PhD Program in Bioengineering and Robotics

Curriculum: Robotics and Autonomous Systems

Research themes

The main goal of the PhD curriculum in *Robotics and Autonomous Systems* is to study, design and build novel solutions and behaviors for robots, teams of robots and, in general, autonomous systems capable of exhibiting a high degree of autonomy and intelligence when performing highly complex tasks in challenging real-world environments.

The focus of the curriculum is two-fold: on the one hand, on key, innovative and disruptive methodologies and technologies, including such topics as sensing, state estimation, knowledge representation, software architectures for robots, real-time scheduling, motion planning, advanced robot control, robot coordination and cooperation, human-robot interaction and collaboration, design of macro/micro robot systems, design of sensors and actuators; on the other hand, on specific areas, e.g., underwater operations, aerial and space, or Industry 4.0, as well as on such diverse application scenarios as manufacturing, material handling and transportation, search & rescue, surveillance and monitoring, ambient assistive living).

The curriculum enforces research practices and education methodologies based on cutting-edge best practices at the international levels, and all the aspects outlined above are dealt with by focusing on the study and the adoption of theoretically sound methodologies and the design of experimentally verifiable solutions, with the goal of meeting robustness and predictability requirements even in unknown, dynamically changing, or even hazardous environments.

The ideal candidates are students with a higher-level University degree, with a strong desire for investigating, designing and developing robot-based systems which can have a huge, disruptive, impact on the society in the upcoming future.

International applications are strongly encouraged and will receive logistic support with visa issues and relocation.

Coordination and control of a team of UAVs

Tutor: Marco Baglietto

Tutors Affiliation: DIBRIS, University of Genova, www.dibris.unige.it

Project Description

The use of multiple Unmanned Aerial Vehicles (UAVs) offers the possibility to study different applications in complex environments, from cooperative task assignments such as monitoring wide areas to formation control and cooperation for a mutual goal, including autonomously transporting a payload [1].
New controlling techniques should be developed for a system composed of multiple UAVs (quadrotors) transporting a payload by flexible rods [2][3].
Utilizing more agents enables carrying heavier payloads during mid to-long-term missions, reducing battery energy consumption per robot in the team. Despite these advantages, cooperative transportation poses several challenging situations, which can be explored related to (among others): coordinated takeoff and landing, recovery strategies in case of a UAV failure, cooperative formation control and reconfiguration basing on onboard sensors.

Requirements:

- Classical Control/Optimal Control
- State estimation and Filtering
- familiarity with ROS/ROS2 environment
- C++/Python
- Matlab/Simulink
- PX4 (optional)

References:

[1] D. K. D. Villa, A. S. Brandão, R. Carelli and M. Sarcinelli-Filho, "Cooperative Load Transportation With Two Quadrotors Using Adaptive Control", in IEEE Access, vol. 9, pp. 129148-129160, 2021.
[2] K. Sreenath, V. Kumar, "Dynamics, Control and Planning for Cooperative Manipulation of Payloads Suspended by Cables from Multiple Quadrotor Robots", Robotics: Science and Systems, 2013.
[3] M. Tognon, C. Gabelleri, L. Pallottino, A. Franchi, "Aerial Co-Manipulation with Cables: The Role of Internal Force for Equilibria, Stability, and Passivity", IEEE Robotics and Automation Letters, vol. 3 no. 3, pp. 2577-2583, 2018.

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Robotics and AI for electronic waste recycling

Tutors: Carmine Recchiuto[1], Michele Olivieri, Jacopo Iottero[2]

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Project Description:

This Ph.D. work foresees a pioneering approach that combines artificial intelligence with robotics to address a growing challenge: E-Waste recycling [1]. The issue of sorting batteries is very topical and relevant, given the growing diffusion of electric or hybrid vehicles and the consequent need to dispose of batteries that have reached the end of their life. Although this is a research topic in continuous development, at the moment there are no fully automated systems for the disassembly and disposal of heterogeneous batteries, also due to the lack of production standards. To date, the disassembly of the batteries is carried out almost entirely by hand by a specialized operator and involves poor ergonomics and a high degree of risk for the operator, as the batteries contain toxic and dangerous substances and may contain residual charge [2]. Furthermore, given the monotony of the disassembly process and the high weight and bulk of the batteries of electric vehicles, this process is mentally and physically stressful for the operator. Disassembling electric vehicle (EV) batteries for recycling presents a complex challenge due to the vast diversity of battery pack designs, materials, and degradation states. The complexity are both in the single actions (e.g. grasping and manipulating) but also in the planning procedure that must be reactive to changes in the environment, failures and also handle the cooperation with a human-operator. An analytical approach to such a huge challenge, though potentially feasible, might require a prohibitive amount of time and probably would suffer robustness issues. However, the recent emergence of foundation models and advancements in reinforcement learning (RL) offer a powerful alternative. Foundation models [6], a type of LLM trained on massive datasets of text and code, can provide robots with a versatile framework for perception and decision-making. These models excel at pattern recognition and information extraction, allowing robots to adapt to the wide variability encountered in EV battery packs. Additionally, recent advancements in RL enable robots to learn complex disassembly sequences. Hierarchical policies training [4] and sample-efficient reinforcement learning approaches [5] have been addressing some of the most important shortcomings of these algorithms thus making reinforcement learning more and more usable in real-life scenarios. The combination of these techniques will allow to train robots for end-to-end policies, encompassing both individual actions and intricate sequences, without the need for pre-programmed solutions for every possible scenario thus making it a promising venue of research for the solution of the EV disassembly challenge. The implementation of artificial intelligence and planning algorithms, together with the interaction between robots and human operators, offers an unprecedented opportunity to increase efficiency and safety in the process of disassembling electric vehicle batteries [3]. In particular, the Ph.D. student is expected to study, design and implement artificial intelligence the semi-automatic disassembly of electric vehicle batteries through human-robot and robot-robot interaction, using advanced collaborative robots (e.g. Universal Robots) and industrial systems. The work will be partially performed at HIRO Robotics, an innovative startup based in Genoa that operates in the automation branch for the disassembly of electrical and electronic waste, and partly at the DIBRIS department in the “RICE Lab,” a fully equipped facility for software development with ground robots (quadruped and wheeled), humanoid robots for socially assistive applications, and aerial robots.

In particular, HIRO Robotics has developed various automation lines suitable for the disposal and sorting of WEEE waste such as flat screen monitors and electronic boards, thanks to the use of artificial intelligence algorithms and proprietary adaptive robot control. The company also holds several patents in this area.

Requirements:

Applicants are expected to have good programming skills (C++, Java, or Python) and a profound interest in cutting-edge research in autonomous robotics. Previous experience with Artificial Intelligence techniques and Human-Robot Interaction strategies will be considered.

When applying for the Ph.D. scholarship, the student will be encouraged to propose solutions to address one or more of the aspects described in the proposal.

References:

- [1] Grau Ruiz, M. A., & O'Brolchain, F. (2022). Environmental robotics for a sustainable future in circular economies. *Nature Machine Intelligence*, *4*(1), 3-4.
- [2] Tarrar, M., Despeisse, M., & Johansson, B. (2021). Driving vehicle dismantling forward-A combined literature and empirical study. *Journal of Cleaner Production*, *295*, 126410.
- [3] Johnson, M., Khatoon, A., & Fitzpatrick, C. (2022, November). Application of AI and Machine Vision to improve battery detection and recovery in E-Waste Management. In *2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)* (pp. 1-6). IEEE.
- [4] Luo, J., Xu, C., Geng, X., Feng, G., Fang, K., Tan, L., Schaal, S., & Levine, S. (2023). *Multi-Stage Cable Routing through Hierarchical Imitation Learning*. https://arxiv.org/abs/2307.08927v5
- [5] Luo, J., Hu, Z., Xu, C., Tan, Y. L., Berg, J., Sharma, A., Schaal, S., Finn, C., Gupta, A., & Levine, S. (2024). *SERL: A Software Suite for Sample-Efficient Robotic Reinforcement Learning*. http://arxiv.org/abs/2401.16013
- [6] Brohan, A., Brown, N., Carbajal, J., Chebotar, Y., Chen, X., Choromanski, K., Ding, T., Driess, D., Dubey, A., Finn, C., Florence, P., Fu, C., Gonzalez Arenas, M., Gopalakrishnan, K., Han, K., Hausman, K., Herzog, A., Hsu, J., Ichter, B., … Zitkovich, B. (2023). *RT-2: Vision-Language-Action Models Transfer Web Knowledge to Robotic Control*. https://robotics-transformer2.github.io

