RESEARCH CENTRE

Inria Centre at the University of Lille

IN PARTNERSHIP WITH:

Ecole Centrale de Lille, CNRS, Université de Lille

2024

ACTIVITY REPORT

Project-Team

DEFROST

DEFormable Robotics SofTware

IN COLLABORATION WITH: Centre de Recherche en Informatique, Signal et Automatique de Lille

DOMAIN

Perception, Cognition and Interaction

THEME

Robotics and Smart environments

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Project-Team DEFROST

Creation of the Project-Team: 2017 November 01

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B9.2. – Art

1 Team members, visitors, external collaborators

Research Scientists

- Gang Zheng [Team leader, INRIA, Researcher, from Jul 2024]
- Christian Duriez [Team leader, INRIA, Senior Researcher, until Jun 2024]
- Quentin Peyron [INRIA, Researcher]

Faculty Members

- Yinoussa Adagolodjo [UNIV LILLE, Associate Professor]
- Jérémie Dequidt [UNIV LILLE, Professor]
- Alexandre Kruszewski [CENTRALE LILLE, Professor]

Post-Doctoral Fellow

- Felix Vanneste [INRIA, Post-Doctoral Fellow, until Apr 2024]

PhD Students

- Antoine Alessandrini [UNIV LILLE, from Oct 2024]
- Paul Chaillou [INRIA]
- Agneyan Dileep [UNIV LILLE]
- Yiru Guo [CSC Scholarship]
- Xin Li [CSC Scholarship, from Oct 2024]
- Weizhe Liu [CSC Scholarship, from Oct 2024]
- Luis Fernando Maldonado Saavedra [INRIA, from Nov 2024]
- Tanguy Navez [UNIV LILLE, until Aug 2024]
- Azouaou Ouyoucef [INRIA]
- Flavie Przybylski [CARANX MEDICAL, CIFRE]
- Sizhe Tian [UNIV LILLE]
- Lingxiao Xun [INRIA, until Feb 2024]
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Technical Staff

- Alexandre Bilger [INRIA, Engineer]
- Maxence Corailler [INRIA, Engineer, from Oct 2024]
- Damien Marchal [CNRS]
- Thor Enrique Morales Bieze [Inria, Engineer, until Mar 2024]
- Thomas Moupfouma [INRIA, Engineer, from Feb 2024]
- Samuel Mohsen Hanna Youssef [INRIA, Engineer, until Sep 2024]

Interns and Apprentices

- Antoine Alessandrini [INRIA, Intern, from Apr 2024 until Sep 2024]
- Yoan Arnaud [CENTRALE LILLE, Intern, until Feb 2024]
- Louis Derambure [ICAM, Intern, from Jun 2024 until Jul 2024]
- Nathanael Haas [INRIA, Intern, from Apr 2024 until Sep 2024]
- Mohamed Said Aimen Lamri [CENTRALE LILLE, Intern, from Apr 2024 until Aug 2024]
- Thibaud Piccinali [INRIA, Intern, until Apr 2024]
- Ziyi Wei [INRIA, Intern, from May 2024 until Sep 2024]
- Anaelle Wiersch [INRIA, Intern, from Jul 2024 until Aug 2024]

Administrative Assistant

- Anne Rejl [INRIA]

Visiting Scientists

- Benjamin MAUZE [ENIT Tarbes, from Jun 2024 until Jul 2024]
- Xin Xu [Hong Kong Polytechnic University, from Mar 2024 until Aug 2024, Visiting PhD student]

2 Overall objectives

The team DEFROST aims to address the open problem of control, modelling and design methods for deformable robots by answering the following challenges:

- Providing numerical methods and software support to reach the real-time constraint needed by robotic systems: the numerical solutions for the differential equations governing the deformation generate tens of thousands degrees of freedom, which is three orders of magnitude of what is frequently considered in classical methods of robotic modelling and control.
- Integrating deformation models in the control methods of soft robots: In soft-robotics, sensing, actuation and motion are coupled by the deformations. Deformable models must be placed at the heart of the control algorithm design.
- Investigating predictable interaction models with soft-tissues and parameter estimation by visual feedback from medical imaging: on the contrary too many cases in surgical robotics, the contact of the soft robot with the anatomy is permitted and it creates additional deformations on the robot.
- Developing generic design methodologies for soft robotic systems to obtain desired performances in terms of motion and generated forces: the design-space of a soft robot is usually composed of a large number of parameters of different nature (geometry, mechanical properties, actuator and sensor location) and which have a coupled and non-linear effect in the robot behavior.

3 Research program

3.1 Introduction

Our research crosses different disciplines: numerical mechanics, control design, robotics, optimisation methods and clinical applications. Our organisation aims at facilitating the team work and cross-fertilisation of research results in the group. We have three objectives (1, 2 and 3) that correspond to the main scientific challenges. In addition, we have two transverse objectives that are also highly challenging: the development of a high-performance software support for the project (Objective 4) and the validation tools and protocols for the models and methods (Objective 5).

3.2 Objective 1: Accurate model of soft robot deformation computed in finite time

The objective is to find concrete numerical solutions to the challenge of modeling soft robots with strong real-time constraints. To solve continuum mechanics equations, we will start our research with real-time Finite Element Method (FEM) or equivalent methods that were developed for soft-tissue simulation. We will extend the functionalities to account for the needs of a soft-robotic system:

- Coupling with other physical phenomenons that govern the activity of sensors and actuators (hydraulic, pneumatic, electro-active polymers, shape-memory alloys, etc.).
- Fulfilling the new computational time constraints (harder than surgical simulations for training) and find a better tradeoff between cost and precision of numerical solvers using reduced-order modeling techniques with error control.
- Exploring interactive and semi-automatic optimisation methods for design based on obtained solutions for fast computations on soft robot models.

3.3 Objective 2: Model based control of soft robot behavior

The focus of this objective is on obtaining a generic methodology for soft robot feedback control. Several steps are needed to design a model based control using FEM approach:

- The fundamental question of the kinematic link between actuators, sensors, effectors and contacts using the most reduced mathematical space must be carefully addressed. We need to find efficient algorithms for real-time projection of non-linear FEM models in order to pose the control problem using the only relevant parameters of the motion control.
- Intuitive remote control is obtained when the user directly controls the effector motion. To add this functionality, we need to obtain real-time inverse models of the soft robots by optimisation. Several criteria will be combined in this optimisation: effector motion control, structural stiffness of the robot, reduce the intensity of the contact with the environment, etc.
- Investigating closed-loop approaches using sensor feedback: as sensors cannot monitor all points of the deformable structure, the information provided will only be partial. We will need additional algorithms based on the FEM model to obtain the best possible treatment of the information. The final objective of these models and algorithms is to have robust and efficient feedback control strategies for soft robots. One of the main challenges here is to ensure / prove stability in closed-loop.

3.4 Objective 3: Modeling interaction with a complex environment

Even if the inherent mechanical compliance of soft robots makes them safer, more robust and particularly adapted to interaction with fragile environments, the contact forces need to be controlled by:

- Setting up real-time modeling and the control methods needed to pilot the forces that the robot imposes on its environment and to control the robot deformations imposed by its environment. Note that if an operative task requires to apply forces on the surrounding structures, the robot must be anchored to other structures or structurally rigidified.
- Providing mechanics models of the environment that include the uncertainties on the geometry and on the mechanical properties, and are capable of being readjusted in real-time.
- Using the visual feedback of the robot behavior to adapt dynamically the models. The observation provided in the image coupled with an inverse accurate model of the robot could transform the soft robot into sensors: as the robot deforms with the contact of the surroundings, we could retrieve some missing parameters of the environment by a smart monitoring of the robot deformations.

3.5 Objective 4: Soft Robotics Software

Expected research results of this project are numerical methods and algorithms that require high-performance computing and suitability with robotic applications. There is no existing software support for such development. We propose to develop our own software, in a suite split into three applications:

- The first one will facilitate the design of deformable robots by an easy passage from Computer-Aided Design (CAD) software (for the design of the robot) to the FEM based simulation.
- The second one is an anticipative clinical simulator. The aim is to co-design the robotic assistance with the physicians, thanks to a realistic simulation of the procedure or the robotic assistance. This will facilitate the work of reflection on new clinical approaches prior any manufacturing.
- The third one is the control design software. It will provide real-time solutions for soft robot control developed in the project.

3.6 Objective 5: Validation and application demonstrations

The implementation of experimental validation is a key challenge for the project. On one side, we need to validate the model and control algorithms using concrete test case examples in order to improve the modeling and to demonstrate the concrete feasibility of our methods. On the other side, concrete applications will also feed the reflections on the objectives of the scientific program.

We will build our own experimental soft robots for the validation of objectives 2 and 3 when there is no existing “turn-key” solution. Designing and making our own soft robots, even if only for validation, will help the setting-up of adequate models.

For the validation of Objective 4, we will develop “anatomical soft robot”: soft robot with the shape of organs, equipped with sensors (to measure the contact forces) and actuators (to be able to stiffen the walls and recreate natural motion of soft-tissues). We will progressively increase the level of realism of this novel validation set-up to come closer to the anatomical properties.

4 Application domains

4.1 Industry

Robotics in the manufacturing industry is already widespread and is one of the strategies put in place to maintain the level of competitiveness of companies based in France and to avoid relocation to cheap labor countries. Yet, in France, it is considered that the level of robotization is insufficient, compared to Germany for instance. One of the challenges is the high investment cost for the acquisition of robotic arms. In recent years, this challenge has led to the development of “generic” and “flexible” (but rigid) robotic solutions that can be mass produced. But their applicability to specific tasks is still challenging or too costly. With the development of 3D printing, we can imagine the development of a complete opposite strategy: a “task-specific” design of robots. Given a task that needs to be performed by a deformable robot, we could optimize its shape and its structure to create the set of desired motions. A second important aspect is the reduction of the manufacturing cost: it is often predicted that the cost of deformable robots will be low compared to classical rigid robots. The robot could be built on one piece using rapid prototyping or 3D printers and be more adapted for collaborative work with operators. In this area, using soft materials is particularly convenient as they provide a mass/carried load ratio several orders of magnitude higher than traditional robots, highly decreasing the kinetic energy thus increasing the motion speed allowed in the presence of humans. Moreover, the technology allows more efficient and ergonomic wearable robotic devices, opening the option for exo-skeletons to be used by human operators inside the factories and distribution centers. This remains to be put in place, but it can open new perspectives in robotic applications. A last remarkable property of soft robots is their adaptability to fragile or tortuous environments. For some particular industry fields (chemistry, food industry, etc.) this could also be an advantage compared to existing rigid solutions. For instance, the German company festo, key player in the industrial robotics field, is experimenting with deformable trunk robots that exhibit great compliance and adaptability, and we are working on their accurate control.

