Decision and Control Techniques for Intelligent Diagnostics and Surgery Using Digital Twins

Ph.D. candidate

Michela PRUNELLA

Cycle

XXXVIII

Tutors

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1. Description of the research program

The research program aims at the development of Intelligent and Autonomous Systems for diagnosis and precision surgery by creating a biological Digital Twin from the elaboration of biomedical data, signals, images and videos. This model may include the anatomical three-dimensional reconstruction and detailed data collected along the health journey of the patient in a growing data set where these informations are dynamically updated. Thus, information from different sources can be correlated to find larger patterns.

In clinical medicine, Machine and Deep Learning methods and techniques require specific algorithms and frameworks for the identification of meaningful patterns, for robust and accurate explanation and for multidisciplinary interpretability. The verification of models is expected to be treated by using data-driven approaches based on an adaptive Digital Twin of the patient. In so doing, image-guided surgical systems can be used in the phases of planning, simulation and test with robotic guidance. Furthermore, healthcare professionals would have all the relevant information at their disposal to make an accurate diagnosis and start the right therapeutic measures for the patient's personal treatment path.

The Digital Twin will be used to define surgery planning technique, based on advanced control methods such as the model predictive control (MPC), so that the operation could be practiced and optimized beforehand, and referenced during the operation to verify anatomy and avoid inadvertent damage to structures. Moreover, model-based predictive control offers great potential for computer-assisted diagnosis (e.g., for early and accurate diagnosis, supported by observed or explainable statistical patterns) and treatment planning through optimization of controllable treatment outcomes, providing quantifiable decision-making.

Advanced image analysis presents an opportunity for high-throughput mapping of genotype-phenotype associations in three dimensions (3D); the processing of images is used to construct a three-dimensional mesh of the organ surfaces where conventional phenotyping, relying on manual analysis, reduce the variables of interest to global volumes and mass. Instead, computational image analysis, by which Machine Learning is used to annotate and segment the images, gains traction as a means of representing detailed 3D phenotypic variation in a standardized and co-registered coordinate space. Phenotypic parameters, such as wall thickness, tumor mass and blood vessel anastomosis are derived from the model as diagnostic and prognostic indices correlated (e.g., to protein level expression) with patho-physiological states or pharmacological treatment; hence, a more powerful approach may be to derive a statistic expressing evidence as explicit model relating genotype to phenotype, hence creating a so-called statistical parametric map.

Among these methods, fluorescence-based tumor imaging (e.g., with Indocyanine green (ICG) contrast agent) is a valuable method in early cancer detection and in minimally invasive image-guided surgical procedures; for these reasons, it could be applied to endoscopic and laparoscopic systems.

A systematic approach is needed in the context of Systems Engineering, notably in electronic and information bioengineering and automation. Moreover, methods for the assessment in surgery such as dexterity analysis, motion tracking, real-time segmentation of surgical instruments and tools from intraoperative images or video, along with virtual reality simulators would be developed as a task trainer in which a baseline set of metrics from education, training, evaluation and research in the technical aspects of surgical and procedural skills can be measured.

2. Schedule of the research activities

First academic year (planned)

	Description	Period	Activity abroad
Study of Intelligent Frameworks for Image processing	Analysis and review of Machine and Deep Learning Algorithms for image processing and diagnostics.	6 months	NO
Study of tools for 3D anatomical rendering	Semantic Segmentation, Classification and Detection of objects of interest. Feature extraction and selection.	3 months	NO
Study about Model Predictive Controls	Methods of automation for performance verification and control modification for the digital twin model for clinical diagnosis and treatment optimization.	3 months	NO

Second academic year (planned)

	Description	Period	Activity abroad
Study of multi-omics sciences integrated into biomedical imaging workflows	Study of multi-omics synergies into Support Decision Systems for predictive diagnosis and therapy planning. Approaches of Systems Biology combining quantitative and high-throughput experimental techniques with computational models.	6 months	YES, University of Edinburgh School of Engineering and Bioengineering Research Institute
Robotics and Surgical guidance	Integration of image-planned surgery with autonomous supervision and control.	4 months	NO
Adding clinical value through technologies	Enabling technologies and tools in model management.	0.5 month	NO
Laboratory activities on Code Programming	Improvement of programming skills in C++, Python, MATLAB.	1.5 months	NO

Third academic year (planned)

	Description	Period	Activity abroad
Experimental validation of new solutions regarding biological and medical use-cases	Implementation of prototypical and advanced solutions on the patient Digital Twin. Holistic and fine-grained statistics and analytics on the state-of-the-art research of the digital twin.	12 months	NO

3. Training and research activities plan

First academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses	Analisi, Controllo e Ottimizzazione di Sistemi Biologici	Feb - Jun 2023	Yes	6
	Research Methodology	Jen - Feb 2023	Yes	2
	Industry 4.0: Optimization, Control and Security	Jen - Feb 2023	Yes	2
B. Master's degree courses	Data Model Identification and Intelligent Control	Nov 2022 - Jen 2023	Yes	6
	Model Predictive Control (Alti Studi di Lucca, Bemporad)	April 2023	Yes	2
C. Soft skill courses	POLIBA Soft skill - Training academy	Dec 2023	Yes	3
D. Participation to seminars	Cycle of seminars on Industry 4.0: Digital Twin – Siemens and Masmec	2023		2
E. Participation to international congresses or workshops				
F. Presentation of research products at international congresses or workshops				
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			**23**
G. Individual research activity				20
H. Supervision of students				
I. Integrative teaching activities				7
J. Preparation of manuscripts for conferences or journals				10
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			**37**
	TOTAL OF ECTS			**60**

Second academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses	Applications of MATLAB	Jun-July 2024	Yes	2
	Stochastic approaches in Systems Biology	January-February 2024	Yes	1.5
	Medical Robotics	Mar – Jun 2024	Yes	6
	Analysis and control of cyber-physical systems	2024	Yes	3
B. Master's degree courses				
C. Soft skill courses	C1 English Preparation	Oct 2023		
D. Participation to seminars	Modeling and simulation of biological and medical systems	Oct-Dec 2023	Yes	3
E. Participation to international congresses or workshops	Seasonal course: From minimally invasive surgery to nanorobotics. A voyage in the field of intervention robotics (Sant'Anna Pisa)	June 2024		5
F. Presentation of research products at international congresses or workshops				
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			**20.5**
G. Individual research activity				20
H. Supervision of students				3
I. Integrative teaching activities				6.5
J. Preparation of manuscripts for conferences or journals				10
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			**39.5**
	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	Artificial Intelligence and Robotics			5
E. Participation to international congresses or workshops	TBD			5
F. Presentation of research products at international congresses or workshops	TBD			5
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			**15**
G. Individual research activity				20
H. Supervision of students				5
I. Integrative teaching activities				5
J. Preparation of manuscripts for conferences or journals				15
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			**45**
	TOTAL OF ECTS			**60**

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