Doctoral School in Materials, Mechatronics and Systems Engineering

Research subjects proposed for the 40th cycle – second call

A mandatory attachment of the application is **a description of the research project (**max. 4 pages**).**
The research project proposal must contain: i) a title, ii) an introduction to the problem with reference to the state of the art, iii) a clear description of the aim and the content of the research, iv) an estimation of the time sequence of the intended activities, v) literature references.

The project's topic must be included within the Doctorate's fields of interest, preferably on one of the following research subjects. The candidate's choice to compete also for the reserved scholarships implies a preference on his/her part for the awarding of that specific scholarship.

Scholarships on reserved topics:

Title: A - Continual Imitation Learning of Robotic Manipulation Skills
Reference person: M. Saveriano
Funded by: Department of Industrial Engineering, project UE HE INVERSE, G.A. no. 101136067, CUP E63C23001600006

Most of the existing imitation learning strategies focus on learning and generalizing a task demonstrated by an expert user. In the EU funded project INVERSE, instead, we will focus in learning an "inverse" task from demonstrations of the "direct" task. For instance, the robot should infer disassembly plans from assembly demonstrations. In this regard, continual learning, where the robot continuously increased its skill repertoire, is the key to effectively invert a demonstrated task. However, continual learning poses several challenges like catastrophic forgetting and safety, which are not fully addressed in the robot learning community.

Title: B - Active Sensing Algorithms for Collaborative Robots
Reference person: D. Fontanelli
Funded by: UNITN and Department of Industrial Engineering, project UE HE MAGICIAN, G.A. n. 101120731, CUP E63C23000730006

The research objective is primarily aligned with the goals of the EU-funded MAGICIAN project, which aims to develop new solutions with collaborative robots for Industry 5.0. The study aims to conceive active sensing algorithms for the control and trajectory planning of robotic manipulators capable of using sensor measurements to enhance the understanding of objects to be manipulated and their imperfections in an industrial context. The fusion of classical estimation techniques with artificial intelligence-based machine learning algorithms, as well as closed-loop fusion with techniques based on the quality and quantity of collected information (such as barrier functions), will enable the synthesis of flexible and scalable solutions applicable to various contexts, beyond the limits defined by the MAGICIAN project.

Title: C - Analyze, understand and imitate the style and skills of professional and racing drivers to design an autonomous system that drives at the limit like a human
Reference person: F. Biral
Funded by: UNITN and Department of Industrial Engineering, Centro Ricerche Fiat, CUP B81B19001480008

A good understanding and accurate modeling of human driver skills and style are essential for the development of modern vehicles and particularly in motorsports, where the racing car must perfectly adapt to the drivers' preferences. However, an objective evaluation and clear understanding of what really matters to imitate professional and racing drivers is quite difficult due to individual driving styles, complex and non-deterministic decision-making processes, which are also influenced by interaction with the environment and poor stability margins when driving at the limits. Reproducing the behavior of racing drivers, taking into account their preferences and driving style, is also important for designing" teaching and training" tools that aim to improve their performance and driving skills or for designing future autonomous/semi-autonomous systems that control the vehicle at its limits. Recent scientific literature, in contrast to traditional methods based on optimal control (such as MPC and NL-MPC) or sampling-based methods, proposes data-driven algorithms that learn from imitation using real-world or computer simulator data. Dataset dimensions, capability to transfer knowledge and self-explainability are key questions that still need to be fully addressed. The objective of this doctoral program is to study, analyze and derive metrics that describe the driving styles of humans, using data from the driving simulator and telemetries collected on real circuits. The PhD student is encouraged to use both optimal control and nonlinear model predictive control approaches, as well as the latest deep neural network-based techniques to understand the distinctive characteristics of professional drivers and their style and skill. The ultimate goal is to design an algorithm that identifies and models/mimics individual driving ability and robustly generates competitive minimum time laps and maneuvers with human-like controls and is also self-explanatory. The algorithm will be tested in the laboratory with a professional driving simulator and possibly also as a racing driving agent for the F-SAE self-driving vehicle.

