Doctoral Programme in Civil, Environmental and Mechanical Engineering

Research subjects proposed for the 39th cycle

A mandatory attachment of the application is a description of the research project (max 6 pages) relative to the research areas of the Doctoral Programme in Civil, Environmental and Mechanical Engineering, **preferably** on one of the research themes suggested below. Candidates applying for a scholarship on a reserved topic (with an ID and in red) must write a project proposal related to the specific topic of the scholarship.

Curriculum A - Civil and Environmental Engineering

- *Reference person:* Bruno Majone (UNITN/DICAM)

Title: Enhancement of hydrological droughts resilience by expanding surface water storage infrastructures

Climate change will severely affect freshwater availability across much of Europe by the end of 21st century. In a warmer climate, many river basins, especially in Southern Europe and the Mediterranean region, are likely to become more prone to periods of water scarcity, with projections indicating up to a 40% reduction in minimum streamflow by the 2080s (see e.g. Forzieri et al. 2014). The economic impacts of droughts in Europe will considerably increase as future droughts are expected to be more severe and long-lasting (Samaniego et al., 2018). Dealing with these climate change effects is indeed not anymore a long-term planning problem; it is rather a short/medium-term management challenge, which has already manifested its potential negative impact in a number of situations (Masante et al., 2019).

In this context, the main objective of proposed research is to investigate the enhancement of hydrological droughts resilience by expanding surface water storage infrastructures, including options like dam heightening, revision of lakes/reservoirs operating space, and construction of small storage reservoirs distributed on the territory. Specifically, the proposed research aims to develop a digital twin able to simulate the interdependent dynamics of coupled human-natural systems for exploring historical and future surface water availabilities and water demands, including the testing of the aforementioned diverse options for expanding water storage and the evaluation of alternative management policies that explore multi-sector synergies and tradeoffs.

As a result, the proposed research aims to provide a modeling framework capable to support the strategic planning of water storage expansion by quantitatively assessing the enhanced drought resilience under historical and projected climatic conditions in selected case studies in Northern Italy. Moreover, the research can provide a blueprint of adaptation options that can be replicated in other river basins, as well as at wider spatial scales to support drought management at the National and European level.

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

Bellin, A., Majone, B., Cainelli, O., Alberici, D., and Villa, F., 2016. A continuous coupled hydrological and water resources management model. Environmental Modelling and Software, 75, art. no. 3541, pp. 176-192, doi:10.1016/j.envsoft.2015.10.013

Forzieri, G., Feyen, L., Rojas, R., Flörke, M., Wimmer, F., & Bianchi, A. (2014). Ensemble projections of future streamflow droughts in Europe. Hydrological Earth Systems Sciences, 18, 85-108.

Majone, B., Villa, F., Deidda, R., and Bellin, A., 2016. Impact of climate change and water use policies on hydropower potential in the south-eastern Alpine region. Science of the Total Environment, 543, pp. 965-980, doi:10.1016/j.scitotenv.2015.05.009.

Masante D., Barbosa, P., & Magni, D. (2019). Drought in Europe – August 2019. JRC European Drought Observatory (EDO), 08 August 2019.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., et al. (2018). Anthropogenic warming exacerbates European soil moisture droughts. Nature Climate Change 8, 421.

- *Reference person:* Lorenzo Giovannini (UNITN/DICAM)

Participants: Nadia Vendrame (UNITN/C3A), Dino Zardi (UNITN/DICAM)

A1 - scholarship on reserved topics

Funded by: University of Trento – Department DICAM (Euregio project "IPN187" INTERFACE - CUP E65F21003390003)

Title: Investigating the role of local and mesoscale circulations in the surface energy balance closure over mountain areas

