and track the position of a circuit board without the addition of any marker on it.
The developed solutions have been evaluated by comparing their characteristics to other well-known approaches, in order to validate the use of these low cost-technologies for AR purposes.
Once the technology has been modified to operate in the industrial environment, it has been integrated in some application to support specific activities. In particular, the considered contexts were Product Design, Manufacturing, Maintenance and Inspection and four AR supports for specific industrial activities have been implemented. The first one is an interactive system for Design Review. The wireless device from video gaming has been here used to interact with virtual prototypes during the evaluation phase of the design of a new product (Fig. 1). The second support regards to the design of spaces and it take advantage of the mobile robot in order to achieve AR for wide environments. The system allows the interior designer to visualize and to interact with virtual objects, so that he can directly see the final result in the real space (Fig. 1).
For what concerns Manufacturing and Maintenance, an interactive support for manual operations on circuit boards has been developed. Pieces of information are directly represented on top of circuit boards by means of the tracking system and they are addressed to manual activities (Fig. 2). Finally, a framework to represent data from sensors and the object state has been implemented. This one works also with a wireless connection and it is addressed to common mobile devices, such as tablets and smart phones (Fig. 2).
Some testing sessions have been carried out to evaluate the performances of the integrated technology and performed some user test to assess the usability of the final application. From these tests, it turns out that low cost technologies can be a valid alternative to technologies traditionally used for AR applications addressed to Industry. In fact, these last ones can achieve good performances, which are acceptable for AR purposes, and the final applications are usable by the user.



1. Two AR application developed in the field of Product Design. On the left, a wireless device from game purposes is used to interact with virtual objects during a design review. On the right, a support for space planning in a real room that exploits a mobile robot



2. On the left an AR support for manual operations during assembly and maintenance tasks on a circuit board. On the right, a visualization system to represent virtual information about sensors during an inspection phase

INTEGRATED ANALYSIS OF MANUFACTURING AND SUPERVISORY SYSTEMS

Anteneh Yemane - Supervisor: **Marcello Colledani**

The design, development and operation of manufacturing systems that highly guarantee desired target performances is a crucial goal in manufacturing as enterprises are facing an increasingly competitive global market. In response, the last decades of manufacturing systems engineering research has generated powerful tools to support the modeling and analysis of manufacturing system performances. Besides, companies are increasingly interested in assisting the design and operation of advanced manufacturing systems by implementing modern digital manufacturing tools. Technological advances in sensor and information technology enable the acquisition and storage of huge amount of information about the behavior of the systems. Thus, decision making in the design and operation of advanced multi-stage manufacturing systems is more and more supported by digital manufacturing tools. In order to be effective in their scope, such tools have to be based on high-fidelity virtual representations of the real system.

At various stages of the manufacturing system life cycle there is a need to consider the link between digital technologies which gather information and the manufacturing systems analysis tools that must be fed with this information. During the design phase, the technical efficiencies of the resources/ machines that shall compose the manufacturing system are considered as nominal values, provided by the equipment producers. In operational phase the reliability of machines is modeled through the characterization of the Mean Time to Failure (MTTF) and the Mean Time to Repair (MTTR) of each failure mode affecting the machine productivity. Although these are assumed to be the mean of statistical distributions, their value is considered as known deterministically. Depending on the level of confidence and knowledge on the estimation of the input parameters they are subjected to uncertainty. Performance analysis with an explicit consideration of the associated uncertainty is of paramount importance for generating system configurations/ reconfigurations that are robust to input parameter estimation uncertainty.

The relationship between the amount of data used for parameter estimation and the subsequent performance evaluation is strong. Results from this research have also shown that uncertainty modifies the performance evaluation results and can significantly affect the related system design decisions. This perspective paves the way for the development of a new manufacturing system engineering theory for the robust design of manufacturing systems under uncertainty. However, in spite of the strong relationship between the two fields they are normally treated independently by researchers and practitioners. To this goal the impact of performance analysis using real data in contrast with precisely known parameters assumptions is investigated. Performance deviations as high as 15% estimation errors are observed by carrying out the analysis ignoring uncertainty in estimations. Moreover, analyses with the traditional approach that assume precisely known parameter estimates from actual data are observed to provide performance guarantee level as low as 43%, which compromises system robustness in achieving desired target performance.

In order to clearly present the relevance of the problem and the differences between traditional approaches and the proposed approach primarily the analysis of simpler manufacturing systems is introduced. Performance analysis of smaller manufacturing systems using exact analytical methods with uncertain parameters estimates is demonstrated. The impact of performance analysis using real data in contrast with precisely known parameters assumptions is investigated. Important findings from this analysis are highlighted and the relationships that explain the observed differences are analytically presented.

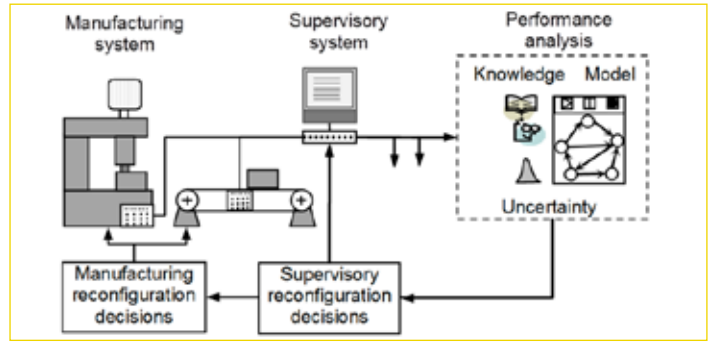
Emphasizing the proven advantages of performance analysis on smaller systems with real data the study extends a similar approach on the development of tools that support performance analysis in complex systems. Alternative approximate techniques that are accurate and efficient in measuring the performance of multi-stage manufacturing systems are proposed. Numerical accuracy and applicability of the proposed methods are presented under different conditions.

Additionally a new method based on the decomposition of multi-stage manufacturing lines for estimating the distribution of the average throughput *TH* is proposed. The method is proved to be accurate and computationally efficient to study long lines. Moreover, the method is used to study and understand important system behaviors under uncertainty, providing important insights in system design under practical scenarios.

A gradient based algorithm for the optimal supervisory systems reconfiguration and manufacturing systems reconfiguration is proposed. The method attempts to improve the estimation of the output performance uncertainty by optimally allocating supervisory resources to reduce performance uncertainty. Exploiting the developed techniques in this work it targets to minimize input uncertainty on the parameters which highly contribute to the output uncertainty. On the other hand it addresses the impact of configurations on performance uncertainty by choosing alternative buffer configurations so that target performances can be guaranteed. This allows system designers to evaluate alternative solutions that satisfy a required level of robustness for the available resources and knowledge on design parameters.

Based on existing buffer optimization techniques, a new approach for the optimization of manufacturing systems under uncertain parameters is proposed. The approach aims at providing the optimal buffer configuration that guarantees the satisfaction of target performances with a given confidence level. By using this method the level of additional information or the necessary buffer configuration required to satisfy the desired level of robustness can be analytically determined.

Finally, based on the result of this study general design and managerial insights are provided in the design and operation of manufacturing systems under uncertainty. The proposed approach is also used for the analysis of an industrial case in automotive industry featuring a buffered multi-stage manufacturing system. Future research works extending the benefits of this research and introducing additional problems in the integrated analysis of supervisory and manufacturing systems are proposed.



1. Integrated data acquisition and performance analysis