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani Piano Nazionale di Ripresa e Resilienza | Università di Trento

Title: D - RESilient hybrid microgrids enabled by COordinated Power Electronic hubs for the GREEN Revolution (RESCOPE4GREEN)
Reference person: E. Tedeschi
Funded by: UNITN and Department of Industrial Engineering, project PNRR M4C2 I1.1 MUR PRIN 2022, Prot. no. P2022W4HFX, CUP E53D23014790001

The focus of the PhD project is the Coordination of Power Electronics Energy Hubs (PE2H) to provide grid services in smart grids. Specifically, the PhD candidate will aim at the coordinated management of various PE2H based on power electronic converters to be connected to traditional three-phase alternating current (ac) networks to allow the interfacing of multiple renewable energy and energy storage systems, electric vehicles and flexible loads, without compromising the stability of the electricity grid and ensuring a more efficient and optimized operation of the power system.
The project will first investigate the capabilities and performance of a single PE2H of appropriate topology in providing ancillary services to the upstream ac network and, possibly, in facilitating the interfacing with portions of direct current (dc) networks. Then, it will focus on the coordination of multiple PE2H to provide, in a coordinated and optimized manner, such support functions to the grid, in order to maintain/increase grid stability margins, reduce losses, improve power quality, and maximize the exploitation of distributed energy resources thereby connected.

Title: E - Digital twins for hybrid power systems: development and experimental validation
Reference persons: G. Moretti, E. G. Macchi (FBK)
Funded by: Fondazione Bruno Kessler, project IPCEI Batterie 2, CUP B62C22000010001

Deployment of Hybrid Power Systems (HPS) has been growing in the last years thanks to increasing penetration of renewables and decreasing costs of battery storage. Redox flow batteries (RFBs) are a promising technology for large scale energy storage particularly suited for HPS. Combination of RFBs and other electrochemical energy storage technologies into HESS is also being evaluated in several project. Both HPS and HESS require complex

control algorithms in order to optimally manage them and predict their behavior. Digital twin technologies enable a smart integration of measured data and models (both physics-based and data-driven) thus enabling better system control based on real-time, historical data and models.
This PhD thesis will focus on developing and validating digital twins for HPS and HESS. The doctoral work will be organized in three phases. First accurate hybrid models for redox flow batteries and other electrochemical storage technologies will be developed. These models will be developed considering digital twinning requirements and integrate measured data to update the virtual representation of the battery and optimize battery use. Next the PhD candidate will set up an experimental test bench suitable for validating digital twins of hybrid power system and hybrid energy storage system using real hardware and simulated hardware. The experimental setup will integrate advanced sensing and controls keeping in mind the data that will be available in commercial systems. More specifically, first a Digital shadow of the RFBs and of the HESS will be validated. Then the control loop from the virtual representation to the physical device will be implemented integrating AI-based solutions.
Finally, the work will focus on studying and demonstrating advanced control logic integrated in the HPS and HESS digital twins.
This grant is funded by project IPCEI Batterie 2 — CUP B62C22000010001.

Title: F - Development of SiC 3D radiation detectors
Reference persons: G.-F. Dalla Betta, M. Boscardin (FBK)
Funded by: Fondazione Bruno Kessler

Silicon Carbide offers unique physical properties which can be exploited for high-performance new radiation detectors. This activity aims at developing radiation sensors with three-dimensional electrodes (either columnar- or trench-shaped) in Silicon Carbide for applications in harsh environments. The PhD research program will be focused on the design, TCAD simulation, material and fabrication aspects, as well as experimental characterization of prototypes.

Title: G - Chipless RFID sensors for environmental monitoring and detection
Reference persons: A. Quaranta, V. Mulloni (FBK)
Funded by: Fondazione Bruno Kessler

The development of low-cost, efficient, printable RFID sensors is a fundamental research domain for the Internet of Things (IoT). Chipless RFIDs are a new and emerging technology that removes the silicon chip from the sensor tag, including both the identification and the sensing function in the tag design. A chipless sensor is made by one or more RF resonant structures, whose frequency is dependent on the dielectric material covering the metallic resonator. This PhD position is about the study of chipless RFID technology for the sensing of environmental parameters. The study is interdisciplinary and will have different combined approaches: -At material level: study and identify the best polymer formulation for maximising the sensitivity to of parameters. At device level: build a sensor prototype with the most promising materials, for multi-parameter detection. Evaluate its performances with RF measurements, establishing also the suitability for wireless detection. The work will be primarily in FBK in collaboration with DII-UniTN.