4.2 Personal and service robotics

Personal and service robotics are considered an important source of economic expansion in the coming years. The potential applications are numerous and in particular include the challenge of finding robotic solutions for active and healthy aging at home. We plan to develop functional orthosis for which it is better not to have a rigid exoskeleton that is particularly uncomfortable. These orthosis will be ideally personalized for each patient and built using rapid prototyping. On this topic, the place of our team will be to provide algorithms for controlling the robots. We will find some partners to build these robots that would fall in the category of "wearable robots". With this thematic we also connect with a strong pole of excellence of the region on intelligent textiles (see Up-Tex) and with the strategic plan of INRIA (Improving Rehabilitation and Autonomy).

4.3 Entertainment industry and arts

Robots have a long history with entertainment and arts where animatronics have been used for decades for cinematographic shootings, theater, amusement parks (Disney's audio-animatronic) and performing arts. This year, we obtained an award for an Art Installation at the Exhibit Panorama 22. The installation "L'Érosarbénus", which was produced at Le Fresnoy for the exhibition Panorama 22, is a collaboration between visual artist Yosra Mojtahedi and DEFROST. This installation, whose aesthetics are inspired by rocky, plant and human forms, is brought to life with the help of Soft Robotics devices. It was awarded the prize "Révélation Art Numérique — Art Vidéo 2020" by the ADAGP. See the ARTE video.

4.4 Medical Applications

Soft robots have many medical applications as their natural compliance make them safer than traditional robots when interacting with humans. Such robots can be used for minimally invasive surgery, to access and act on remote parts of the body through minimal incisions in the patient. Applications include laparascopic and brain surgery, treatment of several cancers including prostate cancer, and cardiology, for example percutaneous coronary interventions. As an example, we received an industry grant (CIFRE) with Robocath to work on autonomous catheter navigation. See Section 9.

Another application is cochlear implant surgery in the project ANR ROBOCOP.

5 Social and environmental responsibility

The team fully endorses the needs for an increased integration of social and environmental responsibility and seeks to align with the 17 Sustainable Development Goals laid out by the United Nations. The team also acknowledges the Net Zero target of the 2050 Paris agreement and is working either on its practices as well as on its scientific objectives to align with the 2030's intermediate GhG emission roadmap.

In terms of social responsibility, the team wants to point out that environmental concerns were mentioned by postdocs, graduated PhD students and visiting master students regarding theirs willingness to make or not a scientific career. This increased expression is something we should pay attention to and for which building a shared vision and clear actions and message is important not only for the team but also for our scientific community and more generally Inria.

This is why, in addition to the best practices recommended by Inria, the team supports the actions put in place either by other teams individuals or collectives as the "Ma Petite Planète" challenge organized by the Staff Organization (AGOS).

5.1 Footprints of research activities

The CRIStAL laboratory and the University of Lille account for their GHG emissions. The CRIStAL accounting is done by Damien Marchal, member of DEFROST. This gives us an overview of our current footprint, which is probably quite common for a research and technology oriented team. Travel, commuting, office occupancy, hardware equipment and operation are the most significant elements of our footprint. The results were presented and discussed during one of our team meeting. In the following are presented our activities for the elements where clear direction and actions have been taken.

5.1.1 Traveling

In terms of traveling, we are following the Inria general travel policy. We are also adopting a frontrunner approach and encourage team members to adopt the more ambitious flyless guide produced by the Inria MakeSenS initiative.

Currently we:

- favor visio-conferencing whenever possible and beneficial,
- choose alternative modes of transportation to flying. Our analysis shows that destination reachable by a train travel bellow 8h allows to reach maximum efficiency in GES emission reduction while still being manageable if the alternative is comfortable high-speed train.
- strategically select the workshop and conferences location we attend to reach the best scientific impact, scientific community building while reducing the transportation footprint.

5.1.2 Daily commuting

With other laboratories from the University of Lille, the team is actively promoting for more sustainable commuting practices and is participating to local initiatives or national ones like being part of the Inria AGOS's team at the national challenge MaiAVélo. In 2024, all Inria centers participated to this event as well as a continuously increased amount of research institutions in France (universities, research institutes, cnrs). In addition, Damien Marchal, member of the team is co-animator of the mobility workgroup for University of Lille. His activities include support for the statistical analysis updates of the University of Lille commuting practices and commuting plans. In 2023 he took part, as a coordinator of the University of Lille workgroups in charge of proposing a sustainability roadmap. The resulting document was voted in June 2023. 2024 and 2025 should be the begining of its implementation.

Finally we also make sure that the team members are informed of the transportation allowances at Inria and favoring sustainability among which the "Forfait Mobilité Durable" and the public transportation allowance.

5.1.3 Sharing objectives externally

The team, not only encourages its members to adhere to the highest practice standard but also to adopt a frontrunner position. This includes sharing our objectives and ambitions with peers and research community (eg: having one slide related to footprint in the team presentations slides). In 2023 and 2024, the CRIStAL laboratory organized several sessions "Fresque du climat" and "Fresque du Numérique" to its members and EP's. In 2023, Damien Marchal, from our team, set up a new master course at University of Lille for computer science students. This master is titled "Enjeux Environmentaux et Société" (society and sustainability). After a general introduction to climate, biodiversity, energy and resources issues, in-depth presentations, strongly relying on Inria members' expertise, have been done including:

- D. Marchal (DEFROST): Climate modeling and simulation.
- D. Marchal (DEFROST): Ghg accounting.
- A. Luxey (SPIRALS): ACV analysis for strategic decision taking.
- S. Cerf (SPIRALS): ACV analysis for strategic decision taking.
- R. Rouvoy (SPIRALS): measuring the environmental impacte of software and IT.
- D. Debarbieux (Norsys, alumni of LINKS): .
- P. Marquet (University of Lille): Good practices as an IT manager and EcoInfo.

These courses were continued in 2024.

5.2 Impact of research results

The team hopes to tackle ecology-oriented research problems related to soft robotics in the near future. Since 2022, we are setting up the research environment to do so, leading to first results in late 2024 and early 2025.

Quentin Peyron, has been hired which research plan focuses on the development of industrial soft robots with a low ecological footprint. The main concept is to leverage the inherent compliance of untransformed plant-based elements, such as wicker branches and bamboo stems, to fabricate soft manipulators with minimal energy consumption and CO2 emission. The research plan also includes the development of new physical architectures, models and control laws to minimize soft robot's energy consumption once online.

Three projects were initiated. First, the team applied and received a BQR grant from Centrale Lille (9500€) for the design and fabrication of a first prototype of eco-designed soft manipulator. Second, it is involved in the PEPR O2R AS1 with a work-package on the eco-design of soft manipulators using wicker and bamboo. This project led to recruiting a new PhD student, Luis Maldonado, who started in November 2024. Third, 12 students from Centrale Lille have been asked to work during four semesters on the design, the characterization and the life cycle analysis of a soft robot fabricated with raw potato material. The goal of this project is to fabricate a lab prototype of bio-sourced robot degrading fast in time, to develop design and control methologies which are robust to these degradations.

6 Highlights of the year

6.1 Summer school "Deformations in Robotics 2024"

The team organized the second edition of the summer school "Deformations in Robotics". This school aims at giving theoretical and practical tools to international young researchers to deal with deformations in robotics at all level (manipulation of deformable objects, soft robotics, etc...). This year the school was largely funded by the PEPR O2R project, giving the opportunity to show and promote the different links between deformable robotics and human sciences, art and design.

6.2 Compliance Robotics Start-up Creation

Compliance Robotics was founded in February 2024 to leverage the groundbreaking research of the DEFROST team in the field of soft robotics. Building on the momentum generated by the i-PhD award received in 2023 by E. Coevoet and one year in the startup studio, which helped initiate the project, the team achieved further recognition by winning the prestigious i-Lab award from BPI. This distinction highlights the innovative potential of Compliance Robotics in advancing soft robotics technology and bringing it closer to real-world applications.

6.3 Open Science Award for SOFA

Presented by the French Ministry of Higher Education and Research, the Open Science Awards for Open Source Software in Research recognize research projects and teams working to develop and promote open source software, thereby contributing to the creation of a vital common good. These awards recognize the production of open source software as a contribution and a result of research. By highlighting remarkable or particularly promising software, these awards aim to inspire both the scientific community and society as a whole.

6.4 DEFROST new team leader

Gang Zheng took the responsability of the DEFROST team in July 2024, continuing the global objectives of his predecessor of pursuing impactfull and quality research in soft robotics modeling, design and control, while promoting open science.

7 New software, platforms, open data

7.1 New software

7.1.1 SoftRobots

Name: SoftRobots plugin for Sofa

Keywords: Numerical simulations, Problem inverse, Soft robotics

Functional Description: Modelling, simulation and control of soft robots. This plugin allows the modeling of deformable robots in the Sofa platform. It allows the modeling of different actuators, such as cable, pneumatic pressure, hydraulics and other simpler types of actuation. It also contains useful tools for animation design or communication with the robot. Coupled with the SoftRobots.Inverse plugin, it also allows the control of these robots. More information can be found on the dedicated website.

URL: `https://project.inria.fr/softrobot/`

Publication: hal-01649355

Contact: Christian Duriez

Participants: Christian Duriez, Olivier Goury, Jérémie Dequidt, Damien Marchal, Eulalie Coevoet, Felix Vanneste

Partner: CRIStAL

7.1.2 Model Order Reduction Plugin for SOFA

Name: Model Order Reduction Plugin for SOFA

Keywords: Model Order Reduction, Sofa, Finite element modelling

Scientific Description: This plugin allows speed-up of SOFA simulations by providing tools to create a reduced version of the SOFA simulation that runs at much higher rates but remains accurate. Starting with a snapshot of the object deformations on a high-dimensional Finite Element mesh, Proper Orthogonal Decomposition (POD) is used to compute a reduced basis of small dimension representing correctly all the possible deformations of the object. The original system describing the object motion is then greatly reduced. To keep numerical efficiency, a hyper-reduction method is used to speed-up the construction of the reduced system.

Functional Description: This plugin allows to dramatically reduce computational time in mechanical simulation in the SOFA framework. A reduced simulation, of much smaller dimension but still accurate is created in an automatic way by the plugin. Building the reduced model may take time, but this operation is made once only. The user can then benefit from a reduced and interactive version of his/her simulation without significant loss of accuracy.

Release Contributions: This is the first version of the plugin.

URL: `https://project.inria.fr/modelorderreduction/`

Publication: hal-01834483

Contact: Olivier Goury

Participants: Olivier Goury, Felix Vanneste, Christian Duriez, Eulalie Coevoet

7.1.3 SoftRobots.Inverse

Name: SoftRobots.Inverse

Keywords: Sofa, SoftRobots

Scientific Description: This plugin implements a method to compute the inverse model of a robot in its environment. The input of the method is the desired position of the effector. The output is the force or the motion that needs to be applied to the actuators in order to minimize the distance with the effector position. This is found by minimizing the constraint equation using Quadratic Programming (QP), i.e. minimizing the violation of the defined constraints.

