Doctoral Programme in Civil, Environmental and Mechanical Engineering

Research subjects proposed for the 37th cycle

A mandatory attachment of the application is **a description of the research project and statement of purpose (**max. 3 pages**)** relative to the research areas of the PhD Programme in Civil, Environmental and Mechanical Engineering, **preferably** on one of the following research subjects:

Curriculum A - Civil and Environmental Engineering

- *Reference persons:* Marco Tubino (UNITN/DICAM), Guido Zolezzi (UNITN/DICAM)
Title: Effects of dams on sediment regime and river morphodynamics in Alpine rivers and assessment of restoration potential

Dams and impoundments support important regulatory functions of river systems that are beneficial for the human society. However, they often determine a marked alteration of the natural flow and sediment supply regimes, which in turn can cause relevant morphological and ecological modifications in the downstream river reaches. While the effects of flow regime alterations have been studied since more than 30 years (Richter et al., 1996), the role played by artificial reservoirs in the fluvial transport of sediments and its associated morphological effects has been investigated only very recently (Wohl et al., 2015). This issue is of high relevance in both industrialized countries, where dams have been built mainly in the 1950s – 1960s, and in developing countries, where large dam construction is presently ongoing at a fast pace (Zarfl et al., 2015)
This research project will focus on Alpine regions, where artificial reservoirs and the related modifications on the river morphological dynamics are at least 40 years old.

The research aims are:

1) To develop suitable quantitative, process-based tools to assess the long-term impacts of Alpine dams on the downstream sediment regime and river morphodynamics, coherently with the historical and present data availability;
2) To detect the potential for restoration of the affected river reaches, accounting for the operational and structural constraints of the existing hydropower production systems.

The project methodology envisages the integration of mathematical modelling approaches with the collection and analysis of field data in target case studies. Modelling will focus on the development and testing of a nested, multi-scale approach, where a chain of models will be used from the catchment to the reach scale. To this goal, concatenation of modelling tools like CASCADE (Schmitt et al., 2017), reach-averaged cross section dynamics predictors (Colombini et al., 1992, Tealdi et al., 2011) and channel pattern predictors (Tubino et al., 1999, Eaton et al., 2010) will be explored.
The field component will integrate the analysis of existing datasets available at public environmental agencies with those of remotely sensed data and with the collection and analysis of in situ field data.
We seek a highly motivated candidate with skills in morphodynamic modelling and river data analysis, and with interest in such an integrated approach.

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Colombini et al., 1992 Conv. Naz. Idraulica e Costruzioni Idrauliche
Eaton et al., 2010 Geomorphology
Richter et al., 2016 Freshwater Biology
Schmitt et al., 2017 Water Resources Research
Tealdi et al., 2011 Advances in Water Resources
Tubino et al., 1999 J. of Hydraulic Research
Wohl et al., 2015 Bioscience
Zarfl et al., 2015 Aquatic sciences

- *Reference person:* Gianni Andreottola (UNITN/DICAM)
A1 - scholarship on reserved topics
Funded by: University of Trento – Department DICAM
Title: DEVELOPMENT OF INNOVATIVE AND SUSTAINABLE PROCESSES FOR SLUDGE MINIMIZATION IN INDUSTRIAL WASTEWATER TREATMENT PLANTS

Industrial wastewater treatment plants produce a substantial amount of sludge which has to be managed and whose disposal is extremely costly.
Different technologies have been studied in the last 15 years for minimizing surplus sludge, but mainly in the field of municipal wastewater treatment plants.
Limited scientific activity is available for wastewater poor in nitrogen and phosphorus, that are produced in many industrial activities.
The PhD research project will analyze the current production of several typical industrial processes (especially in the field of agroindustrial activities) and will apply at Lab and Pilot scale innovative processes and configurations, aimed on one side at significantly reducing the mass production of surplus sludge and on the other side to maintain the whole process environmentally and energetically sustainable.
Research outcomes are expected to be published in high impact factor journals in the civil engineering (in particular in the WWTPs sector).

- *Reference person:* Giuseppe Formetta (UNITN/DICAM)
A2 - scholarship on reserved topics
Funded by: University of Trento – Department DICAM
Title: Understanding the Effects of Bedrock Fractures and Weathering on critical zone hillslope hydrology and stability

Earth's Critical Zone is the thin outer layer of our planet from the top of the tree canopy to the bottom of water aquifers that supports almost all human activity. The critical zone is experiencing changes from growth in human population, wealth and climatic changes. Understanding, predicting and managing all the processes occurring in this important part of earth is crucial to predict and adapt to the intensification of extreme events and climate change. For example, landslides present one of the greatest geologic hazards that currently threaten human society and infrastructure (e.g. review in Sidle and Ochiai, 2006). Extreme precipitation caused more than 9,500 landslides resulting in more than 29,000 casualties globally since 2007 (Kirschbaum et al., 2010), with over $10 billion in infrastructure and property damage (Bowman, 2015).

In this project we aim to explore and quantify: i) the hydrological controls of surface and subsurface processes on water redistribution within the earth critical zone, and ii) the interactions/feedbacks between subsurface water and the underlying bedrock (topographic stress, weathering structures, and fractures), with the ultimate goal of improving landslide hazard (timing and location) prediction. We will explore subsurface saturation and pore pressure development within the critical zone, and at the boundaries of soil and bedrock layers, developing and using a novel 3D hydrologic model. It will simulate the 3D surface-groundwater response to rainfall by routing water into spatially varying layers with different hydraulic conductivity and will be validated in natural landscapes with measurable data. The project is carried out in collaboration with University California Los Angeles (in the person of Professor Seulgi Moon) and will involve sharing of measured data and models.

Research project: Prin 2017 SL7ABC
CUP E64I19001840001

- *Reference persons:* Alfonso Vitti (UNITN/DICAM), Fabio Remondino (FBK)
A3 - scholarship on reserved topics
Funded by: FBK Fondazione Bruno Kessler
Title: Precise positioning in photogrammetric application / Photogrammetry aided by positioning techniques

In the last years, mobile mapping systems, such as hand-held devices, drones and ground vehicles equipped with active or passive sensors, have been widely used for precise 3D data generation based on advanced geo-referencing solutions.
According to specific scenario and application requirements and constraints, different techniques can be adopted to tackle positioning and navigation tasks, e.g. solutions based on global navigation satellite system (GNSS), ultra-wide band (UWB) transceivers and 5G mobile network technologies.
The research should investigate different geo-referencing solutions when using mapping platforms, trying to understand potentials and limitations, feasibility and needs in typical geomatics scenarios, such as mapping of urban and forestry areas, precision farming, hazard monitoring, indoor mapping, heritage documentation.
Some topics that should be considered in the research are:
the forthcoming Galileo high accuracy service, which should be investigated and exploited at the best of it state of implementation;
the fusion of data from multi-frequency and multi-constellation GNSS receivers and AI-enabled stereo cameras or stereo optical and depth sensors embedded in smart phones;
alternative positioning solutions such as those based on UWB and 5G technologies.
The mentioned topics should be investigated in particular for the evaluation of GNSS- based positioning performances and impact on the 3D data in mobile mapping applications, in particular in the photogrammetric field. Positioning technologies such as RTK, PPP and PPP-RTK should be considered along with suitable strategies for the mitigation of GNSS signal degradation and complete temporary loss.
The research is expected to advance the knowledge on the impact of most recent geo-referencing solutions in geomatic mapping based on the photogrammetric principles. High-accuracy positioning is expected to improve the quality of 3D geometric and spatial data and modelling to be used in professional applications. The output of the research will be made accessible through scientific papers

- Reference persons: Alberto Bellin (UNITN/DICAM), Bruno Majone (UNITN/DICAM)
A4 - scholarship on reserved topics
Funded by: MUR – Departments of Excellence
Title: Combined effects of climate change and water uses on water resources: digital twins of the intertwined natural and anthropogenic systems

Water resources are under threat by the combined effect of climate change and overexploitation for agricultural, industrial and human consumption. Global freshwater demand is projected to increase by 57% by 2055; from 3.5 10^{12} m^3 (3500 km^3) in 2000 to 5.5 10^{12} m^3 (5500 km^3) in 2055, thereby posing additional stress to a resource already under multiple threats. Coping with these threats requires a combination of actions ranging from new technologies to consume less water in agriculture, food production and other industrial activities to renewed and better managed infrastructures and innovative policies. To be effective all these actions need to be adequately informed. To gain knowledge and better inform future directions in the water sectors this research topic aims at developing a suite of models, organized as digital twins of the intertwined natural and technological systems, for simulating the complex interplay between water needs and stresses caused by climate change and the uneven distribution of water demand. The digital twins will allow to simulate scenarios and evaluate the effectiveness of actions aimed at reducing the stress on the natural system while satisfying water demand.

The applicant may develop a proposal in one of the research topics described below.

