NATIONAL PH.D. PROGRAM IN AUTONOMOUS SYSTEMS

Intelligent systems for industrial robotics

Ph.D. candidate

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Cycle

XL

Tutors

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1. Description of the research program

This PhD project focuses on developing advanced planning and optimization strategies for manipulators operating in semi-structured environments. The goal is to leverage the robot's functional redundancies and dynamical capabilities to independently formulate a control policy that meets full compliance with input requirements. By integrating appropriate vision algorithms, the proposed approach aims at enhancing applicability across a wide range of industrial tasks while guaranteeing both adaptability and safety.

Research Gap and Positioning

While the task of planning and optimizing the trajectory of a manipulator is fundamentally important in robotics, the literature lacks a comprehensive, adaptable, and easily integrable approach for industrial manipulators.

To correctly model the manipulator and its environment, various solutions exist in the literature, each performing differently depending on several factors such as the structure of the environment, the required precision required for the specific application, the characteristics of the manipulator, and other boundary conditions, like whether the environment is static or dynamic and the framework with which the robot interfaces. Models can be broadly categorized into analytical and data-driven types. Analytical models offer high precision and maintain low computational weight for solving planning problems. However, they are best suited for static and highly structured environments due to their sensitivity to model uncertainties and difficulties in reconfiguring for real-time applications [7], [5]. The data driven models rely on tools like cameras placed on the manipulator and appropriate vision processing algorithms. They are highly adaptable, even in dynamic and unstructured environments. Despite their adaptability, they generally have lower accuracy due to uncertainties introduced during the processing phase and are more computationally expensive compared to analytical models [6]. Against the discussed background, the proposed approach will be based on a hybrid approach and will be structured as follows:

- Modeling the manipulator and its operating environment, allowing for dynamical and real-time updates.
- Selecting an appropriate control policy, which guarantees all input requirements are met.
- Addressing the combined challenges resulting from the previous steps to provide a comprehensive solution.

Research Objectives

In the proposed approach, a hybrid model combining analytical modeling with adaptive reconfiguration based on features extracted from a camera will be developed. This approach ensures accuracy and adaptability, even in semi-structured environments [2]. To develop a generalized and adaptable methodology for achieving a collision-free trajectory and at the same time optimize boundary conditions [8], chosen, a critical issue is the choice of the correct policy. Literature often leverages the degrees of freedom provided by functional redundancies in specific applications to minimize execution time [4], energy consumption [1, 12], or end-effector vibrations [10], or to maximize manipulability [13, 9], or safety margins [3]. The selection of boundary conditions typically depends on the application's requirements. In industrial contexts, reducing trajectory execution time or energy consumption translates into economic advantages, while minimizing end-effector vibrations is crucial for high-precision applications. These boundary conditions often conflict and are thus incorporated into the optimization problem with weights assigned based on their relative importance. In the proposed approach, these weights will be dynamically chosen based on the control policy. Rather than selecting a control policy a priori, our methodology will dynamically modify the policy to better adapt to the environment, utilizing the manipulator's dynamics, input requirements, and data collected by the camera. This approach aims to maximize the dexterity and redundancy of the robot.

Research Novelty

The analysis of the literature revealed a gap between the proposed solution and the state-of-the-art methodologies for manipulators; although various approaches are formally correct high accurate, these cannot be fully exploited within industrial scenarios due to their complexity of implementation, thus been surpassed by few higher performing methodologies easier to use. The proposed approach will address this gap, positioning itself as a viable alternative to existing methods, to develop a novel methodology that significantly improves the accuracy and adaptability of the robot control system. Specifically, the goal of the proposed work is to formally propose a mathematical framework to characterize the robot control problem, while at the same time applying this methodology in a real industrial scenario to fill the gap between the state-of-the-art approach and the practical methods usually applied in industrial scenarios. Trajectory optimization problems are usually non-convex, and numerous methodologies exist for resolving and simplifying such problems, our approach aims to explore and deepen this aspect [11].

Project reference list

[1] Sourva Dipta Das, Victor Bain, and Pratyusha Rakshit. "Energy optimized robot arm path planning using differential evolution in dynamic environment". In: 2018 Second International Conference on Intelligent Computing and Control Systems (ICICCS). IEEE. 2018, pp. 1267–1272.

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[3] Tudor B Ionescu. "Adaptive simplex architecture for safe, real-time robot path planning". In: Sensors 21.8 (2021), p. 2589.

[4] Byung Kook Kim and Kang G Shin. "Minimum-time path planning for robot arms and their dynamics". In: IEEE transactions on systems, man, and cybernetics 2 (1985), pp. 213–223.

[5] Stefan Klanke et al. "Dynamic path planning for a 7-DOF robot arm". In: 2006 IEEE/RSJ international conference on intelligent robots and systems. IEEE. 2006, pp. 3879–3884.

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[7] Tobias Kunz et al. "Real-time path planning for a robot arm in changing environments". In: 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE. 2010, pp. 5906–5911.

[8] Hsien-I Lin and Ming-Feng Hsieh. "Robotic arm path planning based on three-dimensional artificial potential field". In: 2018 18th International Conference on Control, Automation and Systems (ICCAS). IEEE. 2018, pp. 740–745.

[9] Filip Mari´c et al. "Fast manipulability maximization using continuous-time trajectory optimization". In: 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE. 2019, pp. 8258–8264.

[10] Kyung-Jo Park. "Path design of redundant flexible robot manipulators to reduce residual vibration in the presence of obstacles". In: Robotica 21.3 (2003), pp. 335–340.

[11] John Schulman et al. "Finding locally optimal, collision-free trajectories with sequential convex optimization." In: Robotics: science and systems. Vol. 9. 1. Berlin, Germany. 2013, pp. 1–10.

[12] Abhronil Sengupta et al. "Energy efficient trajectory planning by a robot arm using invasive weed optimization technique". In: 2011 Third world congress on nature and biologically inspired computing. IEEE. 2011, pp. 311-316.

[13] Henghua Shen et al. "Adaptive manipulability-based path planning strategy for industrial robot manipulators". In: IEEE/ASME Transactions on Mechatronics 28.3 (2023), pp. 1742–1753.

2. Schedule of the research activities

First academic year (planned)

	Description	Period	Activity abroad	Activity at the company
Literature review	This initial phase involves a comprehensive study of existing methodologies and approaches related to planning and optimization, including resolution of subproblems such as collision avoidance, collision detection, and trajectory planning. By conducting a state-of-the-art review, we will critically analyze the strategies used to address these issues and identify any gaps in knowledge that need to be filled. This phase also includes an analysis of the requirements to obtain a holistic understanding of the problem.	6 months	NO	NO
Model development 1	This phase will focus on the definition of the hybrid model using the proposed approach.	6 months	NO	NO

Second academic year (planned)

	Description	Period	Activity abroad	Activity at the company
Model development 2	This phase will involves exploring issues related to image processing methodologies and features extraction techniques needed for ensuring the adaptability and dynamism of the hybrid model.	3 months	NO	NO
Development of policy control methodology	This central phase aims at creating a control policy that makes the model adaptable to a wide range of applications. The focus will be on developing robust control methodologies to enhance the model's versatility. This period is planned to be spent abroad at Imperial College London, where a highly specialized research group operates in relevant areas of interest. Collaboration with this group would provide a valuable learning experience and significantly contribute to professional development.	9 months	YES	NO

Third academic year (planned)

	Description	Period	Activity abroad	Activity at the company
Integration and experimentation	In this stage, the various components will be integrated into a unified approach to solve the proposed problem.	6 months	NO	YES

	This will be followed by extensive testing and experimentation with the aim of evaluating the effectiveness of the entire approach. This phase of the project will be conducted at the company, with the objective of integrating the developed results directly into the production processes.			
Writing the thesis	The final phase of the project involves the writing of the thesis document, providing an in-depth analysis of the results obtained and the skills acquired.	6 months	NO	NO

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	01/25 – 02/25	YES	1
	Simulation Systems for Engineering Applications	25-May	YES	1
	Non-integer order systems and controllers	04/25	YES	1
	Introduction to probability and statistical inference	03/2025 – 05/2025	NO	1
	Human Autonomous System Interaction	02/25 - 03/25	YES	1
	Data-driven fault diagnosis and fault prognosis	25-Jul	YES	1
	Intelligent Supervisory Systems	25-Jan	NO	1
	Mathematical methods in deep learning	01/25 - 02/25	YES	2
	Model Predictive Control	25-Apr	YES	2
	Non-Destructive Testing (NDT): Process, Types and Applications in Mechanical Engineering	06/25 - 07/25	NO	1
B. Master's degree courses	Embedded Control	02/25 - 06/25	YES	6
	Machine Learning and Artificial Intelligence	10/24 - 06/25	NO	6
C. Soft skill courses				
D. Participation to seminars	Scuole Nazionale di Dottorato - Bertinoro (FO)	25-Jul		5
	AUTOMATICA.IT - SIDRA	25-Oct		3
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
G. Individual research activity				12
H. Supervision of students				3
I. Integrative teaching activities				1.6
J. Preparation of manuscripts for				4.4

conferences or journals				
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			21
	TOTAL OF ECTS			**60**

Second academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses	Deep Reinforcement Learning for Control of Autonomous Systems	TBD	YES	1
	Game Theory for Controlling Autonomous Systems	TBD	YES	1
	Gaussian processes for modeling and control of robotics systems	TBD	NO	1
	Numerical Methods for Multidimensional Differential Problems	TBD	YES	1
	Parallel robotics: modeling and analysis - DIBRIS (iit)	TBD	NO	0.5
	Robot programming with ROS - DIBRIS (iit)	TBD	YES	1.5
	Artificial Robotic Cognition for the Representation of Purposive Actions - DIBRIS (iit)	TBD	YES	1
	Machine Learning with Python - Early Career Researcher Institute (Imperial College)	TBD	YES	0.5
B. Master's degree courses	AI Application to Industrial Robotics - (POLIMI)	TBD	NO	2.5
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			20
G. Individual research activity				27
H. Supervision of students				3
I. Integrative teaching activities				1.6
J. Preparation of manuscripts for conferences or journals				8.4
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			40
	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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