NATIONAL PH.D. PROGRAM IN AUTONOMOUS SYSTEMS

Model-based condition monitoring, fault diagnosis and control of autonomous systems

Ph.D. candidate

Alessandro DI BIASE

Cycle

XXXIX

Tutors

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1. Description of the research program

Autonomous systems have numerous advantages, as efficiency without the presence of a human, high productivity thanks to a non-stop execution, reduction of cost in the long period, a better resource management. To make a system autonomous, it is necessary to measure or estimate information from the internal and external environment. Once the system knows its own state, and the state of what surrounds it, it has to be able to take decisions. Those decisions must be applied, and the system has to correctly execute them. The system must have accuracy and responsivity, thanks to kinematic and dynamic control. Least, the fault diagnosis has to observe the system behaviour and detect when maintenance is needed, as well as to accurately determine the issue at hand.

Moreover, systems are usually described by non-linear differential equations, so state-estimation, control techniques and fault-diagnosis are useful techniques to improve system's performance. For the acquisition level view point, if the state is not observable, advanced estimation techniques must be sightseen; for the high-level system control, advanced reasoning and planning solutions can be explored to overcome conventional approaches; for the low-level system control, non-linear optimal approaches can be further investigated. Furthermore, fault-diagnosis techniques could be considered and examined to enhance the reliability and safety.

The first key aspect of this research is the examination of the state of the art in the field of optimal control techniques for nonlinear systems, with a focus on state-dependent nonlinear approaches. The aim is to explore different techniques, to compare them, and to analyse the mathematical methods on which they are based.

Then, this research involves an in-depth analysis of the optimality conditions inherent to control solutions derived from non-linear state-dependent techniques. These optimality conditions can be used to evaluate the effectiveness, the efficiency, the performance and limitations of the control solutions developed.

Furthermore, the non-linear state-dependent control can be explored with a different approach: that is, a systematic approach. The aim is to enrich the understanding and potentially uncover novel insights that could significantly impact the non-linear control theory, e.g., by delving into the concepts of differential geometry.

In addition to the theoretical aspect, the practical implementation of control algorithms assumes high importance. This research also aims to address the preliminary analysis of the implementation techniques and numerical approximation methods that can be considered to develop application for real physic systems. These investigations must span both continuous and discrete-time domains. Also, model-based fault diagnosis must be implemented to increase the level of autonomy of the used devices.

The exploration of 'bio-inspired' reasoning methods for planning complex actions stands as a pioneering aspect of this research. Through the integration of machine learning, reinforcement learning, and state-dependent non-linear optimal control, this research seeks to unlock innovative strategies for real-world challenges.

Finally, possible solutions of state estimation solutions for non-linear systems will be also analysed and evaluated, whether new or existing. Indeed, it is also necessary to address the state estimation of the system state to be able to solve in real world scenario the non-linear state-dependent optimal control problems.

Through an initial exploration of the state of the art and subsequent research employing various approaches, this study aims to identify innovative and fundamental acknowledge for non-linear optimal control. At the same mode, the research seeks innovation in the estimation of missing information, high-level control related to decision-making, and fault diagnosis. Advancing these areas results in increased effectiveness and efficiency for autonomous systems, ultimately providing them with greater reliability.

2. Schedule of the research activities

First academic year (planned)

	Description	Period	Activity abroad
State of the art on non-linear state-dependent approaches, mathematical methods and properties for non-linear optimal control problems	This research activity can be divided in two main parts. The first one regards the review of the literature to develop a wide acknowledge and understanding on the non-linear state-dependent control technics. The theoretical exploration will include the analysis of different approaches, the mathematical methods that are used to support the proposed technics, the assumptions and necessary properties to consider for the proper utilization.	November 2023 – April 2024	NO
Analysis of the optimality conditions by control solutions derived from state-dependent approach	Optimal non-linear control does not yet have a valid solution for every system. In this research activity the solution of the optimal control for a generic system is searched with an analytic approach. During this analysis potential conditions and assumptions can be searched, so that to have validity for every system having same dimension. Moreover, these could result useful to establish theorems regarding the optimality, the stability and the convergency region of the identified solution. This activity is characterized by an approach with increasing difficulty: firstly, bidimensional system are to take into account, then the dimension of the used system could grow if results will be satisfactory.	May 2024 – October 2024	NO

Second academic year (planned)