Title: H - Advancing Open-Source Robotics for Cost-Effective Agricultural Digital Twins
Reference persons: D. Fontanelli, M. Vecchio (FBK)
Funded by: Fondazione Bruno Kessler

This scholarship aims to pioneer the development of open-source robotics to create cost-effective agricultural digital twins, bridging the gap between digital and physical farming systems. By leveraging the versatility and accessibility of open-source platforms, it will focus on designing, developing, and implementing robotic systems capable of accurately simulating agricultural environments. These digital twins will enable farmers to predict crop outcomes, optimize resource allocation, and mitigate risks by providing a virtual representation of their fields, thus facilitating informed decision-making processes. Key objectives include the development of scalable and modular robotic platforms that can be customized to suit diverse agricultural needs, the integration of advanced sensors and AI algorithms for real-time data processing and simulation, and the establishment of a framework for the seamless transition between digital twins and their physical counterparts. The project will also explore innovative approaches to reduce costs and improve the accessibility of robotics in agriculture, making cutting-edge technology available to a wider range of users.

Title: I - Development of autonomous and cooperative driving and operation technologies for Off-Highway machines
Reference persons: D. Fontanelli, F. Zendri (DANA)
Funded by: DANA

The project aims to develop and implement enabling solutions for autonomous operations of Off-Highway machines. Specifically, solutions will be developed for autonomous driving and automated execution of specific work operations (material loading/unloading, excavation, etc.), with possible extensions into distributed multi-agent robotics using machine-to-machine interaction protocols (fleet management, machine-to-machine communication, machine-to-machine interaction). The project will primarily consider the architecture of the platform and its components (sensing, actuation, communication), with a modular configuration applicable to various types of machines. Subsequently, solutions for localization and mapping, dynamic obstacle recognition and estimation, trajectory planning, and tracking will be studied to synthesize an autonomous driving algorithm in unstructured environments. Additionally, algorithms for cooperation and interaction among various vehicles will be developed for material loading/unloading or excavation operations. The project will be structured from the outset to achieve high Technology Readiness Levels (TRLs) by leveraging both industrial-derived HW/SW units and innovative algorithms. Experimental development, integration, and verification testing will initially occur in simulated environments before transitioning to physical platforms (such as the experimental mini-dumpers and mini-excavators available at the Dana Rovereto Technology Center).

Title: J - Battery-free Electronic Sensors with tiny machine learning on flexible substrates
Reference person: D. Brunelli
Funded by: MUR – Departments of Excellence project "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP E63C22003890001

Self-powered electronic sensors, 3D printed or made of "textiles” that allow the incorporation of electronic components such as batteries, sensors, actuators, and microcontrollers, represent the frontier of 3D electronics in the next decades. The project aims to explore and develop these self-sustaining, intelligent sensors, leveraging the benefits of 3D printing technology and advanced manufacturing techniques. Sensors will be intelligent thanks to tiny neural network models and the recent advancements in Tiny Machine Learning. The ideal candidate for this project should have a strong background in digital electronics, with specific skills in programming digital microcontroller unit (MCU)-based sensors. They will also work on designing and implementing simple 3D-printed passive and active analog electronic circuits and transducers. A final demonstrator will be developed, namely, to realize a sensor in a flexible system that is self-powered. This final demonstrator will highlight the practical applications and potential impact of self-powered sensors in various fields, such as wearable technology, smart textiles for robots, flexible robotics, and environmental monitoring. The candidate will engage in multidisciplinary research throughout the project, combining principles from electronic engineering, computer programming, and materials science. Additionally, the project will involve testing and refining the power generation and storage capabilities to ensure the sensors are truly self-sustaining. This innovative approach to sensor technology aims to pave the way for new applications and improved efficiency in smart systems.