1) Modeling the Impact of Water Uses and Climate Change on Groundwater Resources:

Evaluation of climate change impacts on water resources is a “hot” topic which is capturing growing interest by scientists, water managers, policy makers and the general public alike. In particular, the effects of future climate and water use scenario, possibly leading to groundwater overexploitation, deserve particular attention due to the important role of groundwater for irrigation, urban consumptions and ecosystem sustainability (e.g. 2000/60/EC and 2007/118/EC). In this contest, reliable projections of long-term evolution of groundwater dynamics are of paramount importance to settle advanced and sustainable adaptation and mitigation plans considering both climate change and linked human effects. Groundwater resources are indeed affected by climate change through the direct interaction with

surface water resources, such as lakes and rivers, and indirectly through recharge, i.e. the water that infiltrates into the subsurface which dynamics is influenced by changes in precipitation, air temperature and soil use. Therefore, quantifying the impact of climate change on groundwater resources requires an accurate estimation of the spatio-temporal distribution of groundwater recharge, in addition to a reliable simulation of groundwater flows possibly including the role of heterogeneity in soil hydraulic properties.

This latter aspect deserves particular attention due to the non linear interplay between external forcing and soil and aquifer heterogeneity acting at all scales from local to global. Although aquifer heterogeneity and its effect on flow and transport has been studied in great detail in stochastic groundwater hydrology, the implementation of similar techniques to the simulation of the overall watershed hydrologic responses (i.e., joint evaluation of river streamflow and groundwater dynamics) is missing in the literature, especially at large spatial scales.

Within this framework, distributed hydrological modeling will represent an excellent tool to unveil the complex relationships between climate, human exploitation and groundwater dynamics and to estimate their joint evolution. The analysis will be conducted by means of a suite of hydrological models. In particular we propose to further develop HYPERstreamHS, a distributed model recently developed by the Hydrology group of the University of Trento, by including modules dealing with groundwater storage dynamics: from simple lumped travel time formulations to process-based groundwater models like e.g. Modflow. The various approaches will be then compared to understand to which extent heterogeneity in aquifer hydraulic properties shape both streamflow and groundwater dynamics.

The ideal case study to assess the effects of climate change and human exploitation on groundwater resources is the Northern part of Italy including both the Alpine and Padanian regions, with the latter being a densely populated area including one of the most important aquifers in Italy, i.e., the Po valley aquifer. A preliminary set-up of the modeling framework will be created for the Adige river basin (about 10000 km2) in order to take advantage of well-instrumented test sites, excellent data availability and established collaborations with regional authorities. Experience gained with modeling this system can be exported to other relevant groundwater bodies.

The expected outcomes of this activity can be listed as follows:

1. Improvement of HYPERstreamHS in order to incorporate explicitly groundwater dynamics. Long time series of groundwater levels and streamflows will be used in a multi-objective calibration framework in order to better identify subsurface flows and groundwater recharge.

2. Coupling of Modflow groundwater model with HYPERstreamHS. In this case particular emphasis will be given to the reproduction of the heterogeneity in the hydraulic properties of the aquifer.

3. Identification and attribution of the main drivers controlling groundwater dynamics in the Adige river basin through trend analysis of available and/or simulated long-term time series of hydrometeorological variables (e.g., precipitation, temperature, snow accumulation, etc.).

4. Implementation of the modeling framework to a meso-scale watershed, i.e. the entire Northern Italy including the Alps and the Po floodplain (about 120.000 km2). In this case the added value of using both monthly time-lapse gravity field estimates provided by the Gravity Recovery and Climate Experiment (GRACE, http://science.nasa.gov/missions/grace/) and groundwater levels data) will be explored in a multi-objective calibration framework, with the aim to reduce epistemic and model parametric uncertainty.

5. Climate change impact assessment on groundwater resources in the aforementioned meso-scale watershed using an ensemble of meteorological forcing projection scenarios available in the EURO-CORDEX experiment.

6. Evaluation of the combined effects on groundwater resources of concurrent changes in climate and water uses by considering different scenario of groundwater exploitation.

Suggested references (to be not considered as exhaustive for the topic):

Avesani, D., Galletti, A., Piccolroaz, S., Bellin, A., Majone, B. 2021 A dual-layer MPI continuous large-scale hydrological model including human systems. Environmental Modelling & Software 139, doi: 10.1016/j.envsoft.2021.105003

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Reinecke, R., Foglia, L., Mehl, S., Trautmann, T. Cáceres, D., Döll,P., 2018. Beyond the bucket – Developing a global gradient-based groundwater model (G3M v1.0) for a global hydrological model from scratch, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2018-120.

2) Hydropower generation in the Italian Alpine Region under a changing climate:

The objective of this research project is to analyse the impact of climate change and the energy market on hydropower production of the Italian Alpine Region (GAR). The analysis will be conducted by means of the multi-scale hydrological model HYPERstreamHS recently developed by the Hydrology group of the University of Trento. The model will simulate the hydropower production and the associated streamflow alterations by modelling explicitly the functioning of relevant hydraulic infrastructures. The research activity will develop along the following lines:

1. Implementation of a model of hydropower production able to simulate the operation of the hydropower plants included in the reference catchment according to the modelled water availability (the model will also simulate the altered streamflow downstream the hydropower plants). This model will be prodromal to the development of a twin digital model of hydropower production. The first prototype will be developed in the Adige river basin and tested by comparing aggregated results at regional scale with historical data of energy production. However, the same modeling approach can be applied down to the single hydropower plant, provided that enough data are available.

2. Scenario analyses of climate change impact on hydropower production in the Italian Alpine region including assessment of vulnerability of the main hydropower systems. In addition, the role of reservoirs as energy storage systems complementing other renewable energy sources, namely solar and wind energy, will be investigated also in relation to climate change scenarios.

3. Effect on hydropower production of the evolution of the electricity market as fostered by the development of new storage technologies and projected changes in wind and solar energy production.

Suggested references (to be not considered as exhaustive for the topic)

Avesani, D., Galletti, A., Piccolroaz, S., Bellin, A., Majone, B. 2021 A dual-layer MPI continuous large-scale hydrological model including human systems. Environmental Modelling & Software 139, doi: 10.1016/j.envsoft.2021.105003

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Piccolroaz, S., Di Lazzaro, M., Zarlenga, A., Majone, B., Bellin, A., and Fiori, A. 2016. HYPERstream: a multi-scale framework for streamflow routing in large-scale hydrological model. Hydrol. Earth Syst. Sci. 20(5), 2047-2061, doi: 10.5194/hess-20-2047-2016.

- Reference persons: Alberto Bellin (UNITN/DICAM), Alessandra Marzadri (UNITN/DICAM)
A5 - scholarship on reserved topics
Funded by: MUR – Departments of Excellence
Title: Micro and nano materials in rivers and aquifers

Nano-particles (e.g. zerovalent iron, carbon nano-onions, etc.) have been observed to be effective in remediating aquifers contaminated by heavy metals and chlorinated solvents, which are among the most diffused pollutants and a legacy of the industrial activities that flourished in the first half of the last century. Nano and microparticles are also contained in pharmaceutical and personal care products (PPCPs) and therefore enter surface and subsurface water bodies as pollutants through waste waters. Another source of pollution in both aquifers and rivers are micro and nanoplastics, produced by the degradation of plastic wastes. They are identified as fragments between 0.1μm and 5 mm and smaller than 0.1μm, respectively. Plastic waste accumulates in the oceans at an alarming rate and recent projections estimate that by 2050 they will exceed in mass the total stock of fish resources. Their presence in the inland waters is also significant. These particles, whatever their origin, enter surface and subsurface water bodies (i.e., rivers, lakes and aquifers), and are ingested by aquatic organisms with adverse effects on both the ecosystems and human livelihood. Despite the importance of these particles, both positive when used to remediate aquifers, or adverse when polluting the aquatic environment, limited tools are available for studying and modelling their fate in the environment.

The aim of this proposed research is therefore to investigate how these particles are transported in the surface and subsurface water bodies and how they interact with the soil and groundwater. Both positive (i.e., the potential for new innovative remediation technologies), and adverse effects will be investigated by means of laboratory experiments and simulations. Laboratory experiments will be tailored to investigate and parametrize transport mechanisms underlying their fate both in free water (i.e. rivers) and in saturated porous media. Physically based models will also be developed, based on experimental results, with the aim of simulating the fate of nano and microplastics in the aquatic environments.

The applicant may choose between the following two research themes

1) Hydrodynamic of micro- and nano-particles:

Experiments will be performed in the Laboratory of Hydraulics at the Department of Civil, Environmental and Mechanical Engineering, using image analysis techniques. The aim of the experiments is to investigate base mechanisms controlling the migration of nano- and micro-particles in water bodies. The activity will be addressed to one of the following two areas of research: 1) analysis of the migration of microplastics in free waters and across the interface with the hyporheic zone (the sediment saturated zone at the interface between surface and sub-surface waters); 2) analysis of the migration of nano- and microplastics in porous media. The group gained experience in producing porous media with optic access. The research activity will take advantage of a hardware and software imaging infrastructure, which allows to conduct the experiments by using techniques such as Particle Image Velocimetry (PIV), Planar Laser Induced Fluorescence (PLIF) and Particle Shadowing Velocimetry (PSV) with fields of view ranging from 1 cm to 1 m. PSV can be used to investigate the migration of microplastics in both free water, under several hydrodynamic conditions, and saturated porous media. The other techniques can be used to analyze complex velocity fields such as those developing at the interface between surface and subsurface environments (PIV) and the migration of solutes or nano-particles (PLIF).