The surface energy balance, i.e. the partitioning of the energy exchange between the Earth's surface and the atmosphere, plays an essential role in determining meteo-climatological conditions in the atmospheric boundary layer. An accurate assessment of its components is therefore crucial for a variety of applications. However, measurements of the surface energy balance terms are still affected by uncertainties. In particular, turbulent heat fluxes measured with the eddy-covariance technique generally do not balance the available energy. Several studies claim that the main reason for this gap is connected to the advection induced by secondary circulations, which can be present even over homogeneous surfaces in convective conditions, but are more common over heterogeneous and complex terrain, as a consequence of differential heating. The systematic lack of closure of the surface energy balance, besides representing an important gap in our understanding of the available energy distribution and in the interpretation of observations, poses various limitations in the use of experimental data for several applications. For example, surface energy balance measurements are used to validate land surface parameterizations implemented in meteorological and climate models, where the closure of the surface energy balance is strictly imposed. Therefore, the comparison between model results and observations is plagued by the uncertainty in the experimental values. Different studies suggest that the uncertainty in the experimental measurements of the surface energy balance components is also critical for the estimation of CO2 fluxes, with obvious repercussions on the evaluation of the carbon cycle. The non-closure of the surface energy balance is particularly important also for several agrometeorological applications, which adopt simple models to determine the potential or actual evapotranspiration.
The present research project aims at evaluating the uncertainties connected to the measurement of the surface energy balance at different sites in the Alpine environment, where processes related to the lack of closure are expected to be particularly significant. Measurements at sites located in different contexts and climatic settings, thus differently influenced by advection, will allow investigating the relationship between the non-closure of the surface energy balance, the surface heterogeneity and the consequent development of different types of local and mesoscale circulations. Data from different sites in Trentino, South Tyrol and Tyrol will be analyzed, covering various morphological and surface conditions, providing a unique testbed to evaluate the role of advection in the closure of the surface energy budget. The outcome from this analysis is expected to be an evaluation of the rate of closure of the surface energy balance at the different sites and under different meteorological conditions, with the aim, in particular, of identifying possible connections with local flow characteristics (especially the development of local and mesoscale circulations) and with the topographic context.

It is expected that this research project will provide, for the first time, a systematic quantification of the non-closure of the surface energy balance at several Alpine sites, investigating in detail the role of local and mesoscale circulations at locations where such phenomena are a well-known and well-researched characteristic of the local flow conditions.

The successful candidate will work in the framework of the Euregio project "INTERFACE – Investigating the surface energy balance over mountain areas", in strict connection with research groups at the University of Innsbruck and at Eurac Research (Bolzano). The research project will also benefit from an unprecedented combination of advanced methodologies in different fields, thanks to the adoption of a sophisticated UAV platform, and the use of large-eddy simulations over complex terrain, which will help in the interpretation of eddy-covariance data.

The results of the present project will be presented at international conferences, such as the EGU General Assembly, the International Conference on Alpine Meteorology, the AMS Conference on Mountain Meteorology and the AMS Symposium on Boundary Layers and Turbulence. Moreover, results are expected to be published in peer-reviewed high-ranked international journals.

- ***Reference persons:*** **A. Siviglia (UNITN/DICAM), H.A. Dijkstra (Utrecht University affiliated to DICAM), M. Toffolon (UNITN/DICAM)**

A2 - scholarship on reserved topics

Funded by: University of Trento – Department DICAM

Title: Chaos and morphological predictions in fluvial and tidal systems

Background:
Traditionally, hydraulic engineering has relied on deterministic models to predict the morphological evolution of rivers and tidal systems. However, recent studies suggests that the complex and nonlinear interplay between flow and sediment transport, particularly when vegetation is present, may lead to chaotic behavior. As a result, there is a growing need for further research to understand the processes and to develop novel approaches that include stochastic models and ensemble methods to quantify the uncertainty of the results, similar to what is done for numerical weather prediction.

Research Questions:

This PhD project aims to investigate the chaotic behavior that can occur in the morphological evolution of fluvial and tidal systems. The study will address the following research questions:
1. What are the mechanisms that lead to chaotic behavior in fluvial and tidal systems, especially when influenced by vegetation?
2. Can we develop models and tools to predict the morphological trajectories in fluvial and tidal systems and quantify the uncertainty?
3. Can we develop a common approach for fluvial and tidal systems?

Methodology:

The project will use a range of methods, including numerical simulations, laboratory experiments, and field observations, to investigate these research questions. We will use existing models and develop new ones to simulate the dynamics of fluvial and tidal systems influenced by vegetation. We will also use analytical tools from chaos theory to identify and quantify chaotic behavior in the models. Finally, we will validate the models and test their prediction skill using field observations.

Approach:

This project will focus on mathematical and numerical modeling of hydro morphodynamic and ecological processes. As a first step, we will explore the deterministic models in more detail by determining the characteristics of the chaotic behavior, specifically by clarifying the route to chaos and its consequences for the predictability horizon. Next, we will use the stochastic approach and ensemble methods to make predictions of the morphological evolution of both fluvial and tidal systems.