Functional Description: This plugin builds on the plugin SoftRobots. Inside the plugin, there are some constraint components that are used to describe the robot (effectors, actuators, sensors). An optimisation algorithm is provided to find the efforts to put on actuators in order to place the robot in the closest possible configuration to the one described by “effectors”, or to a state described by “sensors”. This method used to control the soft robots in the task space is patented.

URL: https://project.inria.fr/softrobot

Publications: hal-01425349, hal-01649355

Contact: Christian Duriez

Participants: Christian Duriez, Eulalie Coevoet

Partner: CRIStAL

7.1.4 SofaPython3

Name: SofaPython3

Keywords: Python, Numerical simulations, Sofa

Functional Description: This plugin allows to use Sofa as a library from any python3 program. It also allows to write new mechanical component for a Sofa simulation in python3.

Release Contributions: Python3 and SOFA are meeting in one plugin: SofaPython3. In 2020, the integration of this plugin within SOFA opens up new perspectives. Not only can a SOFA simulation be described using a Python script with the embedded Python interpreter, but one or several SOFA instances can now created from a Python environment. Even more powerful, you can create new components (e.g. forcefields) in Python using the bindings provided in the plugin. Python-scripted simulations have no limit anymore!

URL: https://sofapython3.readthedocs.io/en/latest/

Contact: Hugo Talbot

Participants: Jean-Nicolas Brunet, Damien Marchal, Bruno Marques, Thierry Gaugry, Frédérick Roy, Guillaume Paran, Hugo Talbot

Partner: CRIStAL

7.1.5 Cosserat plugin

Keywords: Physical simulation, Finite element modelling, Soft robotics, Needle insertion, Frictional contact

Functional Description: An open-source plugin, designed to be compatible with the Sofa framework, facilitates the simulation of 1D objects. Specifically, it caters to the modeling of both rigid and flexible 1D entities, like rods, wires or needles, using the Cosserat beam theory. In this context, we have outlined a range of potential applications for this plugin. If you wish to explore its functionality, you have the flexibility to construct scenes using Python or XML, or you can take it a step further by developing new C++ components. We also welcome contributions from the community to enhance and expand the capabilities of this plugin.

Description related to Soft-body modeling

The Cosserat model has found applications in the realm of continuum robotics, particularly for simulating the deformation of robot bodies with geometries and mechanical properties akin to rods. This model aligns closely with the dynamic deformation patterns exhibited by soft manipulators, as it can effectively replicate nonlinear deformations encompassing bending, torsion, extension, and shearing.

One distinctive feature of Cosserat's theory, within the domain of continuous media mechanics, lies in its conceptualization: it views each material point of an object as a rigid body with six degrees of freedom (three translations and three rotations). In contrast, many other models in continuum media mechanics tend to treat material points as particles with only three translation degrees of freedom.

When modeling linear structures, this framework enables the creation of a structure closely resembling articulated solids, consisting of a series of rigid bodies whose relative positions are defined by their strain states. Consequently, this model serves as a versatile tool for modeling and controlling a variety of systems, including concentric tube robots, continuum robots driven by cables, or pneumatic soft robots with constant cross-sections.

Go into theoretical part of the plugin [Theory](docs/text/Theory.md)

Follow the tutorial : [cosserat_tutorial](docs/text/cosserat_tutorial.md)

URL: `https://www.sofa-framework.org/applications/plugins/cosserat-beam-cable-needle/`

Publication: hal-03192168

Contact: Christian Duriez

7.1.6 SofaGym

Keywords: Plugin SOFA, Reinforcement learning, SoftRobots

Functional Description: Software toolkit to easily create an OpenAI Gym environment out of any SOFA scene. The toolkit provides an API based on the standard OpenAI Gym API, allowing to train classical Reinforcement Learning or Planning algorithms.The toolkit also comprises example scenes based on the SoftRobots plugin for SOFA to illustrate how to include SOFA simulations and train learning algorithms on them.

URL: `https://github.com/SofaDefrost/SofaGym`

Publication: hal-03778189

Contact: Christian Duriez

Partner: CRIStAL

7.1.7 SofaCUDALinearSolver

Keywords: Plugin SOFA, Sofa, GPU, CUDA, Linear Systems Solver

Functional Description: A plugin for SOFA providing direct linear solver on GPU. The implementation is based on CUDA and the cuSolver library.

URL: https://www.sofa-framework.org/applications/plugins/cuda-gpu-computing/

Contact: Alexandre Bilger

7.1.8 SofaGLFW

Name: Simple GUI for SOFA, based on GLFW

Keywords: GUI (Graphical User Interface), Plugin SOFA, Sofa

Functional Description: Integration of GLFW is automatic (automatic fetching and integration with CMake), and linked statically.

This GUI is launchable with the standard runSofa, or can be used with a (provided) stand-alone executable runSofaGLFW (which needs much less dependencies than runSofa)

Lastly, this GUI was designed to support multiple windows in the same time and multiple simulations.

By default, SofaGLFW does not show any user interface. Only the keyboard allows limited interactions with the simulation. That is why a user interface based on Dear ImGui is provided.

Integration of Dear ImGui is automatic (automatic fetching and integration with CMake), and linked statically.

URL: https://www.sofa-framework.org/applications/plugins/modern-gui-using-glfw/

Contact: Alexandre Bilger

7.1.9 Python Sensor Characterization Plateform

Name: Python Sensor Characterization Plateform

Keywords: Python, 3D printing, Sensor Calibration

Functional Description: This platform is designed to synchronize the displacement of 3D Printer with the sensor measurement,and evaluate the performance of the sensors by calculating characteristics such as the hysterisis,linearity, and plotting the calibration curves of sensors.

URL: https://github.com/SofaDefrost/Sensor_Characterization_Plateform

Contact: Yehya Sharif

7.1.10 STLIB

Name: SOFA Template Library

Keyword: Plugin SOFA

Functional Description: Sofa scenes emplates. Contains common scene patterns used regularly to make the writing of scene with Sofa easy. The templates should be compatible with .pyscn and PSL scenes. The library also contains cool utility functions we should always consider to use.

URL: https://stlib.readthedocs.io/

Contact: Damien Marchal

Partner: CRIStAL

7.1.11 Python 3D Toolbox for Realsense

Keywords: Mesh, Point cloud, 3D

Functional Description: This repository provides a set of Python scripts useful for 3D file processing, particularly for files obtained using Realsense depth cameras. It includes an acquisition_realsense.py file for capturing and recording with a Realsense camera, as well as a functions folder containing a collection of processing functions (point cloud, ply, pixels...) and a subfolder utils containing some other useful functions.

URL: https://github.com/SofaDefrost/Python_3D_Toolbox_for_Realsense

Contact: Paul Chaillou

Partner: CRIStAL

7.1.12 SoftRobots.DesignOptimization

Keywords: Finite element modelling, Shape optimization, Soft robotics

Functional Description: This software toolkit contains components for exploring parametric design of any SOFA scene, and is more specifically targeted at soft robots applications. We provide a unified framework for implementing a single parametric Sofa scene and use it both for multi-objective design optimization and model-based control.

URL: https://www.sofa-framework.org/applications/plugins/design-optimization/

Publication: hal-04082562

Contact: Tanguy Navez

Partner: CRIStAL

7.1.13 SofaViscoElastic

Name: SofaViscoElastic

Keyword: SoftRobots

Functional Description: Implements the fundamental linear viscoelastic constitutive laws applied to tetrahedral meshes for SOFA. Viscoelasticity is a property of elastomeric materials that influences their mechanical behavior under dynamic conditions. In fact, viscoelastic constitutive equations are dependent on the stress/strain rate. At low stress/strain rates, a viscoelastic material behaves like a viscous liquid-like material, while at high stress/strain rates, the same material behaves like a Hookean solid. In fact, the simplest viscoelastic models are:

URL: https://github.com/SofaDefrost/SofaViscoElastic

Contact: Christian Duriez

Partner: CRIStAL

7.1.14 CondensedFEMModel

Name: Soft Robots Condensed FEM Model for Control and Design Optimization

Keyword: SoftRobots

Functional Description: This plugin for the open-source simulation framework SOFA contains components for learning a condensed FEM model from a soft robot SOFA scene. We also provide an implementation for leveraging the learned model for control, embedded control, calibration and design optimization applications.

URL: https://github.com/SofaDefrost/CondensedFEMModel

Publication: hal-04167863

Contact: Christian Duriez

7.1.15 SOFA

Name: Simulation Open Framework Architecture

Keywords: Real time, Multi-physics simulation, Medical applications

Functional Description: SOFA is an Open Source framework primarily targeted at real-time simulation, with an emphasis on medical simulation. It is mostly intended for the research community to help develop new algorithms, but can also be used as an efficient prototyping tool. Based on an advanced software architecture, it allows the creation of complex and evolving simulations by combining new algorithms with algorithms already included in SOFA, the modification of most parameters of the simulation (deformable behavior, surface representation, solver, constraints, collision algorithm etc.) by simply editing an XML file, the building of complex models from simpler ones using a scene-graph description, the efficient simulation of the dynamics of interacting objects using abstract equation solvers, the reuse and easy comparison of a variety of available methods.

News of the Year: The new version v20.06 has been released including new elements on SoftRobots + ModelOrderReduction integration, in addition to an improved architecture and lots of cleans and bugfixes.

URL: http://www.sofa-framework.org

Publication: hal-00681539

Contact: Hugo Talbot

Participants: Christian Duriez, François Faure, Hervé Delingette, Stephane Cotin, Hugo Talbot, Maud Marchal

Partners: IGG, CRIStAL

7.2 New platforms

7.2.1 Mobile Trunk

Participants: Alexandre Kruszewski, Damien Marchal, Fabrice Dedo, Antoine Alessandrini.

In the context of the SOMOROB project, we are building a platform composed of a 4-wheels differential mobile robot SummitXL combined with our Echelon deformable trunk.

7.2.2 Virtual Twins

Participants: Christian Duriez, Eulalie Coevoet, Damien Marchal, Fabrice Dedo, Gérald Dherbomez.

Within the nationwide TIRREX Equipex+, the DEFROST team is coordinating the setting up of a virtual desktop solutions to host virtual twins of the physical robotics platform. An experiment was conducted on such a service at the CRISTAL laboratory. The experiment was conclusive, and laboratory allocated a credit line for a deployment in 2023. In the meantime, members of the team have already made several virtual twins demonstrating the capabilities of our simulation framework. The twins are all using SOFA and SoftRobots plugin but are exposed as ROS node so they can be controller in a similar way as the real robots they are modeling.

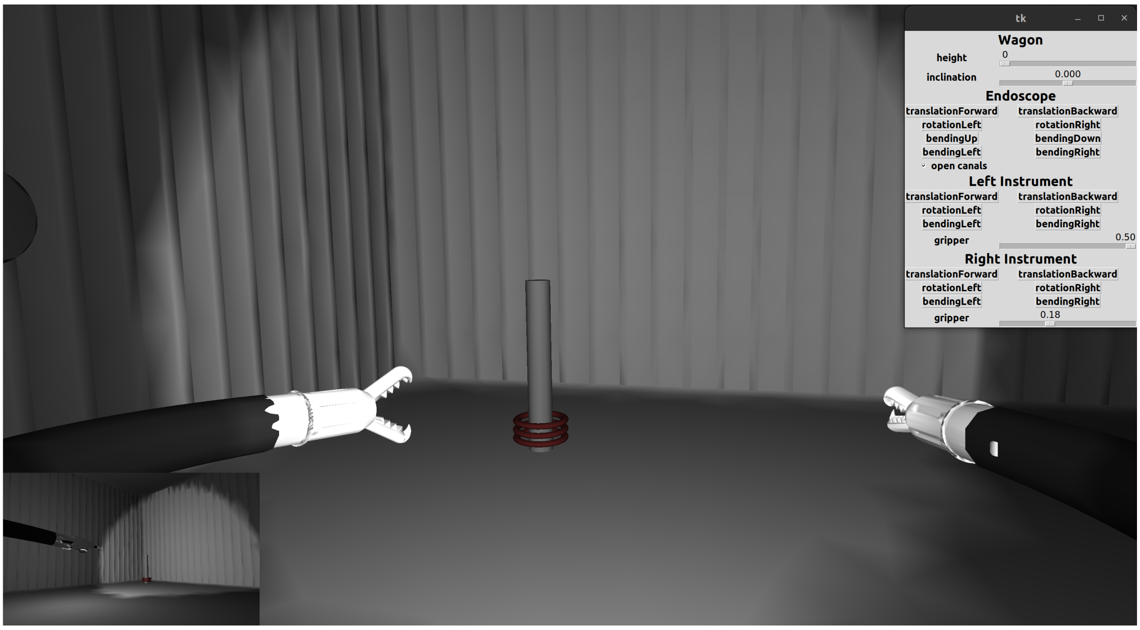

Figure 1: Endoscopic twin in a picking task.

Endoscope twin

The system is a modular and motorized endoscopy platform consisting of two parts: the patient system and the remote manipulation console. The first part, the patient system, consists of a motorized flexible endoscope, and two motorized flexible surgical instruments, mounted on a mobile platform. The second part, the manipulator console, is a dedicated mobile console used to remotely manipulate the patient system. The main intended application is endoscopic dissection of the submucosa (ESD) in colorectal localization. The digital twin models the whole system using SOFA and the plugins BeamAdapter, SoftRobots, and SofaPython3. The twin is open-source and available at Endoscopy repository.

Caroca twin

The system is a large cable-driven parallel robot (CDPR). It is a six degrees of freedom suspended CDPR with eight cables. The current version of the digital twin is a work in progress, it only models a part of the system ; the cables and the coupling with the manipulated object. It uses SOFA and the plugins BeamAdapter, Cosserat and SofaPython3. The twin is open-source and available at Caroca repository.

Micro Parallel twin

The system is a small parallel continuum robot ; it is composed of four legs connected to a gripper. The digital twin models the whole system using SOFA and the plugins BeamAdapter, SoftRobots, and SofaPython3. The twin is open-source and available at MicroParallel repository.

MobileTrunk twin

Within the SOMOROB project aforementioned we are fabricating an hardware plateform of a mobile robot with a deformable trunk. A virtual twin for this robot has been made in SOFA. The model of the 4 wheels differential mobile robot follows the same control as the physical one and the Echelon deformable trunk is controlled using SoftRobots.Inverse. The twin is open-source and available at MobileTrunk

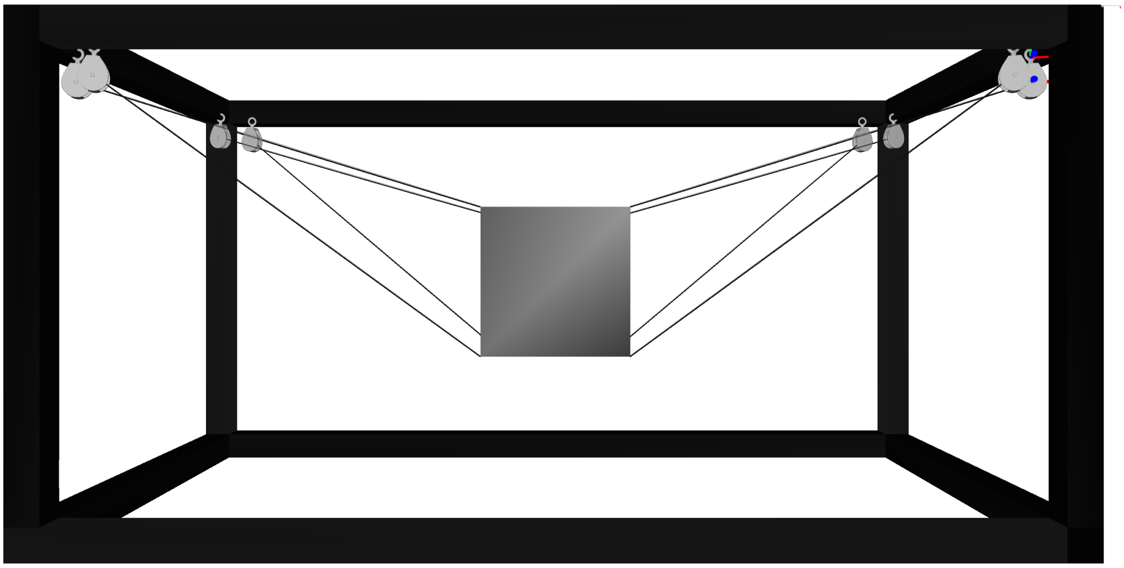

Figure 2: A large cable-driven parallel robot (CDPR) featuring six degrees of freedom suspended CDPR with eight cables.

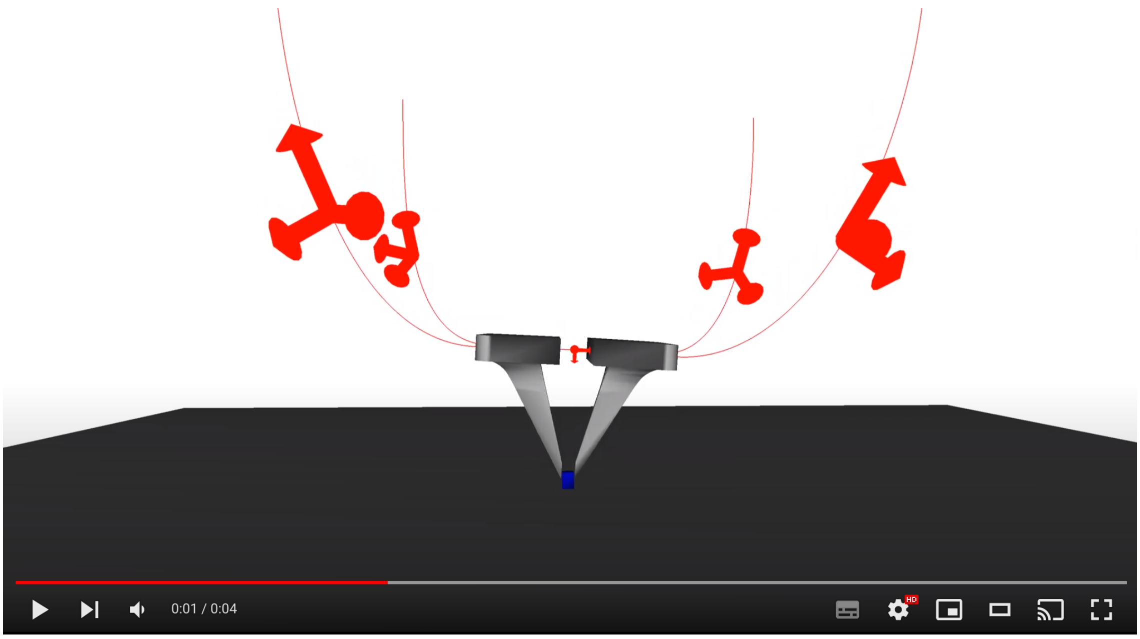

Figure 3: Virtual twin of a the microgripper.

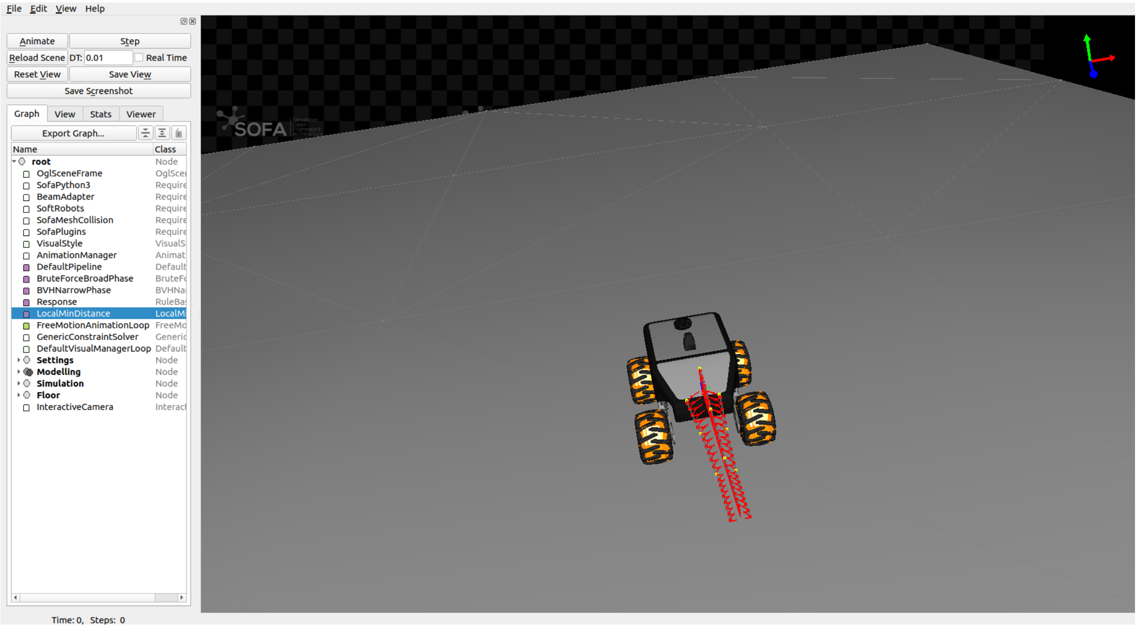

Figure 4: Interactive virtual twin of a four wheel robotic and its deformable trunk.

repository.

8 New results

8.1 Duality of the existing geometric variable strain models for the dynamic modelling of continuum robots

Participants: Azouaou Ouyoucef, Quentin Peyron, Vincent Lebastard, Frederico Renda, Gang Zheng, Frédéric Boyer.

The Cosserat rod theory has become a gold standard for modeling the statics and dynamics of serial and parallel continuum robots. Recently, a weak form of these Cosserat rod models called the geometric variable strain model has been derived where the robot deformations are projected on finite-dimensional basis functions. This model has very interesting features for continuum robotics, such as a Lagrangian form close to classical rigid robots and the ability to tune its performances in terms of computation time and accuracy. Two approaches have been proposed to obtain and compute it. The first is based on the Newton-Euler recursive algorithm and the second, on the projection of the strong form equations using Jacobian matrices. Although these approaches yield identical model forms, their disparate implementations and numerical schemes render each uniquely suited to specific applications. Notably, underlying these disparities lies a profound duality between these models, prompting our quest for a comprehensive overview of this duality along with an analysis of their algorithmic differences [16]. Finally, we discuss perspectives for these two approaches, in particular their hybridization, based on the current knowledge of rigid robotics.(See Fig. 5)

8.2 Modeling, analysis and design of an extensible planar parallel tendon actuated continuum robot

Participants: Azouaou Ouyoucef, Quentin Peyron, Gang Zheng, Frédéric Boyer.

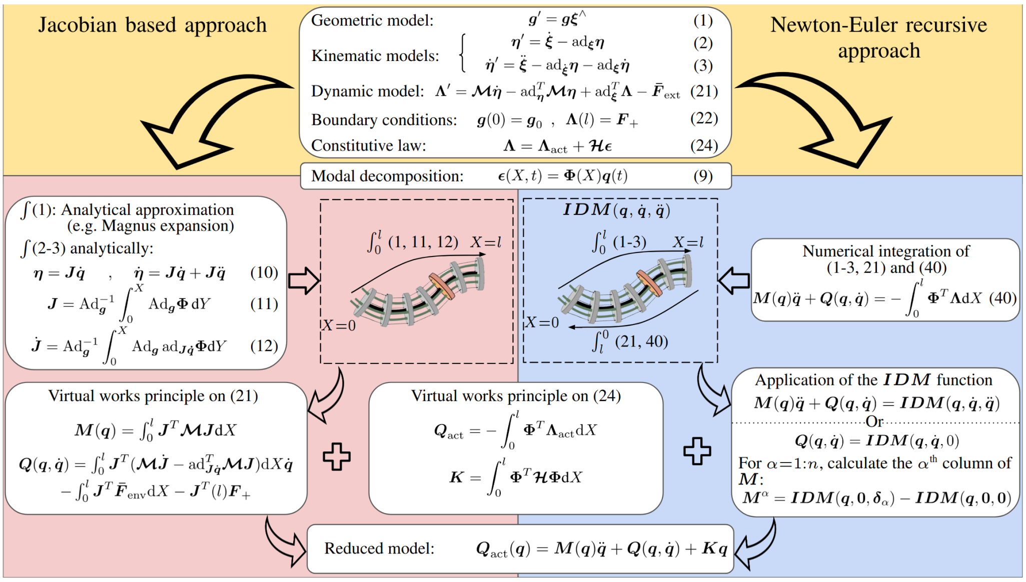

Figure 5: Synthesis of the steps in both approaches side by side. The blue and red areas are relative to the NE recursive approach and Jacobian based approach, respectively. The yellow part corresponds to the full Cosserat rod model.

In this study, we introduce a novel design for a compressible/extensible planar continuum parallel manipulator, characterized by fixed joints and tendon-based actuation with parallel routing. The goal of this design is to generate a planar workspace without adding any rigid translational actuators by considering compressible legs. To optimize the robot's design, its static behavior is first modeled using a Jacobian-based geometric variable strain approach, providing a foundation for performance analysis. We then explore key performance metrics, including workspace, stability, and payload capacity, in relation to critical design parameters: the distance between the robot's legs and the bending-to-compression stiffness ratio. While the leg distance is a well-studied factor in parallel architectures, the influence of the stiffness ratio, despite its significant impact on performance, has received limited attention. Our work investigates the effects of these parameters, culminating in the development of a new modular prototype that leverages these insights to obtain optimal robot performances.(See Fig. 6)

8.3 Design Optimization of a Soft Gripper using Self-Contacts

Participants: Tanguy Navez, Baptiste Liévin, Quentin Peyron, Stefan Escaida Navarro, Olivier Goury, Christian Duriez.

The design of soft robots' deformable bodies is complex, partly due to the trade-off between softness for motion and stiffness for force generation. Self-contacts in soft structures can be used to address this problem but have been marginally investigated. In parallel, parametric designs and computational optimization tools constitute an important trend paving the way toward shareable and reproducible results. In this work [35], we study the potential of self-contacts in the design of soft grippers using a multi-objective design optimization environment. This open-source environment is targeted toward grasping tasks and is used both for design and model calibration. Soft fingers with improved grasping quality and energy are obtained, taking into account different friction coefficients at the contacts and different shapes of the objects to grasp. They are experimentally validated in terms of mechanical behavior and grasping performances.(See Fig. 7)

8.4 Using Haptic Feedback in Digital Rectal Examination Training

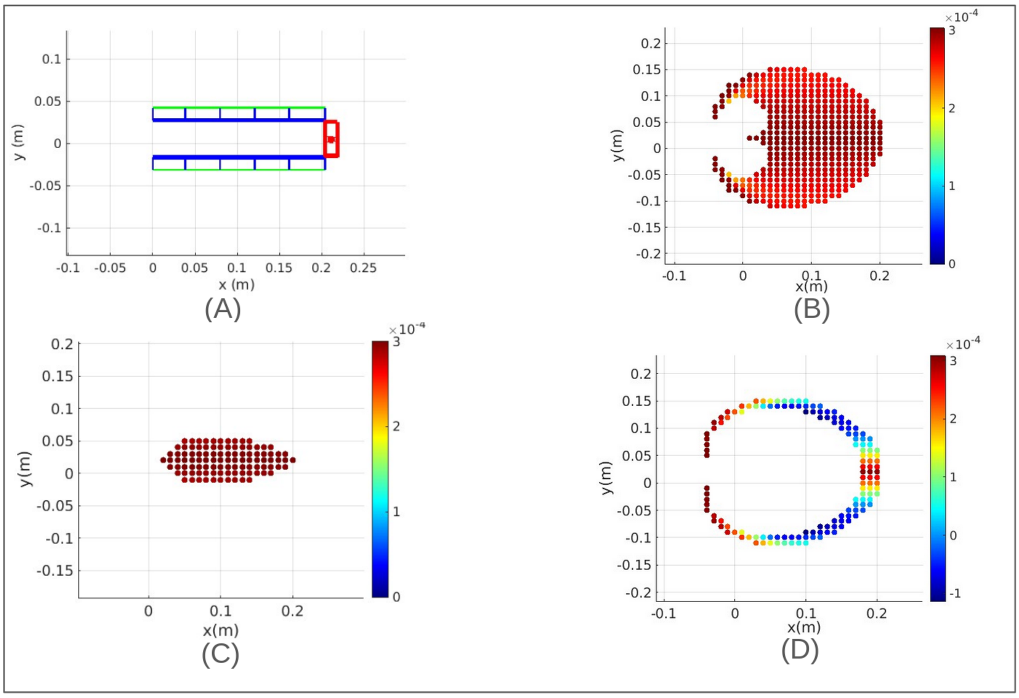

Figure 6: (A) Robot's initial configuration, (B) Workspace and stability zones for the design parameters $d = 4cm$, $u = 1.5\times10^{-4}$, (C) Workspace and stability zones for the design parameters $d = 4cm$, $u = 5\times10^{-3}$, (D) Workspace and stability zones for the design parameters $d = 4cm$, $u = 2.5\times10^{-5}$. The color bar indicates the smallest eigen-value of the Hessian matrix of the potential energy. The blue regions are unstable and the red ones are stable. The null values indicate a type 2 singularity.

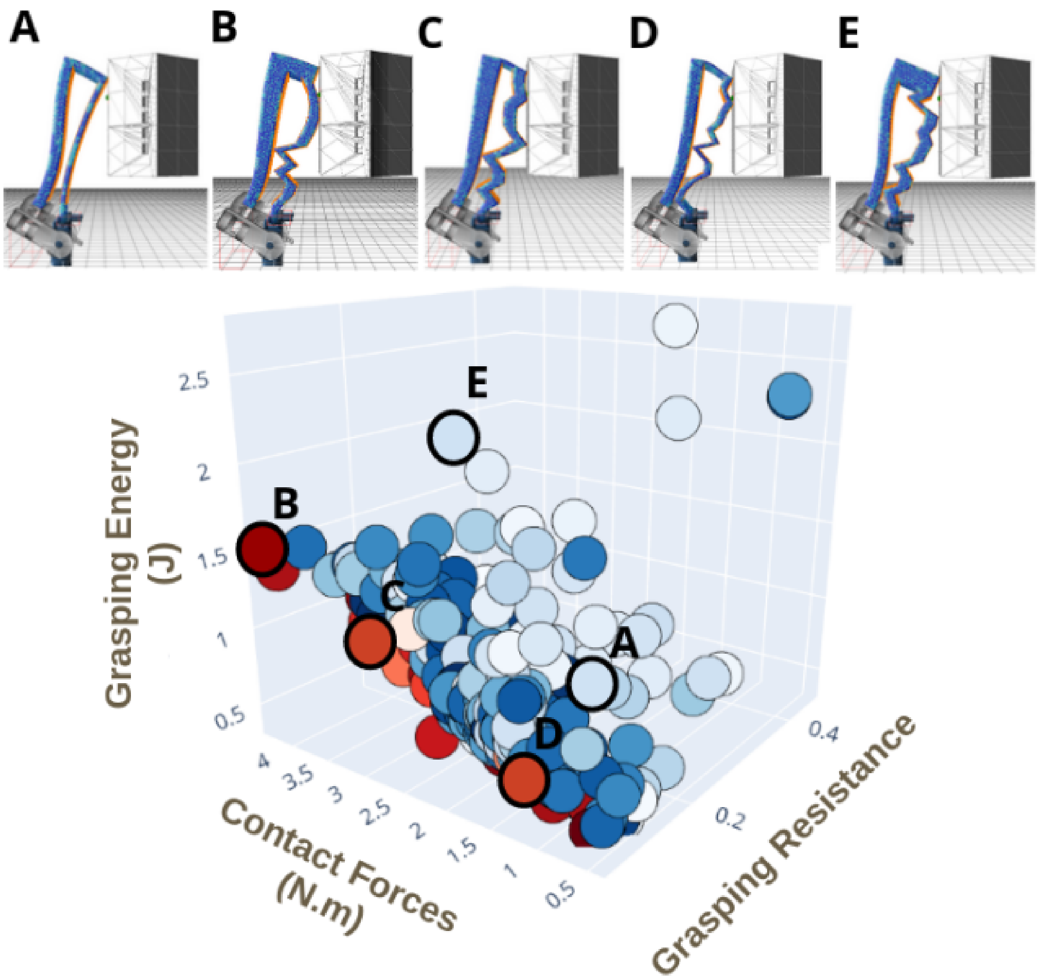

Figure 7: Pareto Front and a few sampled geometries at the grasping pose obtained for 300 trials of the Soft Finger design optimization. Pareto optimal solutions are represented by red dots. Results are generated using the NSGAII algorithm with an initial population of 50 design candidates, probabilities of crossover, and swapping parameters between parents of 0.9 and 0.5, respectively.

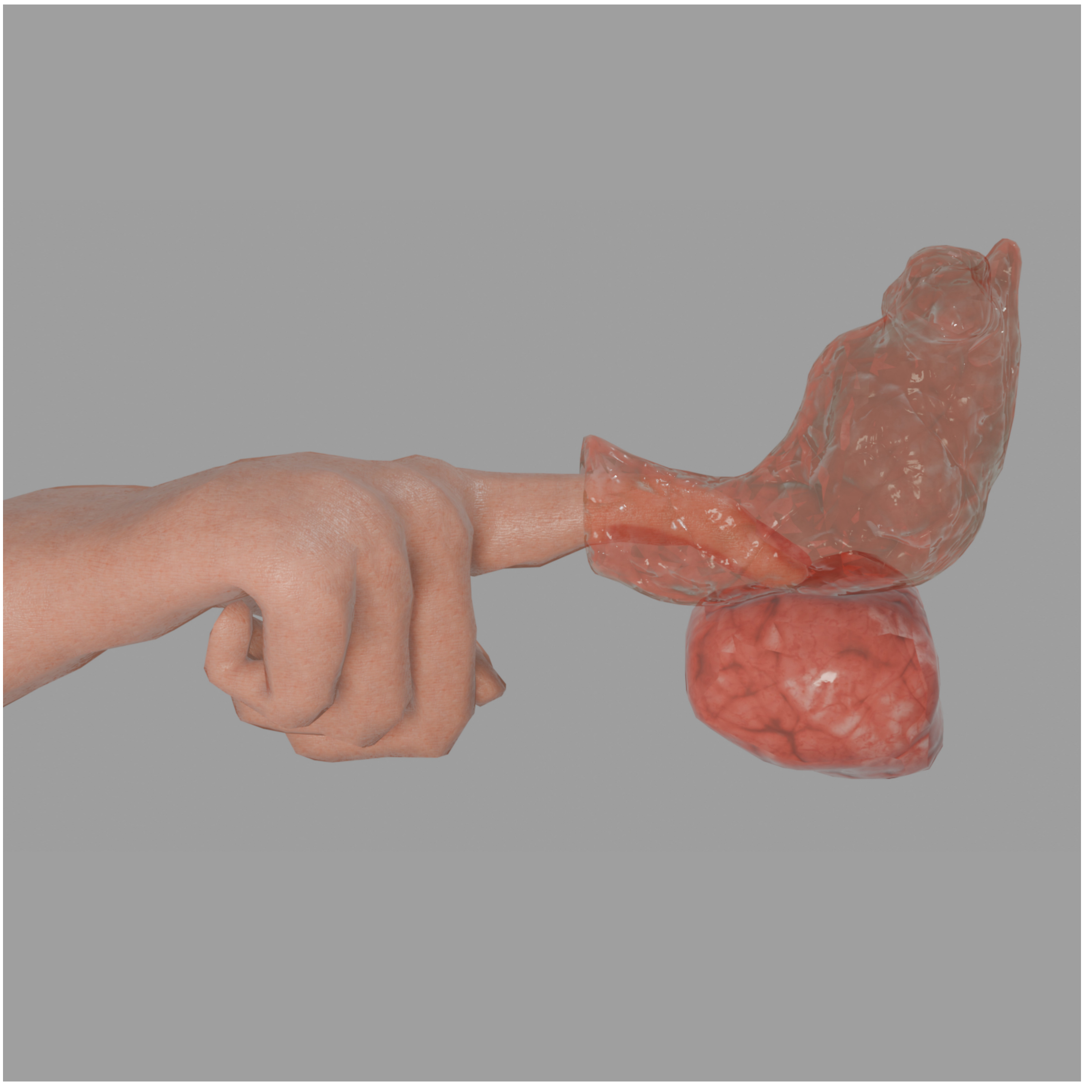

Figure 8: Simulation of the probing finger touch the prostate in SOFA, rendered using Blender.

Participants: Sizhe Tian, Yinoussa Adagolodjo, Jérémie Dequidt.

Prostate cancer is one of the most common cancer globally, particularly among men aged over 50. Digital rectal examination (DRE) is one of the first-line method for diagnosing and screening for the prostate cancer. However, medical students often lack sufficient training in performing DRE effectively. In this regard, we are developing a digital tool that seamlessly integrates digital simulation with haptic feedback to transform DRE training [36]. Our method relies on the Finite Element Method (FEM) to create a detailed model of the probing-finger, organs, and their interactions. The contact forces generated by the probing-finger's movements in simulation, are then fed back to the user via a haptic device. We aim to accurately replicate mechanical properties associated with prostate in different conditions and provide realistic feedback, facilitating the preparation of medical professionals for DRE procedures. This approach has the potential to improve the effectiveness and accessibility of DRE training, ultimately contributing to better patient care and outcomes in prostate cancer diagnosis and management. (See Fig. 8)

8.5 Cosserat-rod Based Dynamic Modeling of Soft Slender Robot Interacting with Environment

Participants: Lingxiao Xun, Gang Zheng, Alexandre Kruszewski.

Soft slender robots have attracted more and more research attentions in these years due to their continuity and compliance natures. However, mechanics modeling for soft robots interacting with environment is still an academic challenge because of the nonlinearity of deformation and the nonsmooth property of the contacts. In this work [19], starting from a piece-wise local strain field assumption, we propose a nonlinear dynamic model for soft robot via Cosserat rod theory using Newtonian mechanics, which handles the frictional contact with environment and transfer them into the nonlinear complementary constraint (NCP) formulation. Moreover, we smooth both the contact and friction constraints in order to convert the inequality equations of NCP to the smooth equality equations. The proposed model allows us to compute the dynamic deformation and frictional contact force under common optimization framework in real time when the soft slender robot interacts with other rigid or soft bodies. In the end, the corresponding experiments are carried out which valid our proposed dynamic model. (See Fig. 9)

8.6 Linear compliant control design for soft robots

Participants: Antoine Alessandrini, Alexandre Kruszewski.

Our research [24] focuses on compliant control of soft robots using a simulation-based model to select the end effector's dynamics. We use a linearized model to introduce a novel compliance-tuning control structure. It comprises a reference model representing the desired behavior, a force estimator, and a state feedback control law. Through real-world tests, we demonstrate the validity of our approach in terms of position control accuracy and adaptive force response. Our approach achieves less than 0.5mm error in position control and up to 55% force reduction in targeted directions, highlighting its potential for safer and more effective human-robot interactions. (See Fig. 10)

8.7 Condensed semi-implicit dynamics for trajectory optimization in soft robotics

Participants: Etienne Ménager, Alexandre Bilger, Wilson Jallet, Justin Carpentier, Christian Duriez.

Over the past decades, trajectory optimization (TO) has become an effective solution for solving complex motion generation problems in robotics, ranging from autonomous driving to humanoids. Yet, TO methods remain limited to robots with tens of degrees of freedom (DoFs), limiting their usage in soft robotics, where kinematic models may require hundreds of DoFs in general. In this work [27], we introduce a generic method to perform trajectory optimization based on continuum mechanics to describe the behavior of soft robots. The core idea is to condense the dynamics of the soft robot in the constraint space in order to obtain a reduced dynamics formulation, which can then be plugged into numerical TO methods. In particular, we show that these condensed dynamics can be easily coupled with differential dynamic programming methods for solving TO problems involving soft robots. This method is evaluated on three different soft robots with different geometries and actuation. (See Fig. 11)

8.8 Learning control strategy in soft robotics through a set of configuration spaces

Participants: Etienne Ménager, Christian Duriez.

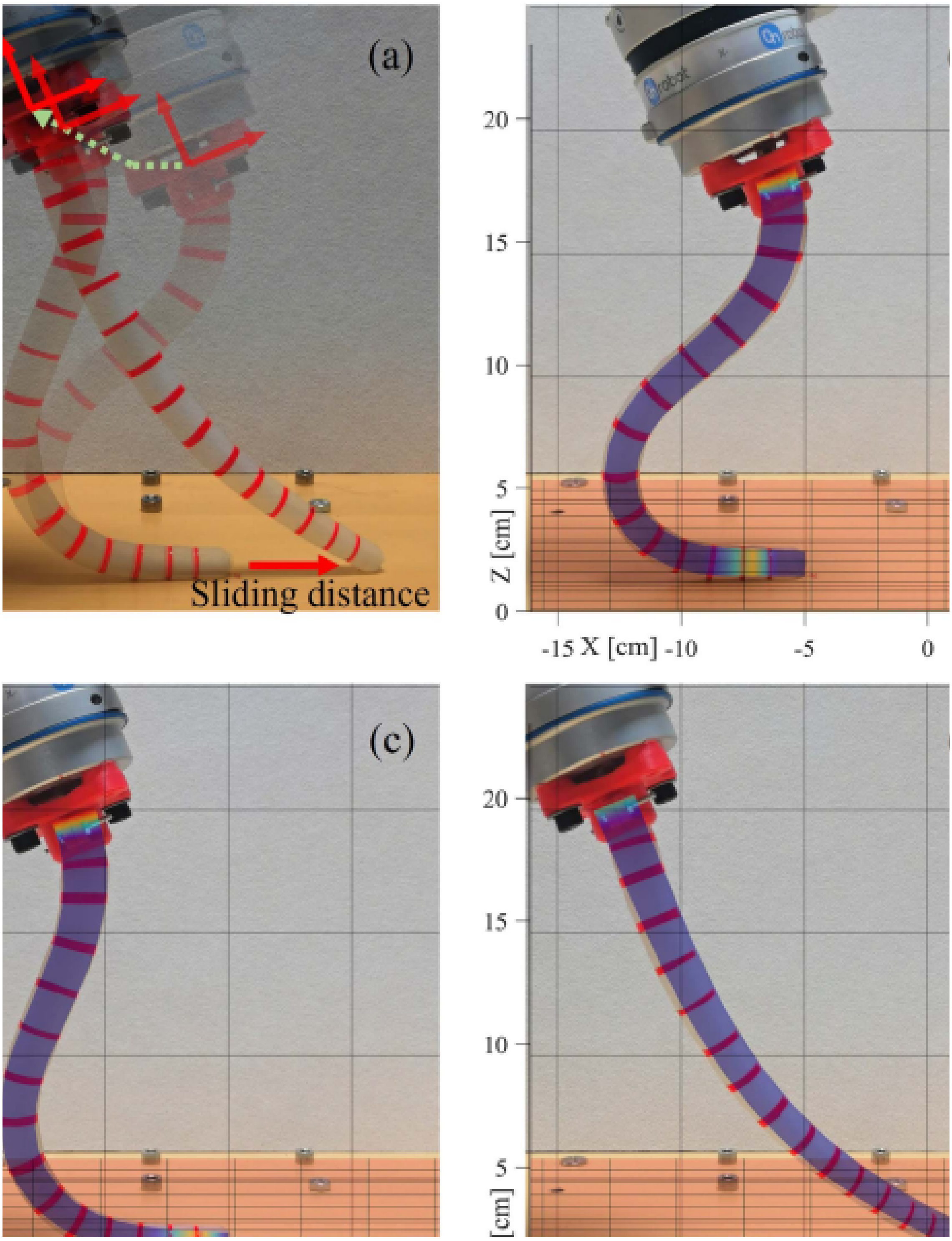

Figure 9: Configuration of sliding test (white) and simulation (blue). (a) The moving path of the base of slender robot. The corresponding times of the subfigures are: (b) t = 0 s. (c) t = 3.2 s. (d) t = 4.5 s.

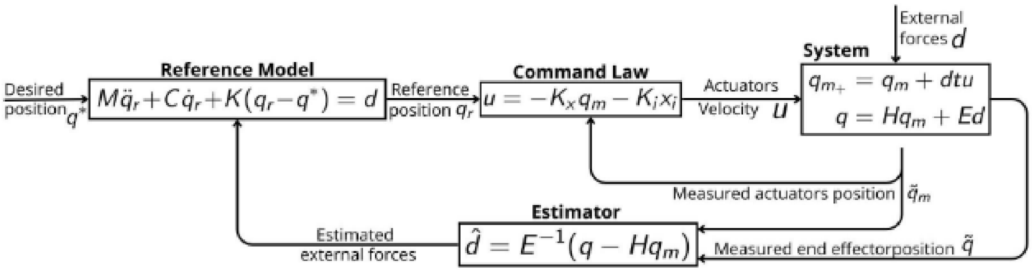

Figure 10: Control structure of the soft robot.

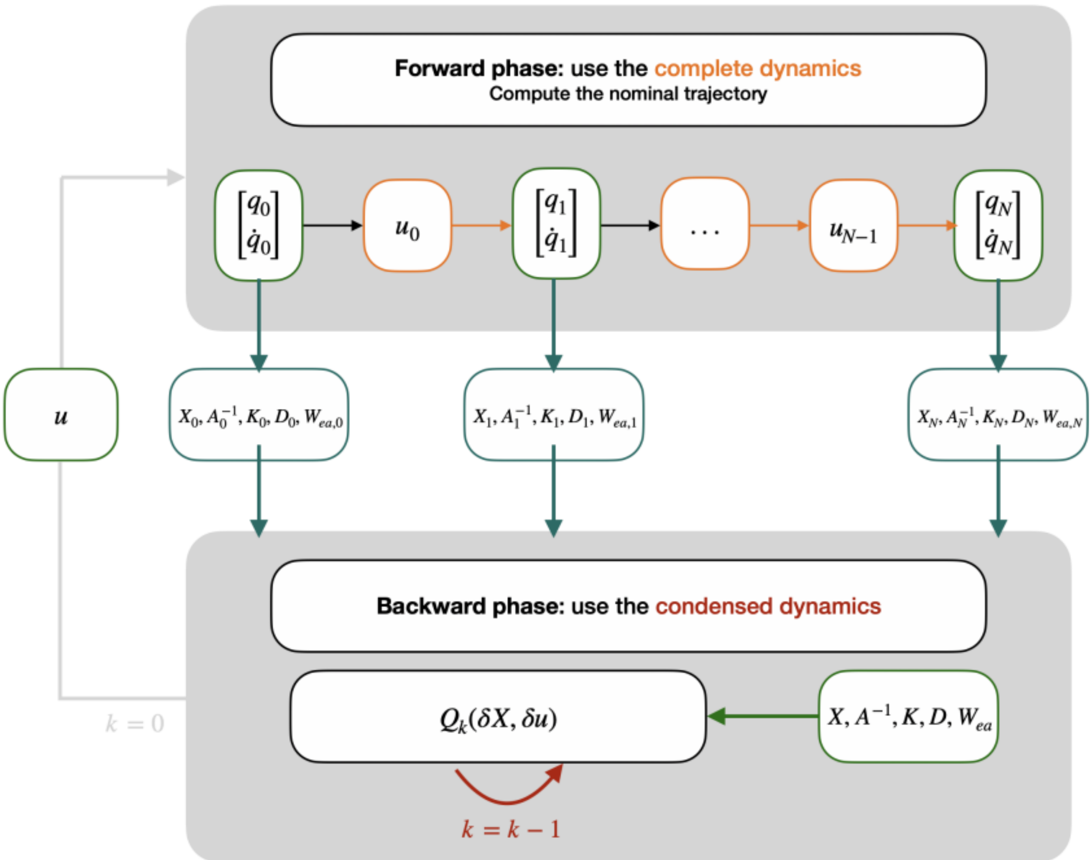

Figure 11: Illustration of the trajectory optimization pipeline. Starting from an initial position, the forward phase computes the different positions and velocities of the complete mesh using the full dynamics (in orange). From the simulation data, a nominal trajectory is extracted, and the mechanical quantities necessary for the DDP are saved (in blue). The nominal trajectory (green) is used with the condensed trajectory (red) to compute the new action sequence that will be given to the forward pass. Several forward and backward steps may be necessary to converge to a solution.

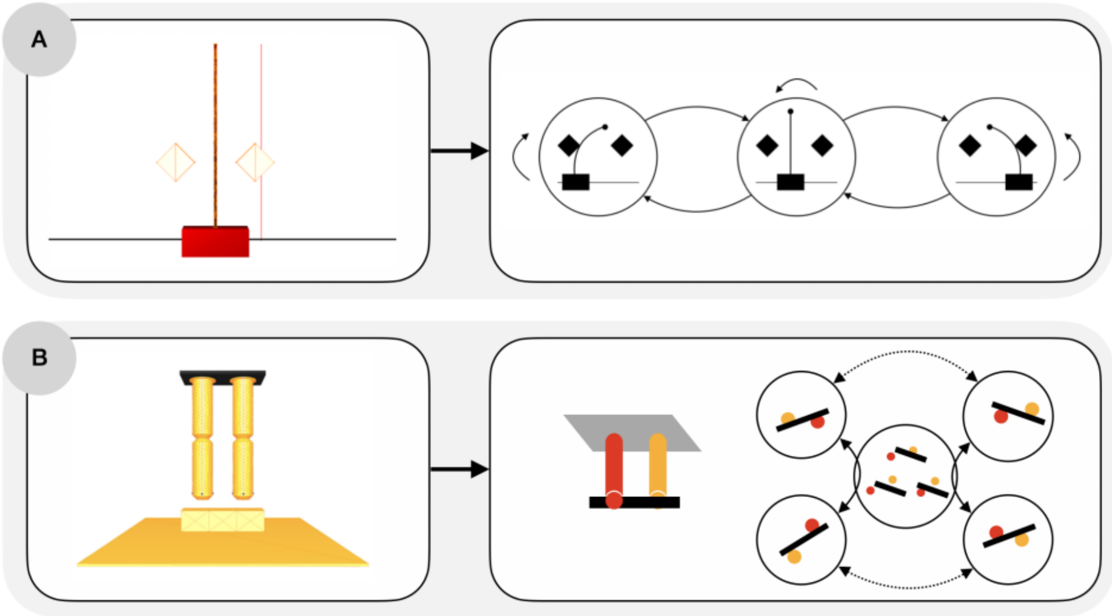

Figure 12: Splitting the state space into different configuration spaces (right) for two soft systems (left) based on the contact configuration. (A) CartStemContact. (B) RodManipulator. In this example, some contact configurations are gathered in one configuration space, not useful for the manipulation task.

The ability of a soft robot to perform specific tasks is determined by its contact configuration, and tran-sitioning between configurations is often necessary to reach a desired position or manipulate an object. Based on this observation, we propose a method for controlling soft robots that involves defining a graph of configuration spaces [30]. Different agents, whether learned or not (convex optimization, expert trajectory, and collision detection), use the structure of the graph to solve the desired task. The graph and the agents are part of the prior knowledge that is intuitively integrated into the learning process. They are used to combine different optimization methods, improve sample efficiency, and provide interpretability. We construct the graph based on the contact configurations and demonstrate its effectiveness through two scenarios, a deformable beam in contact with its environment and a soft manipulator, where it outperforms the baseline in terms of stability, learning speed, and interpretability.(See Fig. 12)

8.9 Optical Servoing of Soft Robotic Instrument for Cancer Imaging

Participants: Paul Chaillou, Jialei Shi, Alexandre Kruszewski, Isabelle Fournier, Helge Wurdemann, Thibault Piccinali, Christian Duriez.

Cancer is an important cause of mortality. Being able to improve accuracy of surgical procedure to reduce post-operative effects is a major concern. Surgery is essential and remains the first frontline treatment of solid cancers. To determine the exact extension of the cancer and preserve non-cancerous tissue at most, robotic imaging can offer accurate scanning information to surgeons. In this work, we use robotic assisted mass spectrometry tissue surface analysis. Our goal is to develop an in-situ cancer detection during the surgery, so that surgeons can scan difficult-to-access area. The main challenge is to provide an easy and safe navigation in a tortuous anatomical environment.

Our envisioned technology is based on the mini-invasive real-time mass spectrometry (SpiderMass Technology), within the context of the Minimally Invasive Surgery (MIS). The SpiderMass Technology can analyse the cells in real-time and distinguish the different cell phenotypes, therefore, making it possible to discriminate types, subtypes and grades of solid tumors. The contribution of this work [25] is that we combine this real-time imaging technology with soft robots, aiming to achieve inherent-safe

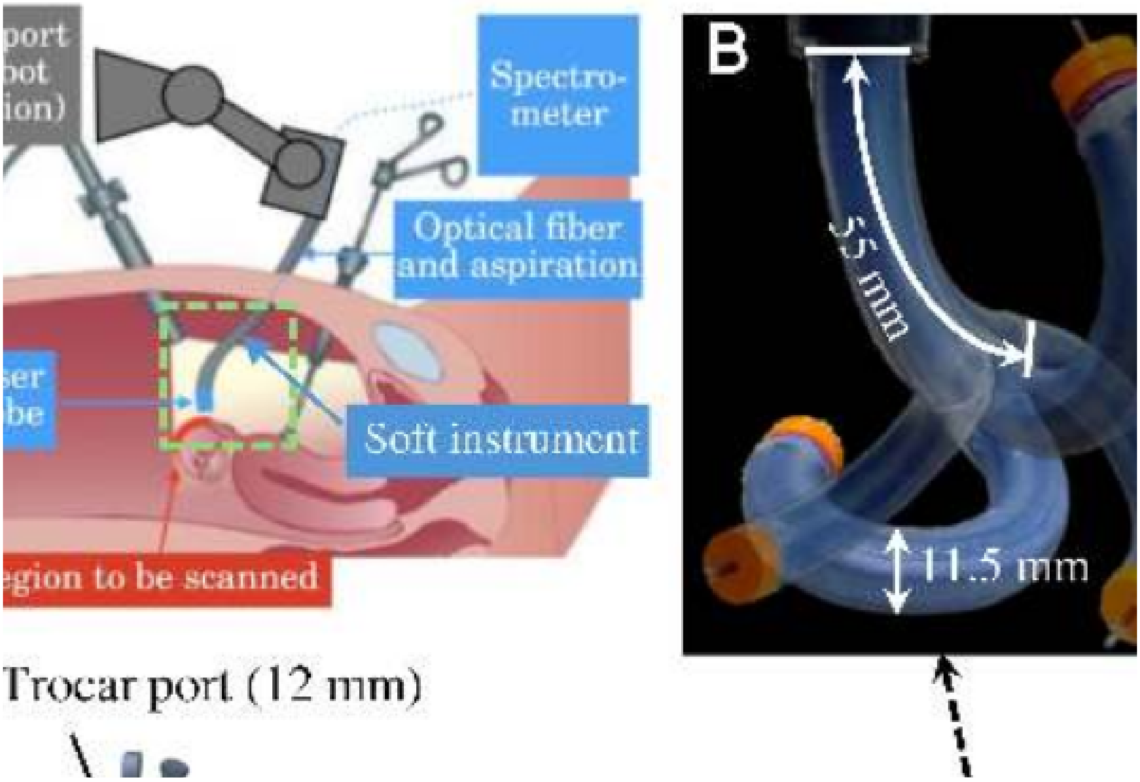

Figure 13: Illustration of the envisioned application: Developed soft robotic instrument for cancer imaging. A) Scheme that display the soft robot in the MIS context. B) Picture that describe different configuration that the soft robot may achieve. C) Picture of the soft robot installed trough the trocar.

scanning. Our system might result in a significant reduction in operation time and impact on the patient's health. As proof of concept, optical servoing have been implemented, using a RealSense D405 3D camera. By estimating and correcting the projected laser dot position directly, we study the precision we could obtained for the laser shot used for the cells extraction before mass spectrometry analysis.(See Fig. 13)

8.10 Towards Realistic Needle Insertion Training Simulator Using Partitioned Model Order Reduction

Participants: Félix Vanneste, Claire Martin, Olivier Goury, Hadrien Courtecuisse, Erik Pernod, Stéphane Cotin, Christian Duriez.

Needle-based intervention is part of minimally invasive surgery and has the benefit of allowing the reach of deep internal organ structures while limiting trauma. However, reaching good performance requires a skilled practitioner. This study presents a needle-insertion training simulator for the liver based on the finite element method. One of the main challenges in developing realistic training simulators is to use fine meshes to represent organ deformations accurately while keeping a real-time constraint in the speed of computation to allow interactivity of the simulator. This is especially true for simulating accurately the region of the organs where the needle is inserted. In this work [29], we propose the use of model order reduction to allow drastic gains in performance. To simulate accurately the liver which undergoes highly nonlinear local deformation along the needle-insertion path, we propose a new partition method for model order reduction: applied to the liver, we can perform FEM computations on a high-resolution mesh on the part in interaction with the needle while having model reduction elsewhere for greater computational performances. We show the combined methods with an interactive simulation

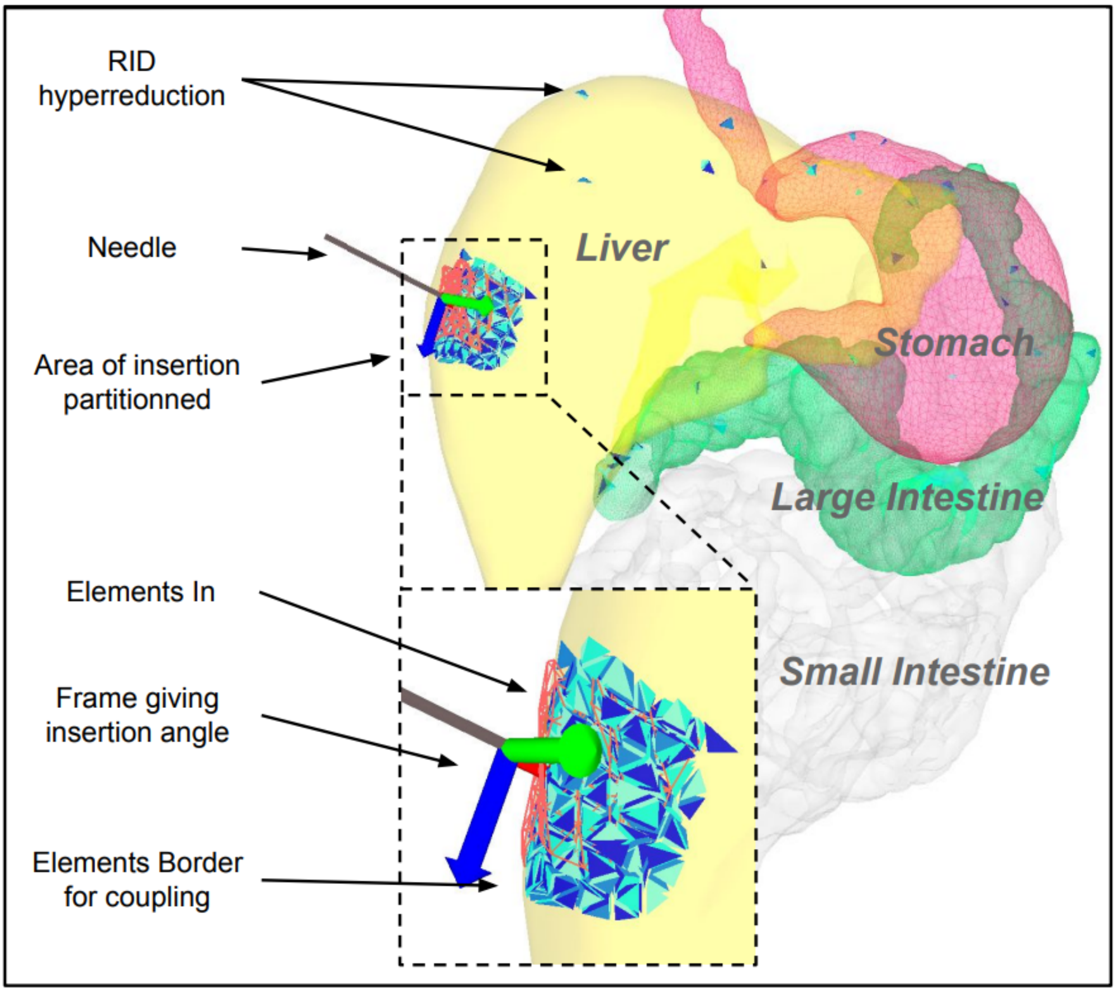

Figure 14: Simulation setup. Focus on the insertion area where we define the partition of the model with, in orange, the elements strictly inside the set F defined in section 2.3. This set is enriched with elements on the boundary of the region (in blue) to maintain coupling between the reduced and the fine region.

of percutaneous needle-based interventions for tumor biopsy/ablation using patient-based anatomy.(See Fig. 14)

8.11 High Rate Mechanical Coupling of Interacting Objects in the Context of Needle Insertion Simulation With Haptic Feedback

Participants: Claire Martin, Christian Duriez, Hadrien Courtecuisse.

Needle-based procedures such as biopsies or radiofrequency ablation (RFA) of tumors are often considered to diagnose and treat liver cancer for their low invasiveness but raise difficulties for practitioners related to needle placement and visibility of internal anatomical structures. Efforts are being conducted to build real-time needle insertion simulators with both visual and haptic rendering, facing challenges related to model accuracy and real-time computational performance. This work [31] focuses on the contact model involved in needle-tissue interactions in order to improve the realism of the resulting haptic rendering. We present a novel method to update the compliant coupling at high rates of a complete contact system involving the mechanics of a large object and the complete model of a flexible needle.

These updates allow to adapt the contact directions to the needle deformations in the haptic thread, with the aim of improving the resulting haptic feedback. Updates of contact directions and the related mechanical system according to high-rate deformations decrease force feedback artifacts associated with low-rate mechanics while maintaining high-rate performances for the haptic loop.(See Fig. 15)

8.12 In silicone and in silico: toward evaluation of pacemaker lead implantation based on soft robotics and computer simulation

Participants: Thomas Moupfouma, Quentin Peyron, Yinoussa Adagolodjo, Sylvain Caubet, Jean-François Ollivier, Christian Duriez.

This work presents a novel soft robotic phantom designed for evaluating medical tools in pacemaker lead implantation procedures, while minimizing reliance on animal testing. The platform integrates a beating ventricle *in silicone* with an instrumented apex, a subclavian vein phantom, and a vision-based system, all immersed in a water tank to simulate the blood flow.This hardware is coupled with a real-time biomechanical simulation, offering a realistic environment for testing medical devices and training *in silico*. This study focuses on the first experimental assessment of the main elements composing the phantom, as well as the potential complementarity offered by coupling soft hardware with physical simulation to evaluate pacemaker lead designs.(See Fig. 16)

8.13 Enhancing TAVI Robot Flexibility Using Semi-Extensible Materials

Participants: Przybylski Flavie, Yinoussa Adagolodjo, Jérémie Dequidt, