NATIONAL PH.D. PROGRAM IN AUTONOMOUS SYSTEMS

Interconnected Digital Twins

Enabling advanced human-machine interaction in autonomous robotic navigation

Ph.D. candidate

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Cycle

XL

Tutors

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1. Description of the research program

The research program focuses on the development of techniques and software architectures to enable a human-machine interaction paradigm based on natural language, in complex autonomous robotic navigation scenarios. In the field of robotic autonomy, robotic agents are usually designed to accomplish given tasks without the human supervision, however, state-of-the-art paradigms usually struggle to encode complex and semantic-rich instructions to guide robots during the mission.
Multi-modal neural networks, along with Large Language Models (LLMs) allow nowadays to merge mission-oriented information and semantic-information to enhance the capabilities of the robotic agents to understand the surrounding environment and perform complex, dynamic tasks. Moreover, LLMs enable the use of natural language, allowing machines to capture structured instructions in the input sentences.
Digital twins, in the form of interconnected software and hardware robotic agents, are a powerful tool to interact with autonomous agents and supervise all of their activities during the operations. They allow to create a development environment thanks to which the human operator can easily interact with the real robot and monitor the mission development. LLM-powered prompts can also be exploited to send dynamic commands to the robot while operating. Moreover, a simulated version of the real robot allows to test the behavior before the actual deployment on the hardware platform.

The project aims therefore at enabling an advanced human-machine interaction based on natural language, via digital twins. The first goal is to implement multi-modal neural networks to achieve a semantic-aware autonomous navigation in complex environments. The idea is to give a command to a robot in natural language and have a system on board the agent to make it understand and execute the instruction. In the literature, although recent developments have significantly enhanced the accuracy and robustness of mapping and planning algorithms, there is still a notable gap in autonomous navigation with semantic understanding. Classic algorithms are still based on spatial distribution of information, without any semantic awareness of the surrounding environment.
The development of multi-modal neural networks (e.g. text-vision models) is required to capture the semantics of the surrounding environment and mix this information with semantic-rich input commands, to perform a complex planning process to accomplish the input task.

The second goal of the project regards the creation of interconnected digital twins to: create a human-machine interaction prompt based on LLMs, test the behavior of the system before the actual deployment on real hardware and create a real-time monitoring environment to visualize data gathered by the robot while operating.
Moreover, the research field of text-vision models is quite new, so there is still a lack of appropriate datasets to train such models. The idea is therefore to overcome this limitation by using digital twins to generate complex data in simulation that can be used to train AI models. In this way their robustness and accuracy can also be investigated and enhanced.

2. Schedule of the research activities

First academic year (planned)

	Description	Period	Activity abroad
Background and related work analysis	Survey on digital twins in autonomous robotics ● architectures and technologies ● implementation (best environments) Survey on multi-modal architectures for object-goal navigation	11/2024 02/2025	NO
Semantic representation	Study state-of-the-art deep-learning models for: ● semantic data gathering in robotic autonomy ● Structured semantic representation of complex environments during autonomous inspections ● Implementation of proprietary solution	02/2025 03/2025	NO
Text-vision navigation models	Multi-modal neural networks mixing perception data and natural language ● Complete preliminary results ● Improve model performance via data generation and re-training Target-driven predictive trajectory using transformers ● Extend model's ability to perceive complex behaviors ● Real hardware testing and optimization	03/2025 11/2025	YES Activity to be conducted with NASA JPL
Publications	1. Transformer-based systems for predictive trajectory in cluttered environments (conference: IROS)		

Second academic year (planned)

	Description	Period	Activity abroad
System implementation	Background analysis update Setup of first Digital Twin ● Legged and wheeled robotic platforms ● ROS Gazebo + transformation tree ● Automatic setup of different worlds and scenarios for complex data generation ● Implementation of cross-modal perception systems in simulation (camera, LiDAR, sonar) Implementation of first AI-model for LLM-based human-machine interaction	11/2025 06/2026	NO
Data gathering in simulation	Setup of different scenarios in simulation ● create a unique and large dataset to be open-sourced	06/2026 08/2026	YES Activity to be conducted with NASA JPL

	Model deployment ● test on software version of the digital twin Data acquisition		
Testing and optimization	Performance analysis ● Check the behavior of the robotic agent in simulation Model optimization ● Re-training using augmented data from digital twin in simulation	08/2026 11/2026	YES Activity to be conducted with NASA JPL
Publications	1. Text-vision architectures for object-goal navigation (conference: ICRA) 2. Survey on digital twins in robotic autonomy (conference: IROS or other) 3. Survey on multi-modal architectures for semantic-aware autonomous navigation (journal: RAL)		

Third academic year (planned)