Dissemination and Impact:

Publications on the methodological aspects, in particular the results from the novel stochastic models, will mainly be in scientific journals. The identification and understanding of clear predictability barriers will have substantial impact on the field of ecomorphodynamics.

Characterization of the PhD candidate:

The successful candidate will have an engineering, mathematical, or physics background, strong programming skills (e.g. C++, FORTRAN, Python, MATLAB), and the ability to perform model work at the interface between hydraulics and ecology.

Fluent spoken and written English, as well as good communication skills, are required.

- Reference persons: Guido Zolezzi (UNITN/DICAM), Marco Tubino (UNITN/DICAM)

A3 - scholarship on reserved topics

Funded by: MUR (Italian Ministry of University and Research) – Dipartimenti di Eccellenza (Departments of Excellence) Project **-** "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP n. E63C22003880001"

Title: Effects of sediment management in river habitat availability

Rivers are fundamental agents of the evolving landscape and provide highly valuable habitats for aquatic, riparian and terrestrial species. Rivers worldwide are increasingly characterized by intense anthropic activities such as regulation of the flow and sediment supply regimes, associate with sediment mining, impoundments and changes in land use. Habitat availability is strictly tied to the multitude of evolving forms and processes at a broad set of scales, connected to the river morphological dynamics. in the last five decades, an alarming decline in freshwater and river-supported biodiversity has been registered, putting many species at serious risk, in relation to heavy modifications of the river morphology due to human effects.

Rivers undergo evolutionary trajectories [Surian & Rinaldi, 2003, Fryirs & Brierley, 2016], which have been investigated mainly in westernized countries but have been poorly investigated in developing areas of the world. Most of these areas are also those still hosting a high abundance and diversity of biological species, which however can be posed at serious risk given the rapid pace of socio-economic development in such areas.

We presently lack (i) evidence of river evolutionary trajectories in low-income, recently developing contexts and (ii) predictive models for the response of river habitat availability to those medium-term changes.

The present PhD proposal focuses on river morphological and habitat alteration associated with anthropogenic changes in the flow and especially sediment supply regimes, to predict the variability of river habitat at multi-decadal time scales. The research will combine the automated extraction and analysis of remotely sensed river data (e.g. Monegaglia et al., 2018) with river habitat data collected at target field sites and mathematical modelling of reach- and network scale river sediment transport and morphodynamic responses. The key outcomes are: (i) an assessment of recent channel adjustments in rapidly developing regions, with focus on the Balkan area; (ii) a predictive tool for river habitat responses to those changes.

References

• Fryirs, K.A., & Brierley, G. J. (2016). Wiley Interdisciplinary Reviews: Water, 3(5), 727-748.

• Monegaglia, & al. (2018). Environ. Model. Softw., 105, 171-186.

• Surian, N., & Rinaldi, M. (2003). Geomorphology, 50(4), 307-326.

- *Reference person:* Alberto Bellin (UNITN/DICAM)

A4 - scholarship on reserved topics

Funded by: MUR (Italian Ministry of University and Research) – Dipartimenti di Eccellenza (Departments of Excellence) Project - "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP n. E63C22003880001"

Title: Hybrid Machine Learning and Process-based modeling in environmental applications

Modeling of natural processes has received a significant burst in the last years thanks to the escalating computational power and availability of data from satellite and near surface surveys, citizen science, new sensors and from large scale modeling of climate in environmental applications. Data are also accumulating on the impact of environmental pollution on human and freshwater ecosystems health. These paradigmatic changes paved the way to the application of Machine Learning algorithms in sectors, such as that of water resources and environmental pollution, traditionally addressed with process-based models.

One of the main challenges of environmental modeling is the interplay between physical and bio-geochemical processes occurring in a heterogeneous media or environment. Heterogeneity, combines with uncertainty, including unknown uncertainty, i.e. uncertainty that exists but cannot be identified (see Rubin et al., 2018). Uncertainty is unavoidable in modeling natural processes and it originates from two sources: media or environment heterogeneity in which the processes occurs and the inability of the model to fully capture process dynamics. Better parametrizations of the physical processes may alleviate the impact of the second source of uncertainty, but the first one is difficult to handle due to our limited ability to model the disordered spatial variability of media properties. The progressive increase of data availability and the

development of data- driven methods open new perspectives in handling uncertainty in modeling natural processes and their interplay with the human activities.

