NATIONAL PH.D. PROGRAM IN AUTONOMOUS SYSTEMS

Robot-as-a-service for the digital industry

Ph.D. candidate

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Cycle

XL

Tutors

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1. Description of the research program

The industrial sector is evolving rapidly, driven by increasing demands for flexibility, efficiency, and responsiveness in manufacturing processes. Traditional rigid automation systems, while effective, often fall short in addressing the dynamic needs of modern industries like automotive and logistics. In contrast, soft robotics, characterized by its compliant and adaptable properties, offers a transformative approach to industrial automation. This research focuses on operational aspects of integrating soft robotics into industrial settings, aiming to develop a comprehensive framework that leverages soft grippers, advanced automation, control theory, Artificial Intelligence (AI), and Large Language Models (LLMs) to create a Robot-as-a-Service (RaaS) model capable of functioning effectively in unstructured environments.

Recent advancements in soft robotics have demonstrated significant potential in fields such as healthcare, agriculture, and manufacturing. Soft grippers, constructed from materials like silicone and elastomers, have a unique capacity to handle delicate and irregularly shaped objects - tasks that rigid grippers struggle with. However, integrating soft robotics into high-mix, high-volume manufacturing is still in its infancy, with current industrial robotic systems often lacking the flexibility and adaptability required to manage the diversity and unpredictability in today's production environments. This research seeks to bridge this gap by developing adaptable soft robotic systems tailored for industrial operations within a RaaS framework, with LLMs enhancing flexibility, responsiveness, and intuitive control.

This project addresses several critical challenges in industrial automation. By combining soft robotics with LLMs and advanced control techniques, this research will deliver a system that is technologically advanced yet practical for operational deployment. The primary objective is to create a modular, plug-and-produce robotic system that minimizes setup and reconfiguration time, facilitating seamless integration into existing manufacturing environments. Specifically, this involves designing soft robotic grippers that can adapt to various shapes and materials, implementing quality control through AI-driven vision systems, and utilizing LLMs to enable responsive, natural language-based commands, thereby simplifying programming and control.

The research methodology involves multiple phases. The first phase focuses on developing soft grippers using advanced materials and computational techniques, with testing for adaptability and durability across various industrial tasks and sensors providing data on grip strength, object shape, and material properties. The second phase integrates LLMs into the control system to enable natural language interaction and decision-making, allowing the system to deliver adaptive, context-aware responses. A key application for LLMs is in task planning and sequencing: LLMs can break down high-level commands into executable steps and adjust the sequence based on real-time inputs from multiple sensors, significantly reducing the need for human oversight. The third phase centers on implementing real-time quality control using vision-based AI to provide continuous adaptability and quality assurance in manufacturing. In the final phase, all components will be unified into an integrated framework, validated through extensive simulations and real-world testing on industrial robots, with a focus on applications in the automotive and logistics sectors.

Potential risks include challenges in material durability for soft grippers, achieving seamless human-robot interaction via LLMs, and managing the complexity of real-time control with advanced AI. However, the anticipated benefits are substantial: increased flexibility in automation, enhanced safety and compliance through adaptable materials, and improved efficiency in human-robot collaboration.

Expected outcomes include the development of versatile soft grippers, LLM-driven natural language interfaces, and algorithms for real-time quality control and dynamic task management.

Demonstrations will showcase practical applications in the automotive and logistics sectors, improving flexibility and efficiency while providing guidelines for integrating soft robotics into existing industrial systems. This project is expected to drive the adoption of flexible, intelligent automation in manufacturing, enhancing industrial competitiveness and contributing broadly to advancements in robotics and AI-driven automation.

In summary, this research aims to redefine industrial automation by harnessing the unique capabilities of soft robotics and LLMs. Through the development of adaptive grippers, natural language interfaces, and advanced control systems, the proposed RaaS framework will enable industries to achieve unprecedented flexibility and efficiency, making a significant contribution to the field of industrial robotics.

2. Schedule of the research activities

First academic year (planned)

	Description	Period	Activity abroad
Comprehensive Literature Review	This initial phase focuses on establishing a strong foundation by conducting an in-depth literature review on core topics, including soft robotics, soft grippers, automation, control theory, and the application of LLMs in robotic systems. This review will identify research gaps, refine research questions, and inform the development of a preliminary project outline. Concurrently, time will be dedicated to learning necessary robotics frameworks, programming tools, and evaluation metrics that will be used in later experiments.	6 months	NO
Proof of Concept for Integration of LLMs with Soft Robotic Grippers	In this phase, theoretical insights from the literature review will be translated into a proof of concept that integrates LLMs with soft robotic grippers. This initial proof of concept will be tested in a controlled setting to evaluate task planning, sequencing, and control via basic LLM-driven algorithms. Tests will assess the system's performance in terms of precision, adaptability, and repeatability. The findings will guide adjustments to both the gripper design and control algorithms, setting a foundation for further development.	6 months	NO

Second academic year (planned)