	Description	Period	Activity abroad
System integration	Real-hardware implementation ● Setup perception and planning logic on real robotic platform Full system Digital twin connection ● Check full interaction between real and simulated robotic agents	11/2026 02/2027	YES Activity to be conducted with NASA JPL / Field AI for model deployment on Spot or Alpha
Performance analysis and optimization	Model structure and performance analysis ● Check real-world behavior ● Sym-to-real gap analysis Optimization via re-training ● Mix data gathered during real-world explorations with simulation data	02/2027 05/2027	YES Activity to be conducted with NASA JPL / Field AI
Testing	Full system testing ● Test the behavior of real-world and simulated agent in complex case scenarios ● (Optional) code optimization for performance constraints	05/2027 09/2027	YES Activity to be conducted with NASA JPL / Field AI
Thesis writing		06/2027 11/2027	YES
Publications	● Full system paper (journal: RAL or conference: ICRA)		

3. Training and research activities plan

First academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses	Numerical methods for Big Data	14/01/2025 13/02/2025	Yes	2
	Deep Learning	11/02/2025 20/02/2025	Yes	2
B. Master's degree courses	Sistemi elettronici digitali (1st module)	01/11/2024 31/12/2025	Yes	6
C. Soft skill courses				
D. Participation to seminars				
E. Participation to international congresses or workshops	2024 IEEE IHTC 1 day	27/11/2024 30/11/2024		1
	2025 IROS 3 days	19/10/2025 25/10/2025		3
F. Presentation of research products at international congresses or workshops	2024 IEEE IHTC Research work with post-lauream scholarship (already accepted for conference)	27/11/2024 30/11/2024		2
	2025 IROS Target-driven predictive trajectory using transformers	19/10/2025 25/10/2025		2
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			18
G. Individual research activity	Background & related work analysis ● AI models for semantic space representation ● Multi-modal navigation models (and object-goal) ● Digital twins in autonomous navigation	01/11/2024 31/03/2025		12 (300h)
	Implementation ● Transformer architectures for target-driven predictive trajectory ● Text-vision navigation	01/04/2025 31/10/2025		22 (550h)
				6 (150h)
H. Supervision of students				
I. Integrative teaching activities				
J. Preparation of manuscripts for conferences or journals	Transformer-based systems for predictive trajectory in cluttered environments (target: 2025 IROS + journal)	01/09/2025 31/10/2025		2 (50h)
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			42
	TOTAL OF ECTS			**60**

Second academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses	Linear and Nonlinear Kalman filtering: theory and applications	10/02/2026 18/02/2026	Yes	2
	Optimization theory	24/03/2026 07/04/2026	Yes	2
	Exploring latest cybersecurity technologies and trends	11/02/2026 18/02/2026	Yes	2
	Non-linear control	09/06/2026 20/06/2026	Yes	2
B. Master's degree courses				
C. Soft skill courses				
D. Participation to seminars	MIT Robotics seminar (5h) ● Multi-robot mission optimization			1.5
	Stanford Intelligent Systems seminar (5h) ● Partially Observable Markov Decision Process (POMDP) for path planning under uncertainty			1.5
E. Participation to international congresses or workshops	2026 ICRA 3 days	TBD		3
	2026 IROS (or other) 1 day	TBD		1
F. Presentation of research products at international congresses or workshops	2026 ICRA Text-vision architectures for object-goal navigation	TBD		2
	2026 IROS (or other) Survey on digital twins in robotic autonomy	TBD		2
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			19
G. Individual research activity	Update Background analysis ● Multi-modal navigation models ● Digital twins in autonomous navigation	01/11/2025 31/12/2025		5 (125h)
	Implementation ● Setup of first Digital twin (ROS gazebo + transformation tree) ● First version of multi-modal architecture incorporating LLMs	01/11/2025 31/05/2026		24 (600h)
	Data gathering ● Create open-source dataset with simulation data ● Model optimization	01/06/2026 31/07/2026		4 (100h)
	Testing and optimization	01/08/2026 31/10/2026		4 (100h)
H. Supervision of students				
I. Integrative teaching activities				
J. Preparation of manuscripts for conferences or journals	Text-vision architectures for object-goal navigation (target: ICRA) Survey on digital twins in robotic autonomy (target: IROS) Survey on multi-modal architectures for semantic-aware autonomous navigation (target: RAL)	01/01/2026 31/03/2026		4 (100h)
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			41
	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				
E. Participation to international congresses or workshops				
F. Presentation of research products at international congresses or workshops				
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			0
G. Individual research activity	Integration and testing ● Real-hardware implementation ● Sym-to-real gap analysis ● Full system integration (simulation and real robot) ● Performance analysis	01/11/2026 31/01/2027		16 (400h)
	System optimization ● Re-training using mixed data gathered via digital twin (simulation and real-world) Final testing	01/02/2027 31/08/2027		20 (500h)
	Thesis writing	01/06/2027 31/10/2027		20 (500h)
H. Supervision of students				
I. Integrative teaching activities				
J. Preparation of manuscripts for conferences or journals	Full system paper (target: RAL or ICRA)	01/07/2027 31/08/2027		4 (100h)
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			60
	TOTAL OF ECTS			**60**

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