2) Modelling the transport of nano- and micro-plastics in surface and subsurface water bodies

This research theme deals with modelling the migration in the Earth's subsurface of nano- and micro-particles. Effectiveness of nano-particles in remediating contaminated aquifers and modeling the propagation of nano- and micro-plastics, seen as contaminants, in aquifers are the two objectives of this research activity. Modelling will be performed by solving flow and transport-deposition models for colloidal particles in saturated porous media. Regarding the transport of micro and nano plastics in the freshwater environments, the proposed research will analyze their transport by considering the processes of aggregation, vertical settlement and advective-dispersive transport within inland waters and hydrologic transport along the subsurface pathways of hyporheic zone and groundwater. The analyzed topic will provide benefits to the society at local and global scales as groundwater is one of the most important freshwater resources and its contamination may have important environmental consequences that reflect on many aspects of human quality of life. Similarly, surface waters have a high value which is impaired by microplastic pollution.

Suggested references (to be not considered as exhaustive for the topic):

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O'Carroll, D., Brent, S., Krol, M., Boparai, H., Kocur, C.2013 Nanoscale zero valent iron and bimetallic particles for contaminated site remediation. Advances in Water Resources 51: 104-122, doi: 10.1016/j.advwatres.2012.02.005.

Pak, T., de Lima Luz, L.F., Tosco, T., Ruiz Costa, G.S., Rodrigues Rangel Rosa, P., Lopes Archilha, N. 2020 Pore-scale investigation of the use of reactive nanoparticles for in situ remediation of contaminated groundwater source Proceedings of the National Academy of Sciences, 117 (24) 13366-13373; DOI: 10.1073/pnas.1918683117.

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- *Reference person:* Marco Tubino (UNITN/DICAM)
Participants: Marco Redolfi (UNITN/DICAM)
A6 - scholarship on reserved topics
Funded by: MUR – Departments of Excellence
Title: River morphodynamics: connectivity and non-equilibrium

Introduction

Rivers are fundamental connecting agents of the evolving landscape, as they represent the template on which water, mineral and organic sediment, living organisms and chemical elements are transferred, and support a variety of aquatic, terrestrial and riparian ecosystems together with human activities. The morphodynamic processes that determine the shape of the river, depending on hydrological, sedimentological and geometrical conditions, have been mainly studied under the assumption that the

river system is in dynamic equilibrium. For example, the formation of river dunes and bars have been extensively studied by considering constant discharge and sediment supply, which allow for the development of an equilibrium morphological configuration. Furthermore, most of the existing morphodynamic models refer to the reach scale, i.e. a hydro-morphologically homogeneous portion of the channel, though processes at this scale are clearly conditioned by those occurring at hierarchically higher scales.

Disequilibrium between sediment supply and transport capacity and the presence of evolutionary trajectories, as well as the morphodynamical response to a variable flow regime, such as the hydrological cycle, are still to a large extent unexplored. Moreover, rivers are strongly connected with other components of the earth system (Wohl, 2017) by exchanging water and sediment and by responding to alterations such as climate change, growth of vegetation, building of in-stream structures and gravel mining activities. This connectivity invariably leads to changing conditions on a multitude of temporal scales, from the daily scale (e.g., discharge variation due to precipitations or water releases from upstream dams), to the scales of decades or centuries (e.g., climate change, alterations of the sediment production in the basin). As a result, rivers are often out of equilibrium (Church, 2015), and they follow morphodynamic trajectories, depending on intensity, duration, and nature of the environmental stressors.

Research aims and methodology

The general aim of the project is to investigate the non-equilibrium hydraulic and morphodynamic processes that govern the fundamental units of the rivers, namely: steady and migrating alternate bars (Colombini et al. 1987, Bertagni et al., 2018), central and multiple bars (Repetto et al., 2002; Crosato & Mosselman, 2009), channel bifurcations and confluences (Redolfi et al., 2019, Ragno et al, 2021); braided networks (Bertoldi et al., 2009; Ashmore, 2013).

This will be accomplished by using a combination of:

- numerical modelling, based on existing numerical schemes for reproducing hydrodynamics, sediment transport and bed evolution;
- physical modelling at the hydraulic laboratory of the Department of Civil Environmental and Mechanical Engineering, where a large experimental facility is available;
- statistical data analysis and interpretation of results on the basis of theoretical and conceptual models.

The ideal candidate will have a background in Environmental Engineering, River Geomorphology or related fields. Candidates should also possess strong computer, scientific, and analytical expertise, have excellent communication (oral and written) skills, have the ability to work independently and as part of a team, self-motivation, adaptability, and a good attitude for critical thinking. Since foreseen activities include model development, the candidate is required to have computational proficiency (or the will to pursue it) preferably in Fortran, R/python/Matlab and GIS products.

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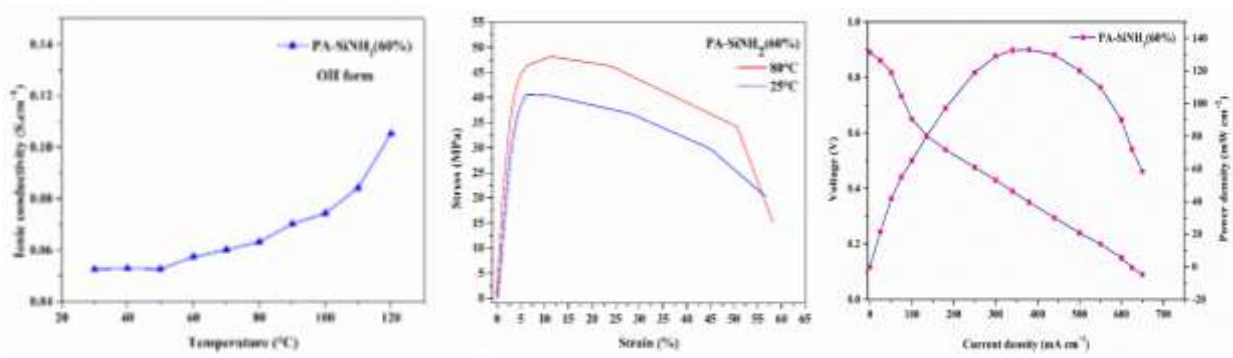
Curriculum B - Mechanics, Materials, Chemistry and Energy

- *Reference persons:* Paolo Scardi (UNITN/DICAM), Luca Deseri (UNITN/DICAM), Narges Ataollahi (UNITN/DICAM)
Title: Advanced anion exchange membranes for Fuel Cells with improved conductivity and mechanical stability

Fuel cells (FCs) are essential for the phase-out of fossil fuels, primarily in transportation systems. They are in fact the leading devices for exploiting hydrogen in energy production, with high efficiency and no polluting emissions. However, there are still some open challenges to making fuel cells commercially viable. Alkaline anion exchange membrane fuel cells (AAEMFCs) employ solid polymeric electrolytes, which conduct hydroxide ions, with the advantage over other FCs of functioning with low (ultimately eliminated) loadings of precious metal electrocatalysts, reducing cost. To this end, a careful design of the membrane is required, to give it both high ion conductivity and thermo-mechanical stability. In this project, an experimental and theoretical modelling investigation into the enhancement of anion exchange membrane FCs will be undertaken; this will involve the synthesis of oxide materials and functionalized polymeric membranes, along with micro- and multi-scale mechanical simulations, using the finite element method as well as density functional theory and classical molecular dynamics. Hence, assessing the efficiency of functionalized oxides and positive influence on membrane durability is a main target of the work, potentially leading to longer life-times for polymer electrolyte membrane FCs. The project involves building FC prototypes to power small electronic devices.