The proposed research will focus on the different evolutions of the Neural Networks and will be developed along two main directions: 1) the inclusion of physical constraints into the ML algorithms with the objective of excluding unphysical connections among the neurons and the development of new activation functions compatible with the process under investigation; 2) development of hybrid models taking advantage of the capability to learn from the data of the ML algorithms and the respect of physical constraints typical of process-based approaches.

The research will be conducted in one or more of the following areas:

1) Impact of water (over)exploitation, droughts and climate change on water resources. Here a hybrid model combining the capability of process-based models with data-driven approaches is expected to provide enhanced modeling capabilities and provide reliable estimates of water resources. Focus will be here on groundwater which is indeed a critical water resources endangered by overexploitation, contamination and droughts;
2) Risk analysis and impact on human health of environmental contamination. This research aims at identifying the nexus between pollution indicators (possibly simple to determine) and human health in impacted areas. High levels of contamination with the most relevant impact on human health occur often at specific locations (hot spots) and specific time (hot moments) and identifying them requires new modeling paradigms;

3) Modeling the interplay between renewable energies and their effect on the timing of hydropower production leading to streamflow alteration. This theme is relevant because the energy crisis and the progressive transition to renewable energy sources renewed the interest on hydropower systems, which management is expected to change in view of the growth of other renewable sources (i.e., solar and wind). In fact, reversible (pump storage) systems are a valuable alternative to batteries for accumulating solar and wind energy when they peak. In the presence of significant alterations of the natural regime due to hydropower exploitation process-based hydrological models show typically low performances (because hydropower data are often not available), while data-driven approaches are more flexible and may help in identifying unknown nexuses among the data and provide new visions in this important energy compartment.

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

Maria Grazia Zanoni, Bruno Majone, Alberto Bellin, 2022. A catchment-scale model of river water quality by Machine Learning, Science of The Total Environment, 10.1016/j.scitotenv.2022.156377.

Xu, T., Liang, F., 2021. Machine learning for hydrologic sciences: An introductory overview. Wiley Interdisciplinary Reviews, Water 8, 1–29. doi:10.1002/wat2.1533.

Nearing, G.S., Kratzert, F., Sampson, A.K., Pelissier, C.S., Klotz, D., Frame, J.M., Prieto, C., Gupta, H.V., 2021. What role does hydrological science play in the age of machine learning? Water Resources Research 57, e2020WR028091.

doi:10.1029/2020WR028091.

Thomas H. Miller, Matteo D. Gallidabino, James I. MacRae, Christer Hogstrand,‖ Nicolas R. Bury, Leon P. Barron, Jason R. Snape, and Stewart F. Owen, 2018. Machine Learning for Environmental Toxicology: A Call for Integration and Innovation, Environ. Sci. Technol. 2018, 52, 22, 12953–12955, doi: https://doi.org/10.1021/acs.est.8b05382.

Rubin, Y., Chang, C.-F., Chen, J., Cucchi, K., Harken, B., Heße, F., and Savoy, H.: Stochastic hydrogeology's biggest hurdles analyzed and its big blind spot, Hydrol. Earth Syst. Sci., 22, 5675–5695, https://doi.org/10.5194/hess-22-5675-2018, 2018.

- ***Reference persons:*** **Alessandra Marzadri (UNITN/DICAM), Giuseppe Formetta (UNITN/DICAM)**

A5 - scholarship on reserved topics

Funded by: iNEST - Interconnected Nord-Est Innovation Ecosystem (ECS00000043 – CUP E63C22001030007**)**

Title: Water management and risk mitigation strategies to reduce the pollution associated to stormwater urban runoff by preserving the natural capital