Title: K - Smart materials integrating embedded optical fiber sensors
Reference person: M. Lobino
Funded by: MUR – Departments of Excellence project "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP E63C22003890001

The project focuses on the study of new type of smart materials (composites, polymer or metallic) with integrated optical fiber sensors, which would allow in situ real-time monitoring of both the manufacturing process and the service life, is highly desirable. Due to their unique characteristics of weight, minimal footprint, high sensitivity to temperature and strain, immunity to electromagnetic interference, possibility to operate in a hazardous environment and in the presence of electric currents, optical fiber sensors offer clear unmatched advantages over traditional sensors. However, the interrogation of the fiber sensor is still problematic as it requires expensive cumbersome equipment. We propose to study the integration in integrated optics and develop such interrogators demonstrating a SWAP-C improvement. In particular, Optical Frequency Domain Reflectometry (OFDR) is quite promising as allows to measure the strain and temperature over hundreds of meters with sub-cm resolution. In the context of smart materials. By interrogating an optical component or fiber assembly in reflection, OFDR technology is able to measure and analyze loss and polarization effects spatially, or distributed along the optical path. The Optical Backscatter Reflectometry (OBR) technology measures distributed loss and backscatter with a sampling resolution as low as 1mm, providing an unprecedented level of detail to pinpoint and analyze optical effects in short optical assembly networks that could be embedded in mechanical parts. In particular, by a specific signal processing it is possible to measure strain, temperature distribution and vibrations over the whole extent of the fiber.

Title: L – Modeling and control of the manufacturing chain of functional technologies: from material functionalization to 3D printing
Reference persons: M. Saveriano, A. Tirella, P. Rech
Funded by: MUR – Departments of Excellence project "Dipartimenti di Eccellenza 2023-2027 (Legge 232/2016)", CUP E63C22003890001

Controlled fabrication of functional materials, including 3D printed electronics, is an emerging field with appealing applications in several areas including Internet of Things, Robotics, Biomedicine and Biotechnology. Additive manufacturing, like 3D printing, enables the production of technologies with unique features like complex printing patterns, as well as the possibility to combine different functional inks to obtain embedded, conformal, flexible and/or stretchable devices, which is hardly attainable by traditional manufacturing methods. However, 3D printing remains a trial-and-error process, mostly due to the lack of feedback control on the printing process.
This PhD project aims to develop a new data-driven approach to model the whole 3D printing process, ensuring precision and accuracy of printed objects. The model will exploit modern techniques like physics-informed neural networks to increase the accuracy and robustness, while significantly reducing the amount of training data needed to achieve the desired performance. Functional material and ink properties will be characterized and included in the model. Finally, sensory data will be exploited to control the printing process, reducing the number of attempts needed to fabricate a product and, as a consequence, the amount of waste material being produced.

Proposed research topics for the positions without scholarship.

Title: Imitation learning of robotic skills from high-dimensional and multi-model training data
Reference persons: M. Saveriano, D. Fontanelli

Imitation learning is a paradigm in which an agent learns to perform a task by imitating the behavior of an expert shown in demonstrations. The approach is gaining significant traction due to having tremendous potential for learning complex behaviors from demonstrations. Imitation learning accelerates the learning process by improving sample efficiency, while also reducing the effort of the programmer. However, while recent approaches show that it is effectively possible to learn policies from high-dimensional data, the multimodality aspect if often ignore. This research will focus on developing novel approaches to learn complex control policies from high-dimensional and multi-modal training data, and in extending the generalization capabilities of the learned policy to let the robot operate in different environments.

Title: Certifiable generalization of learned control policies
Reference persons: M. Saveriano, A. Del Prete

Modern robots are asked to operate in unstructured and highly dynamic environments. Learned control policies have shown superior generalization capabilities with respect to classical controllers in many robotic applications. However, it is still unclear how to certify a learned control policy when the robot operates in a different domain. This research activity will focus on rigorously defining the generalization bounds of learned policies, for instance relying on PAC-Bayesian analysis, and in developing novel learning approaches specifically designed to maximize the generalization bounds.