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Underwater Inspection and Maintenance with Marine Robots

Tutors: Giovanni Indiveri and Enrico Simetti

Tutors Affiliation: Department of Informatics, Bioengineering, Robotics, and Systems Engineering - DIBRIS

Project Description

Systems composed of heterogeneous robotic platforms are increasingly studied for their use in the marine environment. The robotic team can be composed of underwater vehicles (carrying sensors, e.g., water quality sensors, hydrophones, magnetometers, etc.) and surface vehicles (typically with a support role, for example for the localization of underwater vehicles, or carrying large payloads such as sparkers). In certain cases, an underwater vehicle can be physically connected to a surface through a tether cable, to exploit the extended communication range of the surface vessel, and possibly power from it.

The applications of such systems are diverse and range from water quality monitoring to offshore aquaculture inspection, to geotechnical exploration [1]. Among the scenarios, the monitoring and inspection of underwater cables and pipelines with marine robots could drastically reduce costs of the maintenance of offshore wind farms [2]. In the above reference scenarios, different research challenges emerge, including low-level control strategies, reliable navigation and guidance in real-world conditions, limited communication ranges and bandwidths and coordination and distributed task allocation and monitoring.

Within this PhD proposal, we want to investigate the use of such systems focusing on two main aspects. The first deals with the low-level control strategies, reliable navigation and guidance in real-world conditions of each of the team members. The second one relates to the possible integration of acoustic sensor payload modules (e.g. multibeam, forward looking, sidescan sonars) and the exploitation of the related acquired data for mission (re)planning.

Requirements: Very good knowledge of Matlab and C++ is required.

References:

- Simetti, E., Indiveri, G., & Pascoal, A. M. (2021). WiMUST: A cooperative marine robotic system for autonomous geotechnical surveys. Journal of Field Robotics, 38(2), 268-288.

- Campos, D. F., Matos, A., & Pinto, A. M. (2021). Multi-domain inspection of offshore wind farms using an autonomous surface vehicle. SN Applied Sciences, 3(4), 1-19

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Robot avatars and their embodiment

Tutors: Alessandro Carfì, Fulvio Mastrogiovanni

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Project Description

The current notion of robot avatars translates as "teleoperated robots capable of conveying to their operator some resemblance of *being there*". However, current avatars are very limited. They resemble human-like bodies, and therefore are characterized by the same (if not worse) intrinsic and morphological limitations in terms of sensing and motion functions, and do not leverage the complementary capabilities of human and robot bodies if not at a limited extent.

The goal of this PhD project is to investigate methods and technologies to develop the next generation of robot avatars. To this aim, the student (1) will question the current thinking in the current technology-driven development of robot avatars, and (2) will carry out a science-based investigation of the fundamental challenges that must be addressed to design and develop groundbreaking robot avatars. In so doing, the student will be involved in a series of motivating industry-oriented use cases, involving manufacturing, constructions, and maintenance.

Among the research topics that the student may have to consider, the following ones are of particular relevance: (1) use of non-humanoid-like robot bodies as a preferred embodiment, and therefore the need for the human operator to cognitively "adapt" to new morphologies and, in general, robot capabilities, even on-demand; (2) use of discrete and continuous gestures to control the robot on the occasion and for different purposes to enforce ergonomic measures; (3) mixed-initiative robot architectures, whereby the robot avatar may exhibit a varied level of autonomy in the execution of commanded actions; (4) the rendering of information sensed or inferred by the robot avatar in non-conventional ways, for example through the use of VR/AR; (5) the use of digital models of the robot avatar help the operator predict possible outcomes of the robot actions.

Requirements:

Software design and development (C/C++/Python), AR/VR, ML.

References:

E. Merlo, E. Lamon, F. Fusaro, M. Lorenzini, A. Carfì, F. Mastrogiovanni, A. Ajoudani. An ergonomic role allocation framework for dynamic human-robot collaborative tasks. Journal of Manufacturing Systems 67, 111-121.

A. Carfì, F. Mastrogiovanni. Gesture-based human-machine interaction: taxonomy, problem definition, and analysis. IEEE Transactions on Cybernetics 53 (1), 497-513.

S. Macciò, A. Carfì, F. Mastrogiovanni. Mixed reality as communication medium for human-robot collaboration. Proc. 2022 IEEE International Conference on Robotics and Automation (ICRA).

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A multi-modal, cognitive extension to surgeons for robot-assisted surgery

Tutors: Alessandro Carfì, Fulvio Mastrogiovanni

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Project Description

Robot-assisted surgery allows surgeons to operate at an unparalled precision. Between the surgeon and the robot a close sensorimotor loop is established, where information from an intra-body camera is delivered to the surgeon's eyes, and their hand motions are replicated with super-human dexterity and precision by micro-manipulators acting on the body organs. However, such modality is limited to a quantitative betterment (intra-body camera, motion precision) of what a surgeon would experience in any case. We argue that since a human-machine interface is in place, that should be leveraged to provide surgeons with super-human capabilities as far as perception is concerned, which may not be otherwise achieved.

In this PhD work, the student will investigate and design the human-machine interfaces of robot-assisted surgery of the future. To that aim, it will be necessary to rethink the current tenets of robot interfaces for robot-assisted surgery in different respects. In fact, current interfaces for robot-assisted technology represent the end-point of surgeon needs quite back in time. It is necessary to understand current surgeon needs to design novel interfaces. The work will be done in close collaboration with San Martino Polyclinic in Genoa, and in particular with the Urologist Clinic, with the possibility of accessing a Da Vinci robot from Intuitive Surgical.

In this framework, the PhD student will investigate scientific and technological aspects of human-machine interfaces for next generation robot assisted surgery. The following activities will be considered: 1) the use of wearable sensors to collect data about the surgeon's status to build joint models of their behaviors and the actions they carry out; 2) methods and techniques to model the status of the internal body organ under surgery, in terms of its real-time pose and deformations; 3) rendering techniques for the surgeon, including both visual and non-visual cues; 4) integration with a virtual assistant to allow the surgeon to manipulate the augmented visual representation during the intra-operative phase.

Requirements:

Software design and development (C/C++/Python), Computer Vision, AI/ML.

References:

R. Lastrico, S. Macciò, A. Carfì, P. Traverso, F. Mastrogiovanni. Estimation of kidney's blood vessels deformations for robot-assisted surgery. Proc. 18th International Conference on Intelligent Autonomous Systems (IAS-18), 2023.

A. Carfì, F. Mastrogiovanni. Gesture-based human-machine interaction: taxonomy, problem definition, and analysis. IEEE Transactions on Cybernetics 53 (1), 497-513, 2023.

M. Kilina, T. Elia, Y. K. Syed, A. Carfì, F. Mastrogiovanni. Embodiment perception of a smart home assistant. Proc. of the 14th International Conference on Social Robotics (ICSR), 2022.

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Methods and techniques to synthesize in-hand manipulation actions

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Project Description

Hands are key enablers to complex sensorimotor loops in humans and other primates. It is generally accepted that a full hierarchy of complex behaviors involving a wide range of sensory data and control actions is in place also in the case of the simplest of manipulations. In-hand manipulation requires advanced motor and cognitive skills. Orienting an object in one's hand requires mental imagery and simulation, perspective object use, the planning of manipulation steps, integrate motion execution and visuo-tactile-motor coordination. Current approaches in the literature emphasize one among such aspects. A principled rethinking of the whole in-hand manipulation pipeline is needed.