The point and diffuse sources of pollution of surface and groundwater environments linked to the presence of urban stormwater drainage networks are widely recognized as one of the main causes for the loss of ecosystem services (e.g. carbon sequestration, chronic chemical contamination, etc.) and biodiversity of cities and downstream connected areas (Marsalek, 1991, Petrucci et al., 1994, Müller et al., 2020). Within this context, it is expected that the extreme events associated with climate change (e.g. floods and droughts) may exacerbate these contamination levels by: i) increasing the atmospheric deposition during dry periods and ii) increasing the wash-off of atmosphere and the erosive capacity of the runoff during extreme rainfall events. Moreover, the growing presence of contaminants of emerging concern (CECs e.g. heavy metals, organic micropollutants, pesticides, polycyclic aromatic hydrocarbons (PAHs), microplastics) introduces new challenges in the management of urban runoff (e.g. Li et al., 2012; Gasperi et al., 2014, Werbowski et al., 2021). In the recent years, in the management of stormwater drainage networks, increasing attention has been given to the application of Nature Based Solutions (NBS) (e.g. Browder et al., 2019) with the idea of exploiting the potential of the "natural capital" to improve the stormwater quantity and quality management (European Commission 2015, Liquete et al., 2016, Frantzeskaki 2019).

Starting from this background, the PhD student will develop and apply innovative models and tools at different spatial (i.e. neighborhood areas, streets and urban landscape) and temporal (e.g. storm event, seasonal and annual) scales to evaluate the benefits of integrating in the built heritage some Nature Based Solutions (e.g. existing or planned wetlands, green roofs, bioretention systems, etc.) to: i) reduce the losses of ecosystem services and biodiversity, ii) predict the presence and fate of CECs in the fluvial receptors and iii) mitigate the effects of climate change in terms of both water quantity and quality management.

Expected outcomes of the PhD activity can be listed as follows:

1. design and model, in different urban areas, new intervention strategies aimed at reducing the hydraulic-hydrological risk associated with extreme rain events;
2. develop a modeling tool to characterize the quality of stormwater and the fate of the CECs along the stormwater urban drainage network;
3. implement suitable NBS to improve the quality of rainwater and propose strategies for its reuse;
4. propose optimization/management strategies to exploit the potential of these techniques to improve the management of water quality of urbanized catchments.

The proposed research ranks in the context of the Italian National Recovery and Resilience Plan and in line with the iNEST (Interconnected Nord-Est Innovation) project. The expected results of this PhD scholarship are extremely innovative and in agreement with the aims of the European Green Deal (European Commission, 2019) to prevent and reduce pollution and to promote a sustainable use of water.

The ideal candidate will have a background in Civil or Environmental Engineering 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 positive attitude. Since foreseen activities include model development, the candidate is required to have computational proficiency (or the will to pursue it) preferably in R/python/Matlab and GIS products. It is intended that the developed tools and/or models are produced as free software.

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

Browder, G., Ozment, S., Rehberger Bescos, I., Gartner, T., Lange, G.-M. 2019. Integrating Green and Gray: Creating Next Generation Infrastructure. Washington, DC: World Bank and World Resources Institute. © World Bank and World Resources Institute. https://openknowledge.worldbank.org/handle/10986/31430.

European Commission, 2015. Nature-Based Solutions and re-naturing cities. Final Report of the Horizon 2020 Expert Group on Nature-Based Solutions and Re-Naturing Cities.

Frantzeskaki, N., 2019. Seven lessons for planning nature-based solutions in cities. Environ. Sci. Policy 93, 101–111. https://doi.org/10.1016/j.envsci.2018.12.033.

Gasperi, J., Sebastian, C., Ruban, V., Delamain, M., Percot, S.,Wiest, L., Mirande, C., Caupos, E., Demare, D., Kessoo, M.D.K., 2014. Micropollutants in urban stormwater: occurrence, concentrations, and atmospheric contributions for a wide range of contaminants in three French catchments. Environ. Sci. Pollut. Res. 21 (8), 5267–5281. https://doi.org/10.1007/s11356-013-2396-0.

Li, W., Shen, Z., Tian, T. et al. 2012. Temporal variation of heavy metal pollution in urban stormwater runoff. Front. Environ. Sci. Eng. 6, 692–700. https://doi.org/10.1007/s11783-012-0444-5.

Liquete, C., Udias, A., Conte, G., Grizzetti, B., Masi, F., 2016. Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits. Ecosyst. Serv. 22, 392–401. https://doi.org/10.1016/j.ecoser.2016.09.011.

Marsalek, J. 1991. Pollutant loads in urban stormwater: review of methods for planning-level estimates. JAWRA Journal of the American Water Resources Association, 27: 283-291. https://doi.org/10.1111/j.1752-1688.1991.tb03133.x.