	Description	Period	Activity abroad
Application to Industrial Tasks	This phase will focus on enhancing the soft gripper's functionality and applying it to common industrial tasks, including object manipulation, grasping, and sorting tasks. Through iterative testing, the control algorithms will be refined to improve grip strength, adaptability, and accuracy across various object types. Sensor fusion techniques will also be explored to enable the use of sensory data, such as pressure and force, to inform control decisions. A detailed analysis of the results will be conducted to identify the system's strengths and limitations, forming a solid foundation for further refinement.	6 months	NO
Widening and Optimization of LLM Algorithms for Soft Robotics	This stage will deepen the application of LLM algorithms to enhance the soft gripper's adaptability and control capabilities. By collaborating with experts on LLM applications in robotics, advanced resources will be utilized to refine and optimize the LLM-based interface, enabling complex task adaptability. Initial experiments will focus on improving performance through contextual decision-making, aligning with AI-driven robotics research goals. This phase will likely be conducted in Professor Ken Goldberg's lab at UC Berkeley, California (USA).	6 months	YES

Third academic year (planned)

	Description	Period	Activity abroad
Integration of Advanced LLM Algorithms with Soft Grippers and Industrial Pick-and-Place Tasks	This phase will focus on integrating advanced LLM algorithms with soft grippers, targeting complex industrial pick-and-place (P&P) tasks. The system will undergo extensive testing in real-world scenarios, with emphasis on precise task execution and control. Optimized sensor fusion and LLM-driven adaptability will ensure that the system can handle varied industrial applications effectively. This phase will involve refining the user interaction model for improved usability in industrial settings.	6 months	NO
Characterization of the Integrated System with	In this final phase, the fully integrated system will be rigorously characterized through demonstrations in realistic industrial	6 months	NO

Demonstrations in Industrial Scenarios, and Thesis Preparation	scenarios, focusing on tasks that reflect automotive and logistics applications. Comprehensive data analysis will assess performance, strengths, and limitations. Following this, thesis preparation will begin, documenting the research process, technical contributions, and future directions, with particular emphasis on soft robotics, automation, and LLM integration. This will lead to final preparations for presentation and defense.		

3. Training and research activities plan

First academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses	Distributed/Decentralized Control and Optimization of Large-Scale Systems	Jan – Feb 2025	Yes	1
	Deep learning	Feb 2025	Yes	2
	Human Autonomous System Interaction	Feb – Mar 2025	Yes	1
	Robot programming with ROS – Dibris (UniGE – IIT)	September 2025	Yes	1.5
	Cognitive Robotics for Human-Robot Interaction – Dibris (UniGE – IIT)	September 2025	Yes	2
B. Master's degree courses	Dynamical Systems Theory	Sep 2024 Jan 2025	No	3
	Embedded Control	Feb – Jun 2025	No	3
C. Soft skill courses				
D. Participation to seminars	AUTOMATICA.IT – SIDRA	Oct 2025		3
	Coursera - Generative AI with Large Language Models	Nov – Dec 2024		3
	The Construct – ROS2 Basics in 5 Days (Python)	Nov 2025		3
	ShangAI Lectures	Oct – Dec 2024		5
	Scuola Nazionale di Dottorato – Bertinoro (FO)	Jul 2025		5
E. Participation to international congresses or workshops	2025 IEEE 21st International Conference on Automation Science and Engineering (CASE) - At Millennium Biltmore, Downtown Los Angeles	17/08/25 - 21/08/25		5
F. Presentation of research products at international congresses or workshops	2025 IEEE 21st International Conference on Automation Science and Engineering (CASE) - At Millennium Biltmore, Downtown Los Angeles	17/08/25 - 21/08/25		2
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			39.5
G. Individual research activity				12.5
H. Supervision of students				2
I. Integrative teaching activities				1.6

J. Preparation of manuscripts for conferences or journals				4.4
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			20.5
	TOTAL OF ECTS			**60**

Second academic year (planned)

	Description	**Period**	**Final Exam**	**ECTS**
A. Ph.D. courses	Theory and Practice of Learning from Data (UniGE - IIT)	TBD	Yes	2
	Mechatronics and AI (UniGE - IIT)	TBD	Yes	2
	Data-driven fault diagnosis and fault prognosis	TBD	Yes	1
	Intelligent Supervisory Systems	TBD	No	1
	Game Theory for Controlling Autonomous Systems	TBD	Yes	1
	Deep Reinforcement Learning for Control of Autonomous Systems	TBD	Yes	1
B. Master's degree courses	AI Applications to Industrial Robotics (PoliMI)	TBD	Yes	5
C. Soft skill courses				
D. Participation to seminars				
E. Participation to international congresses or workshops	2026 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)	TBD		5
	2026 IEEE International Conference on Robotics and Automation (ICRA) - Vienna, Austria	TBD		5
F. Presentation of research products at international congresses or workshops				
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			23
G. Individual research activity				25
H. Supervision of students				3
I. Integrative teaching activities				1.5
J. Preparation of manuscripts for conferences or journals				7,5
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			37
	TOTAL OF ECTS			**60**

Third academic year (planned)

	Description	**Period**	**Final Exam**	**ECTS**
A. Ph.D. courses				
B. Master's degree courses				

C. Soft skill courses				
D. Participation to seminars	TBD			3
E. Participation to international congresses or workshops	TBD			5
F. Presentation of research products at international congresses or workshops	TBD			2
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			10
G. Individual research activity				35
H. Supervision of students				3
I. Integrative teaching activities				1.6
J. Preparation of manuscripts for conferences or journals				10.4
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			50
	TOTAL OF ECTS			**60**

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