OH conductivity (1.05×10^{-1} S.cm^{-1} at 120°C), mechanical stability (46.5 MPa), and polarization curve and power density (133 mW.cm^{-2}) in a single fuel cell at 80°C for polyamine membrane containing modified silica

- *Reference persons*: Rosa Di Maggio (UNITN/DICAM)
Participants: Narges Ataollahi (UNITN/DICAM)
Title: Coating for common surface

The goal of this project is to develop coatings on common surfaces (such as knot, glass or wooden doors) by spraying or spreading coatings capable of sanitizing them against viruses, including Sars-Cov-2, and bacteria in a short time and with long-lasting effects (weeks and months). The basic idea is to prepare sols containing virucidal substances capable, once sprayed or spread on a surface, to develop a coating that is as adherent and continuous. The goal is to produce sol, the use of which replaces the practice set during the pandemic of constantly sanitizing surfaces with ethyl alcohol-based sol, which however evaporates making the transitory treatment and the atmosphere of the premises literally unbreathable. An effectively adherent sol containing non-evaporable virucidal substances would allow periodic and as needed sanitization. The project is part of a wider range of coatings on surfaces of different types and nature that induce improvements in chemical-physical characteristics,

such as thermal insulation or protection against degradation/corrosion and also the induction of bactericidal and virucidal activity. It has been established that Sars-Cov-2 is a virus that owes its prolonged persistence to the fact that it is associated with bacteria.
Therefore, the success indicators of the project may be the following: producing adherent coatings on glass and metal (standard foils) and demonstrating their bactericidal activity for about 12 hours.

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[1] N. van Doremalen, et al., Aerosol and surface stability of HCoV-19 (SARS-CoV-2) compared to SARS-CoV- 1, N Engl J Med; 2020, 382:1564-1567
[2] Cristina Balagna, et al., Virucidal effect against coronavirus SARS-CoV-2 of a silver nanocluster/silica composite sputtered coating, Open Ceram; 2020; 1:100006
[3] S. Behzadinasab, et al., A Surface Coating that Rapidly Inactivates SARS-CoV-2, ACS App Mat & Interf; 2020, 12: 34723−34727.

The PI has previous experience both in the development of sol and similar coatings on paper and wood and therefore has the task of transferring these skills to this new goal. These reasons and the solid scientific reputation of the proposer are a guarantee of achieving short-term results that can be transferred to Trentino companies for commercial development.
This would lead to the publication of the results obtained during the project in high-level international scientific journals in adequate time.
The coatings must contain antibacterial agents, which are compounds capable of interfering with bacterial growth and multiplication, unlike the disinfectant, which is only active against metabolically active bacteria. In our project we will address mainly metallic inorganic substances which, with an appropriate and minimal dosage, will come into contact with the bacteria on the surface.
The first indicator will be to demonstrate the feasibility of a sprayable sol containing the antibacterial substance through the quality of the obtained coating, evaluated through superficial microstructural measurements.
The second indicator will be to evaluate the antibacterial activity by contacting surfaces treated with the Kirby-Bauer method of diffusion in agar plates. This last activity will be carried out in collaboration with expert groups of biological activity measurements with which we are in contact, both of UNITN and of the CNR of Florence.

- ***Reference persons: Edoardo Gino Macchi (FBK-SE), Nicola Pugno (UNITN/DICAM)***
Participants: Luigi Crema (FBK-SE)
B1 - scholarship on reserved topics
Funded by: FBK Fondazione Bruno Kessler
Title: Development and validation of multiphysics-multiscale tools for redox flow battery design

Redox flow batteries (RFBs) are a promising technology for large scale energy storage. In RFBs power and energy are decoupled: the former depends mainly on the size of the stack while the latter on the size tanks containing the redox active species. This feature make RFBs ideal for economical, large-scale energy storage. However, cost reduction are in order for allowing a widespread diffusion of this technology. The required cost reductions involve two main components of the system: the electrolytes and the stack. Both need to be optimized for enabling a large scale diffusion of RFBs.
Flow batteries are a complex system their design and optimization usually leads to a trade-off between cost and performances (energy and power density, efficiency, cycling life). Cell and stack design is a core task required for the development and upscaling of flow battery systems but redox flow cells models can be very complex due to the multitude of physical phenomena that need to be considered: electric fields, fluid flow, mass and specie transport in different components, electrochemical reactions, heat transfer. All these phenomena need to be considered for building a digital twin of cell and stack and enable to identifying cell-limiting mechanisms, forecasting cell performance and optimizing the design. Despite some commercial software (e.g., COMSOL) can support this activity these tools present a lack of flexibility and serious constraints concerning their use on HPC platform as well as their performances (this also limit their use to small scale cells). Furthermore multiscale models that couple detailed cell models and system level models are not currently available.
For the above mentioned reasons, in this PhD topic we propose to develop a multiphysics-multiscale tool aimed at supporting redox flow cell and stack design and upscaling. This tool will also enable

design optimization supported by different algorithms. The selected candidate will be in charge of developing the models extending opensource modelling platforms such as OpenFOAM and integrating optimization tools such as Dakota. The platform will be composed of three different main components tightly connected with each other: 1) Multiphysics cell and stack model (using for example OpenFOAM), 2) System level model based on transient 1D-0D models (using OpenFOAM, OpenModelica or python) 3) optimization tool. The outcome from the multiphysics cell model will be used either as input or for computing the parameters required by the system level model. Different type of optimization will be developed based on the final objective.
The simulation models will be validated with experimental data from known chemistries and representative prototypes, and show how new chemistries can be explored. The candidate will be in charge of developing and implementing the physical models, validating the models based on experimental data, integrating different model for building a multiscale tool and integrating the optimization algorithms in the work flow to enable design optimization. In order to enable a strong cross-contamination of ideas and experience, we propose that the candidate will also support the experimental activities related to the validation of redox flow cells with known and new chemistries.

- Reference persons: **Diego Misseroni (UNITN/DICAM), Nicola Pugno (UNITN/DICAM)**

B2 - scholarship on reserved topics

Funded by: MUR – Departments of Excellence

Title: Optimal design of hierarchical micro-structured materials for wave propagation control and 3D Micro Mechanical Systems (MMS)

The project aims to develop high-performance hierarchical microstructured materials for the elastic wave propagating control and/or 3D Micro Mechanical Systems (MMS). The experimental validation of the theoretical and numerical results will be conducted on 3D samples printed with the 3D printer bought within the “Departments of Excellence” framework.

Within this context, the candidate can choose one of the following two topics:

1) 3D High-performance hierarchical microstructured materials:

For this purpose, multidisciplinary approaches will be exploited. New analytical tools, sophisticated computational methods and innovative experimental protocol will be developed for designing new engineered optimal architected materials. The optimal microstructure will be determined via topological and parametric optimization methods. The primary advancement of knowledge concerns the study of intelligent materials cable to opening and widening band gaps depending on external stimuli, (e.g. seismic events) to achieve cloaking and/or shielding. This project would complement the previously obtained PhD scholarship (within cycle 35) focused on the static analysis of micro-structured materials from the dynamical aspect.

The research results will be:
(i) published in high impact international journals in the field of mechanics of solids and structures, applied physics, computational mechanics, materials engineering, and additive manufacturing;
(ii) presented at national and international conferences;
(iii) the realization of proof-of-concept reprogrammable multi-functional metadevices.

2) 3D Micro Mechanical Systems (MMS):

With the cited 3D printer, we can realize Micro Mechanical Systems (MMS) as recently proposed in ref. [1]. We will explore the rapid prototyping, including the possibility of realizing 3D MMS, e.g. for the traction of nanomaterials using as actuator a commercial nanoindenter.

The research results will be:
(i) published in high impact international journals in the field of mechanics of solids and structures, applied physics, materials engineering, and additive manufacturing;
(ii) presented at national and international conferences;
(iii) the realization of proof-of-concept 3D MMS for the mechanical characterization of nanomaterials.

[1] Wang, Yuejiao, et al. (2019) "3D printed micro-mechanical device (MMD) for in situ tensile testing of micro/nanowires." Extreme Mechanics Letters 33, 100575

Curriculum C - Modelling and Simulation

- *Reference persons:* Annunziato Siviglia (UNITN/DICAM)
Participants: Lucas Mueller (UNITN/Dep. Maths)
Title: One-dimensional numerical modeling of the cardiovascular system for clinical applications

Numerical models of the Cardiovascular System (CS) provide scientific frameworks for advancing our understanding of the underlying physical processes. Nowadays they offer the possibility to consider new therapeutic planning and the design of implantable devices (e.g., medical stents) to mitigate impact of cardiovascular diseases (CVD) in our lives. Among the variety of modeling approaches existing in the literature, one-dimensional models, coupled to lumped-parameter models, are gaining importance among the bioengineering communities, mainly because they provide a reasonable compromise between level of detail of described processes and computational complexity. In fact, such models allow to span across spatial scales from systemic simulations to detailed tissue perfusion studies.
Notwithstanding their relevance, numerical models of the CS need further advances regarding (i) the way by which the interaction of blood and vessel wall is described (general tube law), (ii) their capability of simulating situations which are far from supine position at rest, (iii) the coupling with a model for the dynamics of cerebrospinal fluid in the spinal subarachnoid space.
In this context, the goal of the project is to advance the current state of the art for one or more of points (i), (ii), and (iii) and incorporate the new findings within an existing closed-loop geometrical multiscale model of the human circulation which was developed at DICAM between 2011 and 2014 in the framework of Dr. Müller's PhD and is currently available at the Department of Mathematics at University of Trento.
The research will involve analysis and improvements of mathematical models, development of numerical schemes, analysis of experimental data to parametrize and eventually further develop models and a final clinical application using the new features implemented in the closed loop model.
The successful candidate will have a strong mathematical background, skills in coding (e.g., C++, FORTRAN, Python, MATLAB) and a desire to work at a modelling level at the interface between fluid mechanics and cardiovascular physiology. Fluent spoken and written English, as well as good communication skills are required.