Müller A, Österlund H, Marsalek J, Viklander M., 2020. The pollution conveyed by urban runoff: A review of sources. Sci Total Environ. 709:136125. https://doi.org/10.1016/j.scitotenv.2019.136125. Epub 2019 Dec 18. PMID: 31905584.

Petrucci, G., Gromaire, M.C., Shorshani, M.F., Chebbo, G., 2014. Nonpoint source pollution of urban stormwater runoff: a methodology for source analysis. Environ. Sci. Pollut. Res. 21 (17), 10225–10242. https://doi.org/10.1007/s11356-014-2845-4. Epub 2014 Apr 24. PMID: 24760596.

Werbowski, L.M., Gilbreath, A.N., Munno, K., Zhu, X., Grbic, J., Wu, T. et al. 2021. Urban stormwater runoff: a major pathway for anthropogenic particles, black rubbery fragments, and other types of microplastics to urban receiving waters. ACS ES&T Water, 1, p. 1420. https://doi.org/10.1021/acsestwater.1c00017.

Curriculum B - Mechanics, Materials, Chemistry and Energy

- *Reference persons:* Nicola M. Pugno (UNITN/DICAM), Barbara Mazzolai (IIT)

B1 - scholarship on reserved topics

Funded by: University of Trento – Istituto Italiano di Tecnologia (IIT)

Title: 3D nanoprinting 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, as described in the following.
Due to their low density and impressive mechanical properties, plants provide examples of lightweight yet 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.
Invertebrates with a soft body, as, e.g., octopus, can squeeze and move in any spaces. The octopus can also bend and elongate its eight arms, while the skin adapts 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.

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:* Oreste S. Bursi (UNITN/DICAM)

Participants: Marco Broccardo (UNITN/DICAM), Giacomo Oliveri (UNITN/DICAM)

B2 - scholarship on reserved topics

Funded by: MUR (Italian Ministry of University and Research) – Dipartimenti di Eccellenza (Departments of Excellence) Project - "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP n. E63C22003880001"

Title: Metamaterials and metasurfaces for space applications

The goal of this thesis is to introduce a holistic approach to the design of metamaterials and metasurface antennas for space applications. Electromagnetic issues for frequencies between 10 GHz – 20 GHz and both far- and near-field radiation control should be considered. Moreover, thermal, structural and random -geometrical and material - issues should be part of the design. In this respect, novel concepts are going to be explored like structured fabrics that derive their properties both from the constitutive materials and their geometry. Therefore, their design can target desirable characteristics, such as high impact resistance, thermal regulation or electrical conductivity. Also, multifunctional properties of chiral mechanical metamaterials can be explored in view of vibration attenuation and bandgap features, impact energy absorption and negative coefficient of thermal expansion.
By means of this approach, for instance, the control of the aperture field above the metasurface could be pursued to generate the desired radiation pattern. Thus, arbitrary aperture distribution could be generated with control on amplitude, phase and polarization. The objectives of this thesis are summarized below:
1- Use of structured fabrics for tunable mechanical properties
2- Adoption of chiral mechanical metamaterials for multifunctional applications
3- Metamaterials and metasurfaces capable of generation with arbitrary phase and amplitude distribution radiation patterns.
3- Validation of the design procedure with numerical simulations capable of taking into account uncertainty issues.

Curriculum C - Modelling and Simulation

- *Reference persons:* Nicola M. Pugno (UNITN/DICAM), Barbara Mazzolai (IIT)

C1 - scholarship on reserved topics

Funded by: University of Trento – Istituto Italiano di Tecnologia (IIT)

Title: Modelling and fabrication of growing robots

Growth allows plants to adapt their body to changing environmental conditions, and to move searching for nutrients, water and/or light. The study of these biological mechanisms and behavioral strategies is the basis of a new paradigm for robot locomotion called moving-by-growing. Growing robots, with their capability to better challenge unstructured and extreme environments, have been already demonstrated to be viable solutions for burrowing granular mediums, exploring archaeological sites, and have potential applications in rescue scenarios.
However, their use in water environment is still unexplored and can bring to potential applications in environmental monitoring and ecosystems preservation.
This project aims at developing novel growing robots able to move and explore marine environment by building their bodies based on the external stimuli perceived while safely interacting with the surrounding.
Similar to aquatic plants, the body structure of the robot will be soft. This body feature will allow the robot to easy adapt to marine conditions and explore benthonic areas.
In summary, the expected work spans from materials characterization to design, fabrication, and testing of novel growing robots in marine environment. The expected outputs are patents and publications on high impact journals on the field.