In the PhD project, the student will have to question the current thinking in the typical in-hand manipulation pipeline, with the goal of designing a hierarchical continuo-discrete sensorimotor architecture taking into account both motion and cognitive loops. On the one hand, the student will develop an in-the-loop forward model of the hand-object-environment interaction dynamics with the aim of performing simulations. On the other hand, the student will partake to the development of the TER:glove, a novel data glove design. Both simulations and experiments with TER:glove will be used to collect datasets about hand-object-environment phenomena. These will be employed to synthesize manipulation motions.

Among the topics that the student is expected to carry out, we can highlight: a) the design and implementation of digital twin models of one or more in-hand object manipulation actions to model hand-object-environment interaction phenomena; b) modeling and development of a hierarchical sensing-control architecture for sensate robotic hands, on the basis of current use of machine learning techniques; c) design and conduct experimental campaigns using TER:glove on a series of use cases: d) synthesize in-hand manipulation actions to be tested and validated with robot hands.

Requirements:

Software design and development (C/C++/Python), Embedded systems, AI/ML.

References:

L. Seminara, S. Dosen, F. Mastrogiovanni, M. Bianchi, S. Watt, P. Beckerle, T. Nanayakkara, K. Drewing, A. Moscatelli, R. L. Klatzky, G. E. Loeb. A hierarchical sensorimotor control framework for human-in-the-loop robotic hands. Science Robotics 8 (78), eadd5434, 2023.

A. Carfì, F. Mastrogiovanni. Gesture-based human-machine interaction: taxonomy, problem definition, and analysis. IEEE Transactions on Cybernetics 53 (1), 497-513, 2023.

H. Ali, V. Belcamino, A. Carfì, V. Perdereau, F. Mastrogiovanni. In-hand manipulation planning using human motion dictionary. Proc. 31st IEEE International Conference on Human and Robot Interactive Communication (RO-MAN), 2022.

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A distributed, cognitive architecture for Cephalopods-inspired robots

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Project Description

With respect to mammals and humans in particular, cephalopods evolved along completely independent evolutionary lines. Whilst their bodies have been widely studied, and robots mimicking their morphology exist, the study of their distributed brain architecture is still at early stages. However, adopting Marr's three level computational theory approach, it is now possible and timely to synthesize a cognitive architecture based on current knowledge about cephalopods, and to investigate a possible implementation in a simulated Cephalopod body. While designing such a distributed architecture, we hope to identify design principles for intelligence and sensorimotor loops of an organism completely different from mammals.

The PhD student will undertake a study across the emerging biology, neuroscience, and computational aspects of Cephalopod organisms, with the aim of proposing a distributed, sense-act architecture to generate Cephalopod behavior. In so doing, the student will first model a synthetic Cephalopod organism using Cosserat continuum mechanics, then will design a distributed cognitive architecture, and finally will test it in a series of use cases leveraging the simulator.

The student will carry out the following activities: a) studying and modelling Cephalopod bodies using Cosserat rods, for example using open source simulation software like Elastica (web: https://www.cosseratrods.org/); b) designing and modelling a functional, cognitive theory for Cephalopod sensing and control aspects, to be translated into a suitable computational model; c) implementing a cognitive architecture functionally mimicking such and integrating it with the simulator, in order to perform validation tests.

Requirements:

Software design and development (C/C++/Python), AI/ML.

References:

L. Seminara, S. Dosen, F. Mastrogiovanni, M. Bianchi, S. Watt, P. Beckerle, T. Nanayakkara, K. Drewing, A. Moscatelli, R. L. Klatzky, G. E. Loeb. A hierarchical sensorimotor control framework for human-in-the-loop robotic hands. Science Robotics 8 (78), eadd5434, 2023.

W. Wasko, A. Albini, P. Maiolino, F. Mastrogiovanni, G. Cannata. Contact modelling and tactile data processing for robot skin. Sensors 19 (4), 814, 2019.

X. Zhang, F. K. Chan, T. Parthasarathy, M. Gazzola. Modeling and simulation of complex dynamic musculoskeletal architectures. Nature Communications, 10:4825, 2019.

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