- *Reference persons:* Oreste S. Bursi (UNITN/DICAM), Gabriele Zanon (UNITN/DICAM)
C1 - scholarship on reserved topics
Funded by: University of Trento – Department DICAM
Title: Modeling and testing of welded structural joints machined with laser cutting technology

Laser cutting represents a modern and effective technology able to complement and/or replace well-established mechanical and thermal processes. The importance of this technology is undeniable to make joints characterized by complex geometry like those realized using circular hollow section elements. As a result, time, cost and quality of laser cutting technology greatly affect further processing and, thus, the overall labor cost.
While exhibiting undoubted technical/practical benefits, the interaction between laser cutting and subsequent welding process on structural behaviour of joints has not yet been fully explored.
Hence, the study of thermal processes and structural behaviour taking into account both geometrical and metallurgical aspects, are still the subject of depth study and of strong interest, especially in the field of structural steels subjected both low-cycle and high-cycle fatigue loadings.
Both strength and ductility requirements, especially versus non linear behaviour of joints subjected to cyclic loadings, as highlighted by Eurocode 3 Part 1-8, demand a thorough study on the modifications induced by thermal processes on structural steels joints.

On this basis, in order to optimize both geometry and thermal processes parameters, the candidate has to carry out a series of standard and advanced tests on both materials and structural joints as well as FE analyses at the material and geometry level.
Both the thorough study of the effects due to thermal processes used to realize structural joints and the study of joint geometries allows for the optimization of the geometries and thermal processes. The outcome of the research activity will consist in technical reports and journal papers.

- Reference person: **Nicola Tondini (UNITN/DICAM)**
C2 - scholarship on reserved topics
Funded by: University of Trento – Department DICAM
Title: Seismic behaviour of hybrid fire walls with "fusible" links

In single-storey buildings the stability of boundary fire walls has to be maintained despite the collapse of the roof structure exposed to fire. In case of steel structures, previous studies have shown that the stability of boundary walls, when they are solidly attached to the steel columns of the building structure, could be ensured with the help of partially strengthened column base as well as its foundation. The application of the existing guidance makes it possible to erect safe boundary fire walls in low-rise single-storey steel buildings (up to 8 meters high) without any fire protection. However, it is problematic to apply the same design recommendations to high-rise single-storey buildings, since they lead to economically unreasonable boundary wall solutions. In such cases, an interesting and cost-effective option could be to use “fusible” links to connect the boundary fire wall to the building structure, in such a way that in the fire situation the failing structure may collapse without causing any damage to the fire wall. Moreover, lightweight sandwich panels (comprising two thin flat metal faces and an insulated core) could become an appropriate steel fire wall solution, offering numerous benefits in comparison to other solutions, including fire resistance, durability, flexibility, easy dismounting, cost effectiveness and fast construction times. Since the proposed solutions have to be also effective in seismic-prone regions, fire walls, even though not structurally relevant, have also to be properly designed to meet sufficient resistance requirements to earthquake forces, which can lead to implement constructional details in contradiction with the fire design. Thus, the research will be focusing on the seismic behaviour of “fusible” links belonging to fire walls with the aim to find a link solution that is not only capable of withstanding from low to moderate earthquakes but also comply with the fire performance requirement. The research will be both numerical and experimental. The expected outcomes are mainly journal and conference papers as well as design guidelines.

Research projects concerning the research topic
“FISHWALL - Fire and seismic performances of hybrid fire walls in case of single-storey industrial and commercial steel” – Research Fund for Coal and Steel. P.I. Nicola Tondini

- Reference person: **Daniele Zonta (UNITN/DICAM)**
C3 - scholarship on reserved topics
Funded by: University of Trento – Department DICAM
Title: Risk-Based asset management

BACKGROUND
Extreme events, such as earthquake, landslides or floods, can jeopardize the efficiency of the civil infrastructure and have an immediate impact on the community and its recovery time. There is the need to develop tools to predict possible damage scenarios resulting from these events and, in the event, to provide real time information on the state of the infrastructure to allow the public authority to react and undertake countermeasures.
Prediction of damage scenarios is based on formal risk analysis, which includes evaluation of the hazard of the event and the vulnerability of the individual components of the infrastructure network. The vulnerability of a component is usually described through fragility curves [1], functions representing the probability that the component undergoes a particular damage state for a given level of demand.
Sensor and communication technologies offer the possibility to assess real time the state of an infrastructure component (such as a bridge, a building or a link), yet monitoring an entire infrastructure

network is economically unsustainable. A way to overcome this limitation is to install monitoring systems on a limited number of critical components and use a probabilistic approach to extend this information to the entire network.
The idea is to represent the state of the infrastructure through a set of random variables and to use Bayesian networks to model their conditional dependencies [2]: immediately after an event, monitoring observations are used to probabilistically infer the posterior distribution of the state variables.

OBJECTIVE
The PhD student selected will develop a probabilistic framework to support emergency management in the aftermath of an extreme event based on the information recorded by monitoring systems. Hazardous events considered includes: floods, landslides and earthquakes. The system will estimate a posteriori the condition state of an infrastructure network in a post-event scenario based on the state of individual components, appraised through instrumental monitoring. The same framework will also serve as an early warning system, providing alert to the community and decision support to the public authority.

METHOD
- Analyze the state of the art of decision-making.
- Model correlation in hazard and vulnerability among different infrastructure components, with focus on bridges, using Bayesian networks.
- Investigate and analyze monitoring system technologies for real time damage detection of bridges; in-field case studies will be provided by NPlus srl.
- Develop methods for updating fragility curves and state variables of the Bayesian network based on information from monitoring systems.
- Conceive a Decision Support System for risk-based asset management and collaborate to deploy an prototype together with NPlus srl.
- Validate the method on a number of case studies.

EXPECTED RESULTS
- Prototype of Decision Support System for risk-based asset management.
- Pilot application to case studies.
- Scientific papers published in top quartile international journals.

[1] I. Ioannou, J. Douglas, and T. Rossetto. "Assessing the impact of ground-motion variability and uncertainty on empirical fragility curves." Soil Dynamics and Earthquake Engineering 69 (2015): 83-92.
[2] M. T. Bensi, A. Der Kiureghian and D. Straub. A Bayesian network methodology for infrastructure seismic risk assessment and decision support. Pacific Earthquake Engineering

- Reference person: **Daniele Zonta (UNITN/DICAM)**
C4 - scholarship on reserved topics
Funded by: University of Trento – Department DICAM
Title: Logic of Monitoring System Design

BACKGROUND
When designing a structure such as a bridge or a building, a civil engineer follows a well-established, rational procedure, whereby the performance of the design concept is predicted through structural analysis and quantitatively assessed with respect to the target performance. On the contrary, when the same engineer designs a monitoring system, the approach is often heuristic with performance evaluation based on common sense or experience, rather than on quantitative analysis.

OBECTIVE
The objective of this doctoral work is to outline and formalize a rational procedure for the design of monitoring systems, keeping in mind an analogy between structural and monitoring design. Whereas the structural design objective is to achieve stability with an appropriate level of safety, the object of monitoring is to acquire knowledge with an appropriate level of confidence. The monitoring design process includes: definition of the target performance of monitoring (for example the accuracy of knowledge); calculation of the required accuracy of instrumental data, using a model; choice of sensor technology. The design is satisfactory if knowledge accuracy is equal or better than the demand. In

logical terms, structural health monitoring is formally identical to the metrology problem of indirect measurement [1], where the measurand is indirectly estimated based on observation of other physical quantities linked to the measurand. In analogy with the metrology problem, in this we use error propagation technique, based on Bayesian logic [2], to judge a priori the covariance matrix of the target parameters a posteriori, an approach sometime referred to as pre-posterior analysis. It is expected that the PhD candidate will elaborate on this ground and formulate a general process for complex monitoring system design. The method will be demonstrated on one or more pilot case studies, including the Settefonti Viaduct on A1, whose monitoring system is currently operated by Autostrade Tech SpA.

EXPECTED RESULTS
- Method for monitoring system design.
- Pilot application to case studies.
- Scientific papers published in top quartile international journals.

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[1] L. Kirkup and R. Frenkel, An Introduction to Uncertainty in Measurement, Cambridge University Press, 2010.
[2] D. Sivia and J. Skilling, Data Analysis: A Bayesian Tutorial, Cambdrige University Press, 2006.