- *Reference person:* Luca Deseri (UNITN/DICAM)

Participants: Nicola M. Pugno (UNITN/DICAM), Massimiliano Fraldi and Stefania Palumbo (UniNA-Federico II)

C2 - scholarship on reserved topics

Funded by: MUR (Italian Ministry of University and Research) – Dipartimenti di Eccellenza (Departments of Excellence) Project **-** "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP n. E63C22003880001"

Title: Mechanical response of microstructured solids with distributed defectiveness: modeling and simulations through Structured Deformations

Often times complex mechanical responses are encountered in macroscopic media. This is the outcome of either inelastic events arising at various scales or it follows from unconventional material properties.
Practical instances in which all of the above can be encountered are, for example, strain localizations. These are typically due to yielding, fully developed plasticity, or damage, or even nonlinear elastic behaviors, etc. It can be envisioned that even mechanical metamaterials, like the ones exhibiting negative Poisson's ratio, may possibly exhibit distributed buckling in striped zones of the body. Those solids result from special porous architected morphologies, applicable in many areas ranging from bioinspired high performing materials to novel multifunctional multiscale composites for waves attenuation (at the macro and micro-scales), damping, impacts and blasts mitigation, etc. The starting point of this research will be a recently published work [1], where a paradigm for a special architected solid with distributed defectiveness was conceived. There, several nonstandard behaviors were simultaneously obtained through the enhancement of distributed jumps between the relative displacements of the defect-free micro-zones of the material. Neither inelastic constitutive laws at the sub-macro level of such defect-free zones nor the requirement of initial distributed discontinuities (e.g. voids, slips, etc.) had to be required in those systems. It was through relative sliding among (geometrically regular and rigid) defectfree zones, connected by pre-stressed hyper-elastic links, that such systems achieved unusual configurations. Among those localized shear modes and tensile buckling-induced instabilities were found. In particular, deck-of-cards deformations—not achievable with classical continua—and an unprecedented 'bulk auxeticity' emerging from a highly packed and symmetric ensemble of rigid domains deforming through chiral modes were actually obtained.
Although some analytical solutions for very special situations were provided, high performing computational modeling of realistic and spatially extended systems will have to be explored. For instance, this is necessary for enabling simulations of prototypes for devices delivering high performing and spatially distributed actuation properties. This can be done through delivering kinematically augmented continua like the ones of the theory of Structured Deformations (SDs) [2,3 and ref.s cited therein]. The latter is corroborated through a discreteto- continuum transition obtained by means a passage to the limit of an infinite number of rigid (or even deformable) domains of infinitesimal size allowing mutual sliding (and even other kinds of discontinuities) on one another. In the light of SDs, results in [1] demonstrate that architected materials discussed above is the very first biaxial paradigm of a solid reflecting
micro/sub-macroscopic geometrical changes at the macroscopic scale. The potential of such paradigms does need to be expanded through the proposed novel study.

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Curriculum D - Architecture and Planning, Landscape

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D1 - scholarship on reserved topics

Funded by: University of Trento – Department DICAM (Horizon Europe Coordination and Support Action SOLO – CUP E63C22003060006)

Title: Exploring the relationships between land take, soil sealing and ecosystem services in European cities

Land take, defined as 'the transformation of natural and semi-natural land to urban and other artificialized land' (EEA 2019), is one of the main challenges of sustainable urban development. Expanding urbanization threatens biodiversity, causes the loss of agricultural land, and alters climate at multiple scales. Land take drivers are manifolds, including population growth and migration, economic development, changing preferences and lifestyles, and transport infrastructures, but policies such as planning regulations and financial incentives also play a key role (Colsaet et al. 2018). In the European Union, despite a slowdown of the process, land take between 2012 and 2018 still progressed in most cities (Cortinovis et al. 2022), questioning the feasibility of the ambitious objective of achieving "no net land take" by 2050 (EC 2011).
Strictly linked to land take is the process of soil sealing. It is estimated that, in Europe, around 50% of artificial areas is sealed. Soil is a non-renewable resource and sealing causes an irreversible loss of several soil functions, jeopardizing the provision of key urban ecosystem services such as stormwater management, microclimate regulation, and carbon sequestration (Panagos et al. 2022). To ensure soil health and safeguard soil functionality also in urban areas, the recent EU Soil Mission has included a specific objective to achieve "no net soil sealing and increase the reuse of urban soil".
The relationship between drivers of urbanization, land take, and soil sealing and the provision of ecosystem services is complex and depends on the spatial strategies that guide urban development, as well as on the actions that are taken on the ground. Increasing the density of existing settlements to protect non-urbanized land may promote soil sealing and further reduce the availability of green and permeable areas, and the associated ecosystem functions and services. On the other hand, there is a strong call to integrate more green spaces and nature-based solutions (e.g., green roofs, sustainable urban drainage systems) in artificial areas, but the potential cumulative impacts of these actions on soil sealing and land take are still unknown.