	Description	Period	Activity abroad
Reinforcement of the theoretical acknowledge for the methodologies of proposed non-linear optimal control, with insights from differential geometry	The first research activity is to be complemented with a second theoretical exploration, focused on specific methodologies for the proposed non-linear control technique. These methodologies are characterized by a systemic approach and are less developed than more common ones, that are explored in the first research activity. These methodologies need to be identified and analysed to determine which aspects have already been developed and which can be further investigated to add value. In particular, the usefulness of differential geometry in deriving properties of state-dependent non-linear control is also investigated.	November 2024 – April 2025	NO
Analysis of implementation techniques and numerical	This research activity can be divided in two main parts. The first one regards the analysis of the implementation techniques to adopt for the application of the previously identified solution	May 2025 – October 2025	YES I am interested in planning this activity abroad

approximation, including discrete-time, of the developed algorithms, and development of solutions for systems with increased autonomy and insights of fault diagnosis	of the non-linear optimal control. Methods of numerical approximation can be investigated to search the best solution for the problem. The control has to be tested with a continuous-time and even discrete-time simulation. Aspects like execution time, evaluating of hardware and software resources are considered. In the second part, similarly, tests are executed on physics systems with high-level of autonomy. A ball-bot, an inverse pendulum, a scale reproduction of a vehicle, fixed and mobile robot arms are possible devices to consider for tests. Moreover, a model-based fault diagnosis can be exploited to increase the autonomy of the adopted device.		to carry out tests on additional devices beyond those available at the Polytechnical University of Marche

Third academic year (planned)

	Description	**Period**	**Activity abroad**
Exploration of 'bio-inspired' reasoning methods for planning complex actions using machine learning, reinforcement learning, and state-dependent nonlinear optimal control	Further reasoning methods are explored, centred on the ones “bio-inspired”. These methods are considered for the planning of complex actions. Possibles methods includes the employment of machine learning, reinforcement learning and non-linear state dependent optimal control.	November 2025 – April 2026	NO
Analysis and potential state estimation solutions for nonlinear systems with a state-dependent approach.	Non-linear state-dependent optimal control requires the state to be observable. If this condition is not guaranteed, which often occurs, it is necessary to develop a state estimator. State estimation techniques for non-linear systems are to be researched, taking into account the previously established assumptions and conditions. Additionally, existing estimators can be modified, adapting them to the context and ensuring that the conditions and assumptions of both are met.	May 2026 – October 2026	NO

3. Training and research activities plan

First academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses	Control for optimization	10 hours		1
	Optimization via extremum seeking	10 hours		1
	Introduction to Optimal Linear Quadratic Control	20 hours		2
	Game Theory for Controlling Autnomous Systems	20 hours		2
	Others			12
B. Master's degree courses				
C. Soft skill courses				
D. Participation to seminars				6
E. Participation to international congresses or workshops				
F. Presentation of research products at international congresses or workshops				
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			24
G. Individual research activity				
H. Supervision of students				
I. Integrative teaching activities				
J. Preparation of manuscripts for conferences or journals				
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			36
	TOTAL OF ECTS			**60**

Second academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses				18
B. Master's degree courses				
C. Soft skill courses				
D. Participation to seminars				6
E. Participation to international congresses or workshops				
F. Presentation of research products at international congresses or workshops				

	TOTAL OF ECTS FOR TRAINING ACTIVITIES			24
G. Individual research activity				
H. Supervision of students				
I. Integrative teaching activities				
J. Preparation of manuscripts for conferences or journals				
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			36
	TOTAL OF ECTS			**60**

Third academic year (planned)

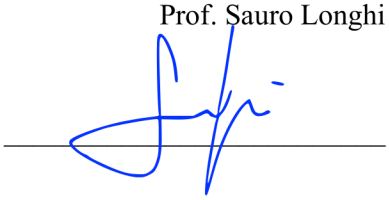
	Description	**Period**	**Final Exam**	**ECTS**
A. Ph.D. courses				
B. Master's degree courses				
C. Soft skill courses				
D. Participation to seminars				
E. Participation to international congresses or workshops				
F. Presentation of research products at international congresses or workshops				
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			10
G. Individual research activity				
H. Supervision of students				
I. Integrative teaching activities				
J. Preparation of manuscripts for conferences or journals				
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			50
	TOTAL OF ECTS			**60**

4. List of the publications written by the candidate in the triennium

Alessandro Di Biase

Alessandro Di Biase

Prof. Sauro Longhi



Prof. Andrea Bonci