- Reference persons: **Nicola Pugno (UNITN/DICAM), Barbara Mazzolai (IIT Pontedera)**
C5 - scholarship on reserved topics
Funded by: University of Trento – Department DICAM
Title: Multi-physics analysis of viscous polymeric materials for growing robotic roots

Soil is one of the harshest environment challenging motion and exploration of autonomous systems. However, several natural models exist that are well adapted to this hostile habitat. Plants, among many, offer excellent examples of body adaptation, penetration strategies, motion, distributed control and extended colonization. Their structures colonize vast areas, overcoming high pressures, interacting with the surrounding and modifying the rhizosphere. Their strategies of colonization and motion can guide novel designs for multifunctional autonomous systems to be effective in confined, highly impeded environments.
This project aims at analyzing the growing and branching capabilities of robotic roots moving in soil by pressured fluidic material able to change its mechanical properties in interaction with ions present in soil. Numerical models, such as those based on hierarchical lattice spring/spring-block models for mechanics/tribology or multiple peeling for adhesion- describing elastic and non-linear elastic –e.g. plastic– properties will be adopted to analyze the multi-physics of viscoelastic polymeric materials and define their ability to create structural stability and anchoring to the system.
The expected work spans from biological studies of biological and polymeric materials to modeling and characterization of material-soil interactions. The expected outputs are patents and publications on high impact journals on the field.

- Reference persons: **Nicola Pugno (UNITN/DICAM), Barbara Mazzolai (IIT Pontedera)**
C6 - scholarship on reserved topics
Funded by: IIT Pontedera- Istituto Italiano di Tecnologia
Title: Nanofabrication of multifunctional biomimetic structures inspired by natural organisms

Evolution has brought to the development of fascinating biological structures. Nanofabrication technologies provide valuable tools to fabricate artificial biomimetic materials with properties that imitate the natural structures.
This project aims at developing novel multifunctional biomimetic artifacts by merging nanofabricated materials with tailored mechanical properties and microfluidic structures, fabricated by two photon lithography, with functional electrospun fibers and 3D printed multi-materials.
Several biological properties and functionalities will be investigated as models to develop artificial systems embedding sensing and actuation abilities. In particular, plants and soft invertebrates will be the focus of such research.

Due to their low density and impressive mechanical properties, plants provide examples of lightweight but robust structures (e.g., bamboo, plant seeds). These characteristics are achieved thanks to a hierarchical structure that combines porous architectures with density gradients and hollow parts to increase the flexural stiffness while keeping a lightweight. Soft invertebrates (e.g., octopus) have a soft body that can bend, elongate, and squeeze while their skin adapt to each movement providing at the same time camouflage properties. Camouflage is obtained by chromatophores activated by light, resulting in a skin that combines sensing and actuation properties both at the microscale. The above biological properties represent some of the research activities will be proposed within this project.

In summary, the expected work spans from biological investigation to design, fabrication, and characterization of the resulting prototypes. The expected outputs are patents and publications on high impact journals on the field.

- Reference person: **Andrea Massa (UNITN/DISI)**

C7 - scholarship on reserved topics

Funded by: Department of Information Engineering and Computer Science (DISI)

Title: Innovative transdisciplinary paradigms for the synthesis and optimization of multifunctional and multiphysics reconfigurable metamaterials through the System-by-Design

The possibility to engineer artificial materials able to exhibit desired effective physical properties and "wave manipulation" capabilities has emerged in the last years as a cornerstone of a wide variety of ground-breaking innovative concepts in electromagnetic, acoustic, and mechanic applications. The potentialities enabled simply by combining common materials (through suitably mixtures/ordered arrangements) in terms of performance, features, flexibility, and potentially reconfigurability has gathered the interest of a vast community of engineers, scientists, chemists, and physics with strong interdisciplinary skills, and it has fostered the emergence of the new area of Metamaterial Science and Engineering, with important applications already demonstrated in academy and industry.

Within this framework, the community has recently witnessed a gradual but steady shift regarding the methodological and technological approach to static and reconfigurable metamaterial synthesis. While early strategies relied heavily on modeling, analysis, and design techniques as well as implementation technologies allowing to obtain a certain material equivalent property on a single physical domain (e.g., electromagnetic wave manipulation), current approaches increasingly aim at the synthesis of structures delivering simultaneous reconfigurable performance in terms of multi-physics quality factors.

Such a trend naturally opens the path to a wide set of new opportunities in terms of research and industrial goals. On the one hand, the accurate numerical modeling and simulation of reconfigurable artificial materials requires innovative solutions and methodological approaches to overcome the existing challenges owing to the inherent multi-physics and multi-scale nature of the problems at hand. On the other hand, the design of useful systems comprising multifunctional and multi-physics reconfigurable metamaterials requires suitable innovative paradigms to be customized in order to handle the arising complexity. Consequently, advanced artificial material modeling will have to be combined with next-generation optimization and synthesis approaches potentially comprising artificial intelligence techniques.

Within this framework, the generalization and customization of the System-by-Design (SbD) paradigm to the synthesis and optimization of multifunctional and multi-physics reconfigurable metamaterials appears to be a potentially disruptive strategy to address Metamaterial Science and Engineering problems. In fact, while SbD has already been employed to enable the effective solution of electromagnetic metamaterial multi-scale synthesis problems, its application in complex multi-physics scenarios is still to be demonstrated.

The objective of the PhD research activity will therefore be to study, design, model, and validate innovative reconfigurable metamaterial concepts in a vast range of engineering domains including electromagnetics, acoustics, and mechanics. To this end, the activity PhD Student will join a transdisciplinary team of Researchers and Professors working on a wide variety of domains from fundamental metamaterial science and engineering to advanced numerical modeling of reconfigurable materials, as well as applications of Artificial Intelligence in metamaterial design.

The expected outcomes of this activity can be listed as follows:

1. Study and development of innovative multi-physics modeling and simulation strategies for reconfigurable electromagnetic / mechanical metamaterials. The activity will be specifically focused on multi-scale periodic and quasi-periodic structures with strong electromagnetic-mechanical physical relations.
2. Multi-physics homogenization and equivalent properties derivation. The possibility to model in a macro-scale effective manner the equivalent properties of the reconfigurable multi-physics metamaterials (e.g., through suitable optimization models) will be addressed by suitably combining numerical full-wave simulation techniques and artificial intelligence strategies.
3. Generalization of the SbD paradigm to the design of conceptual multifunctional and multi-physics reconfigurable metamaterials. The activity will focus both on the methodological choices for the implementation of the SbD loop, on the definition of the single functional blocks that are comprised in the overall strategy, and in the possibility to handle the curse of dimensionality arising in the associated optimization process.
4. Application of the developed design strategies to the synthesis of innovative electromagnetic-mechanic wave manipulation devices. The possibility to design devices able to suitably manipulate the electromagnetic / mechanic waves through reconfigurable artificial materials will be addressed in different applicative scenarios arising in Metamaterial Science and Engineering.

Suggested references (to be not considered as exhaustive for the topic):

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[4] M. Salucci, G. Oliveri, N. Anselmi, and A. Massa, "Material-by-design synthesis of conformal miniaturized linear phased arrays," IEEE Access, vol. 6, pp. 26367-26382, 2018.
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[6] G. Oliveri, E. T. Bekele, M. Salucci, and A. Massa, "Transformation electromagnetics miniaturization of sectoral and conical horn antennas," IEEE Trans. Antennas Propag., vol. 64, no. 4, pp. 1508-1513, April 2016.
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- Reference persons: Marco Broccardo (UNITN/DICAM), Oreste S. Bursi (UNITN/DICAM)
C8 - scholarship on reserved topics
Funded by: MUR – Departments of Excellence
Title: From Natural to Anthropogenic Seismicity: A Holistic Risk Framework based on Probabilistic graphical models and Vine Copula theory

Intro
The primary goal of earthquake engineering is to ensure life safety and reduce the financial impact to acceptable levels. In addition to natural seismicity, the more recent anthropogenic seismicity is posing a societal quandary and an economic challenge for the feasibility of projects that rely on the use of deep-underground resources. This project tackle at the fundamental level the methodological framework for computing seismic risk in both cases, providing novel insights into static versus dynamic risk analysis.

Candidates can prepare proposals on the following themes:

1) A static vine copula approach for natural seismic risk analysis:

Since the late 60s, the computational methods to quantify seismic risk have been conceived as the convolution of three components: hazard, vulnerability, and exposure. The first attempts of computing anthropogenic-seismic risk are based on the same principles, although accounting for non-stationary seismicity. These classical approaches, which follow an apparent logical structure, had the advantage of decomposing seismic risk into different tasks, which have been handled—separately—by a different group of experts. Differently, this research proposal calls for a—holistic— approach for seismic hazard and risk quantification, which is based on merging the three components by using the most recent advancements in probabilistic graphical models, vine copula theory, and stochastic simulators. Rather than following the current research trends which constrain these methods within the current paradigm of seismic risk computation, we will use them to reformulate the foundations of the probabilistic framework. This will address the following open questions:

- What is the correct probabilistic structure among the seismic and engineering variables defining the natural seismic risk?
- What is the role of the neglected dependencies in the seismic risk computation?

We tackle this research brief using the vine copula theory. Precisely, we use the vine copula approach to formulate the multivariate probability distribution of all the variables defining the seismic hazard and risk framework. Moreover, we introduce a novel hierarchical stochastic model for simulating and forecasting statistically compatible ground motion time series. This enables the combination of computational science and engineering tools with the most recent advancements in uncertainty quantification and reliability analysis for estimating structural and infrastructural responses. Finally, we validate the framework with a series of benchmark analyses on complex structural and infrastructural systems.

2) A dynamic vine copula approach for anthropogenic seismic risk analysis:

In recent years, the increase in anthropogenic seismicity due to subsurface exploitation has posed a new scientific and technological challenge. Moreover, the trend is expected to continue in the next years as the exploitation of subsurface resources is an essential component of the green transition. Currently, the anthropogenic seismic risk has been tackled with the same approach of natural seismicity. However, its nature is fundamentally different. First, it is an anthropogenic and industrial hazard, which by definition should have different safety standards; second, it is a dynamic risk that depends on a time-varying stochastic feedback system. The problem is time-varying because the activity producing the hazard (usually fluid injections) is time-varying. The feedback is given by the monitoring system, which is, in general, present in these activities. Lastly, the problem is inherently

stochastic has the uncertainties related to subsurface problems are simply vast. The key research questions read as follow

- How should we merge the know-how of computational science and engineering with health monitoring at a fundamental level?
- Can we formulate a robust probabilistic forecast of the seismic activity and the associated risk in the case of anthropogenic seismicity?

We tackle this research brief by combining vine copula theory and elements of probabilistic graphical models. Specifically, we define a Markovian time-variant probabilistic structure that accounts for all the dependencies governing the anthropogenic seismic risk. The framework is a dynamic extension of the static framework proposed for natural seismicity, fully integrated with the data acquisition scheme. Moreover, we extend the hierarchical stochastic model for simulating and forecasting anthropogenic ground motion time series and dynamic risk computations. Finally, we use the framework for developing a probabilistic forecast model of anthropogenic seismic activity and the associated risk.

Expected output (for both themes):
The outputs are summarized as follow:

i) Three research papers
ii) National and International conferences
iii) Open-source MATLAB and/or Python package.

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C9 - scholarship on reserved topics
Funded by: MUR – Departments of Excellence
Title: Extreme mechanics of solids and structures

Candidates can prepare proposals on the following themes:

1) Wrinkling and folding in anisotropic biological tissues:

Medical studies show how wrinkling is a physiological manifestation in mammalian tissues. This is the case in blood vessels, such as arteries, where wrinkling may play a key role in their health and functionality.
As matter of fact, arteries are, and have been treated as, nonlinear, anisotropic, and multilayered composite media. Recent research [1] has paved the way to bringing together engineering and medicine to the extent of providing a real understanding of wrinkling and had some preliminary indication about folding. There, the well-established Ogden-Gasser-Holzapfel model (widely available in renowned commercial codes for hyperelastic analyses of biological tissues) have been utilized to investigate the onset of wrinkling in a simplified flat bilayer geometry. Critical contractile strains have been found both analytically (there was not yet an available treatment for this aim) and numerically. Results suggest, among other findings, that anisotropic properties related with fiber-stiffness and distribution are used in biological layered media to adapt wrinkling and folding behaviors.
However, a lot of discrepancies are still present between experimental and numerical studies, thereby asking for a change of paradigm to deliver reliable and usable predictive approaches. Furthermore, as for some non-biological soft polymeric bilayers, no scaling formulas have ever been provided for such widely nonlinear and anisotropic systems. Also, key and overlooked characteristics associated to the activities of blood vessel's tissues, such as collagen fibers re-orientation [2], remodeling, growth, morphogenesis and residual stresses [3], have never been accounted for in the attempt of providing realistic predictive models.
Since the understanding of wrinkling in artery walls can help to better clarify the actual role of instability-guided mechanisms in tissues' mechanobiology, it is felt that this study may contribute to bringing closer together engineering and medicine, opening new possibilities for diagnosis and for designing possible optimized synthetic active biomaterials.

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2) Novel microstructured solids towards the design of ultra-resistant materials under extreme conditions

Architected microstructured materials pave the way for achieving superior mechanical performances under extreme conditions through the optimization of the microstructure properties as geometry, stiffness, and strength. For example, the effective relative stiffness for a solid with a fixed domain can be optimized as a function of the weight by exploiting specific geometry of the lattice composing the material. This opens the way to the engineerization of new topological materials for a variety of exciting applications, ranging from statics (controlled stress design, adaptive mechanical properties, controlled mechanisms, floppy modes) to dynamics (vibration isolation, acoustic waveguiding, elastic wave focusing and superlensing effects) [1,2,3].
Towards the exploitation of mechanical instabilities for reaching improved strength and stiffness and enhanced energy dissipation, lattice structures with soft and/or prestressed links will be considered. Innovative mechanical responses of structures will be first investigated as related to the presence of configurational and movable constraints. The homogenization of such structures will be then pursued via both energetic and dynamical approaches, allowing for first and second-order approximations. This will lead to the identification of Cauchy and higher-order equivalent continua, which will be exploited for the analysis of global instabilities, whereas local instabilities will be analyzed through a Bloch-Floquet technique.
The research activity will be performed through a blend of theoretical, numerical and experimental approaches.

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- Reference persons: Nicola Pugno (UNITN/DICAM), Luca Deseri (UNITN/DICAM), Massimiliano Fraldi (Università di Napoli-Federico II)
C10 - scholarship on reserved topics
Funded by: MUR – Departments of Excellence
Title: Short and long-range effects in optimization of multifunctional bioinspired materials

Insights gained from how natural systems work and organize complex functions across the scales are widely employed in many physical and engineering fields for optimizing devices and designing new materials with enhanced mechanical, electromagnetic, chemical and thermodynamical properties. A vast number of examples of surprising multi-field interactions in biology and mechanics that can inspire new concepts and applications can be made. For instance, recent experimental results have led to study theoretically the synchronization of the beating phase and frequency of nearby cardiomyocyte cells. This study demonstrates that elastic interactions produce forces that synchronize the phase and frequency of beating in a way that depends on the cells' mutual orientation, substrate elasticity and the inter-cell distance. The results are suggestive of how mechanics plays a key role in cardiac efficiency and could be relevant for the design of cardiomyocyte based micro devices and other biomedical or engineering applications [1]. On another completely different side, microstructure-dependent cross-

property relations for composites linking effective elastic and electromagnetic wave characteristics to one another have been very recently established in [2]. There multifunctional features for a wide group of architected materials have been obtained. Those include the so called disordered “hyperuniform” varieties, featuring direction-independent properties and robustness against defects. Applications of such materials to filters transmitting or absorbing elastic or electromagnetic waves “isotropically”, as well as to the design of multifunctional/reconfigurable composites via inverse methods for coating of spacecraft, building materials, heat sinks for CPUs, sound-absorbing housings for motors, and nondestructive evaluation of materials have been all envisaged as some of the challenges for the next generation of composites.
Both of these two exemplary cases feature the intrinsic multi-disciplinary character of the approaches required to obtain the coupling of near and far-field multiphysics theories (like bio-electric or electromagnetic problems) and continuum mechanics (including nonlinear elasticity, growth and remodeling of tissue mechanobiology). Starting from this observation, the present research proposal is aimed at obtaining novel and thermodynamically consistent formulations for establishing optimal criteria for designing multifunctional/bioinspired materials with enhanced properties. This will be done by accounting for non-local effects, thereby explicitly including non-standard forms of elasticity (e.g. gradient and integral elasticity theories, peridynamics [3], structured deformations [4]) to so incorporate and exploit both short and long-range multi-physics interactions.
Applications to composites with microstructure exhibiting extreme toughness for different engineering uses and to multifunctional systems of biomedical interests are all envisaged as results of this research proposal.

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- Reference person: Daniele Zonta (UNITN/DICAM)
C11 - scholarship on reserved topics
Funded by: MUR – Departments of Excellence
Title: Decision support system based on data fusion from satellite and terrestrial structural health monitoring

BACKGROUND
Many bridges all over the world have passed their design life [1]. Their complete replacement in the short term is economically unsustainable; therefore, managers constantly check their safety with periodic visual inspections and give maintenance priority to the most degraded ones. Inspections cause traffic-jams, might not identify some defects (eg in the prestressing cables) or risk identifying them late [2]. The aging of the bridges makes this approach increasingly onerous.
More accurate and objective information could be acquired by structural health monitoring, with sensors (eg strain gauge, load cells) permanently installed on bridges [3]. However, the cost of a monitoring system is high (€ 50-200k compared to € 0.5-2k for an inspection) and it is impossible to install them to all bridges.
Innovative technologies and data analysis techniques may allow to overcome the problem. DInSAR satellite interferometry [4] allows to monitor slow phenomena of the territory (subsidence, landslides) at a reduced cost. However, the high uncertainty of the measurements and the low sampling frequency do not allow to replace the traditional monitoring of bridges with this technology. Bayesian networks can model the relationships between different structures and extend the results of a few monitored structure to the whole network [5].
As far as the management process, managers prioritize maintenance, repair, and replacement on their asset with their own experience, but the choice may be affected by heuristics and biases [6]. The expected utility theory [7] identifies the most rational allocation of resources by accounting for social,

economic, and environmental impacts. The monitoring information could also be exploited for early warning systems that alert the community of impending environmental dangers, or directly act to reduce the risk. However, the application in civil infrastructure is still limited [8].

OBJECTIVE

The selected student will develop a decision support and early warning system for bridge management based on a combination of low-cost satellite technologies and terrestrial monitoring systems, which identifies structural damage, automatically regulates access to bridges depending on the risk level and provides operators with the optimal allocation of resources for the maintenance program.

The idea is to use DInSAR satellite technology, low cost but not very accurate, to continuously and extensively monitor the distortions of many bridges and integrate this information with data acquired by more accurate but expensive sensors installed on a few strategic structures and extend the results through a Bayesian network. In this way it will be possible to significantly increase the safety of many bridges with a reduced investment.

METHOD

- State of the art of satellite interferometry, Bayesian networks, decision support systems and ealy warning.
- Use of DInSAR satellite interferometry and TerraSAR-X data to obtain information on the behavior of bridges and data fusion with terrestrial monitoring.
- Development of a Bayesian network to extend the information acquired from a few of bridges to an entire stock and risk assessment.
- Development of the decision support and early warning system that identifies anomalous behavior of bridges in real-time and defines the optimal management of a stock.
- Validation of results by application to case studies.

EXPECTED OUTCOMES

- Scientific papers published in high impact factor international journals.
- A prototype of a decision support and early warning system for bridge management, which integrates satellite and terrestrial data, implements a Bayesian network for risk assessment, and identifies optimal management strategies based on the expected utility theory.
- Possible patent(s) on research outputs.

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Curriculum D - Architecture and Planning, Landscape

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Title: Integrated digital systems for knowledge, enhancement and intervention on the historical built Heritage

Any conscious design activity on the historical built heritage, whether conservative or innovative, necessarily develops from a material and cultural knowledge of it. Every physical place is in fact a condensate of matter and memory which, depending on its state, establishes with the present context various relationships of extraneousness or belonging, of continuity or fracture, concrete or evocative, etc. To understand these relationships, and thus legitimise design action, it is necessary to pursue a multidimensional and multidisciplinary knowledge, which today can take advantage of digital technologies applied to history, archaeology, archives, literature, figurative arts, etc. (Digital Humanities), and not only to architecture and engineering. The possibility of digitally accessing 'thematic' data and information (technical, historical, artistic, cultural, etc.) regarding the existing heritage appears therefore to be a fundamental need, also in the light of the recent contingencies of our time, both in the professional sphere, linked to the design or reuse of urban spaces, and in the field of research and enhancement of cultural heritage. This set of data and information, combined with the results that can be obtained through surveying and digital representation, allows to develop an information model of the built environment that can be used for different purposes.

In particular, digital reconstructions, functional to in-depth historical-critical and archival research, always supported by advanced surveying procedures and territorial information systems for mapping, analysing and managing data, today offer the opportunity to create integrated archives of heterogeneous information that can be applied in multiple fields (design, conservation, research, culture, tourism, etc.) and can therefore be addressed to various types of users (designers, private individuals, public administrations, etc.). However, in order to optimise the advantages offered by the new technologies, it is necessary to develop strategies to access data through special interface models capable of facilitating the acquisition of specific information at different scales of detail.

Considering these issues, the research aims to deal with the historical-critical study of Trento's urban development by defining a workflow which, starting from specific areas of investigation, selected for the richness of documentary material and for their peculiar historical-cultural value, can be applied to other areas of the city as well as to other urban contexts and, therefore, can be usable by different users, also involving the university's 'third mission' activity. To this end, it is proposed to involve multidisciplinary competences and diversified experiences. This digital information system could represent a real archive of the historical built heritage, designed to be accessible at different levels, progressively integrated and updated, fundamental for knowledge, for actions of intervention and valorisation of the built context and, more generally, of the territory.

Starting from the idea of *contrada*, historically understood as the public space consisting of a street or a square and the buildings that overlook it, the research aims to focus on two different scales of investigation: the urban one and the architectural one, with particular reference to the context of the city of Trento.

For the selected *contrada*, the research experience must therefore elaborate multidimensional models of the main compositional elements – first and foremost the street itself – which may have useful applications not only for its cultural enhancement, through the virtual representation of the built heritage, but also for analysing and monitoring the land use in view of planning and designing, both of individual architectural elements and of the urban environment as a whole.

The creation of these models implies extensive documentary research, done in local archives and libraries, but also in centres such as Innsbruck and Vienna, in view of Trento's peculiar history. The attention will always be paid to the acquisition and modelling of historical and constructional information

relating to the buildings, routes and pavements of the streets or squares of the *contrada* taken into consideration.
This information, obtained from bibliographic and archival sources as well as from surveys, on the one hand will offer the possibility of reconstructing the historical and cultural context of interest, and on the other one will flow into an organic and structured database, from which material, technical and cultural indications can be gained for the construction of digital models. The models produced, in addition to being sufficiently reliable and accurate, must be visualized dynamically through selected software and be used to produce static cartographic or presentation products accessible to a non-specialist public.

Note
The main disciplines involved in the research are history of architecture (ICAR/18), survey, digital modelling and visual communication (ICAR/17), road construction (ICAR/04).

- Reference person: **Sara Favargiotti (UNITN/DICAM)**
Participants: Marco Ciolli (UNITN/DICAM)
D1 - scholarship on reserved topics
Funded by: University of Trento – Department DICAM
Title: Mountain Agroecology: landscape, food and environmental dynamics in rural mountain areas

Research focuses
The current circumstances that we are experiencing, with the massive spreading of Coronavirus all over the world, especially in the most densely populated urban areas, have activated many reflections about the relation among natural and urban environments. The countryside, the hamlets, the inner areas, the small villages, became among the most valuable places to live, work, relax, and enjoy the everyday life. Very often these areas coincide with the most fragile areas for natural and human risks and where a new development path has to be defined. While urban areas are growing, expanding often-generating problems of congestion and pollution, other areas over Europe are suffering of an increasingly trend of depopulation and marginalization. More than 60% of European population live outside urban contexts (EU 2013, data refer to “intermediate regions” and “rural areas”). The doctoral position investigates the meaning and role of Agroecology in mountain rural areas through the lens of landscape design, transformation and management. It deals with challenges connected to community structure, migrations and demographic dynamics, as well as territorial transformations due to urban development and climate change impacts. The Alpine areas represent a favourable ground where to experiment new approaches due their dynamics and to the fact that many studies focusing on resilience have been carried out including quantification of Land Use Changes, biodiversity and cultural loss. Trentino in particular offers a large amount of data and study cases that can support the research.

Specific topics
The doctoral candidate will specifically be devoted to investigate the values in the relation among the territorial resources of food and water systems as collective resources to protect and take care of territories, to create a territorial strategy, and to promote the enhancement of territorial capital. The research will aim to propose co-design practices as an innovative potential for the adaptation of collective resources in mountain rural areas, and as a tool to change their perception and their transformation capacity towards more resilient and connected settlement constellations. The research will specifically address the topic on the Trentino region as a testing ground, compared and confronted with national and international case studies. The interdisciplinary and multiscalar methodology is based on a design research approach, including GIS mapping, literature reviews, interviews, surveys, participatory design, learning-by-doing, involving local communities, associations, administrators and public authorities.

Expected research outcomes
The doctoral candidate will address the following research topics: a) literature review on agroecology dynamics in mountain areas; b) mapping of urban/rural ecological systems and connection: a data collecting process is used to explore the natural identity of the Trentino case studies areas to contemplate ecological and spatial elements such as physical and immaterial qualities, weakness and

needs of local communities; c) collection national and international of best practices; d) developing tools and strategies that are replicable and scalable; e) communication and dissemination activities: attending national and international events and meetings and elaboration of reports and scientific publications (research papers, essays, etc.).

Note
The position is co-funded by the research projects EIT Climate-KIC “SATURN” and PRIN “B4R. BRANDING4RESILIENCE” both focusing on rural/urban areas in Trentino. The doctoral candidate will be involved in both research projects support the analyses of specific territories and give inputs for co-designing actions and co-visioning scenarios. The doctoral candidate will work around the discipline of landscape ecology with an emphasis on architectural heritage (ICAR/15), rural/urban relation and environmental and landscape management (AGR/05).

Research project: Prin 2017_FAVARGIOTTI
CUP E64I19002500001

Research project: EIT Climate-KIC SATURN 2021_CIOLLI