This research aims at exploring the intertwined issues of land take, soil sealing and urban ecosystem services from a planning perspective, with a specific focus on the European context.
Specifically, the research will address (some of) the following topics:

- Methods and indicators for monitoring land take and soil sealing at different spatial scales (e.g., by comparing existing modeling tools or developing new ones);
- Inclusion of land take and soil sealing in existing policies and decision-making processes at different administrative levels and in different EU countries;
- Impact of alternative urban development strategies and related actions (densification, brownfields redevelopment, greening through nature-based solutions) on land take, soil sealing and ecosystem services;
- Innovative policy tools and planning approaches to address land take and soil sealing that can be applied in the planning practice.

The research will combine several methods, from GIS modelling to policy analysis, in an inter-disciplinary perspective. It will be partially conducted within the EU Horizon Europe project "SOLO" (Soils for Europe), which aims at supporting the EU Soil Mission, by delivering actionable transdisciplinary roadmaps for future soil-related research activities in the EU.
The expected scientific outcomes of the research are three papers. The first paper is envisaged to be a review of the state of the art in research and/or practice. The second paper will focus on the development or application of models to assess land take and soil sealing, potentially applicable to analyze the temporal development of the issues or to assess the impacts on ecosystem services of alternative scenarios or policy targets. The third paper will look at planning policies and tools, and the contents will be selected according to the candidate's specific interest.

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D2 - scholarship on reserved topics

Funded by: Department DICAM (project Horizon Europe Project SELINA – CUP E63C22000790006)

Title: Transdisciplinary knowledge co-production to mainstream ecosystem services evidence in spatial planning

Transdisciplinary knowledge co-production is a reflexive and iterative approach in which actors from science, policy and society co-evolve their understanding of a particular socio-ecological issue to create solution-oriented and socially robust knowledge (Lang et al., 2012). Such an approach can enhance the credibility (adequacy), salience (relevance) and legitimacy (respect for divergent values and beliefs) of the generated knowledge, thus increasing the likelihood of its use in specific decision-making processes (Norstrom et al., 2020). Recent research has shown how transdisciplinary approaches for knowledge co-production hold promise to enhance the integration and implementation of ecosystem services evidence into policy and decision-making processes, such as spatial, urban and land use planning (Geneletti et al., 2020).

The general objective of the proposed research is to develop and apply transdisciplinary approaches to mainstream biodiversity and ecosystem service knowledge in spatial planning. The research will be conducted in the framework of the Horizon Europe project “Science for Evidence-based and sustainabLe decIsions about NAtural capital (SELINA)". The specific objectives are:
-Identifying context-specific barriers, bottlenecks, and challenges to the uptake of ecosystem service evidence in spatial planning and policy-making;

- Developing a case study related to the development of an urban greening plan (as defined by the EU Biodiversity Strategy to 2030), based on the integration of transdisciplinary knowledge and the assessment of ecosystem services, using a variety of biophysical and socio-cultural approaches;

- Cross-analysing the findings of other case studies developed within SELINA in order to assess the effectiveness of the various types of ES evidence in providing different forms of decision support to the different phases of the policy cycle, and draw lessons for the transferability and upscaling to other sectors and contexts.

The expected scientific outcomes of this research are three papers, of which one is envisaged to be a review of the barriers to the generation and uptake to ES-related evidence, and the remaining two are expected to relate to empirical case study applications and comparison. The ideal candidate should have a strong background in urban/environmental studies, and in the biophysical and socio-economic assessment of ecosystem services.

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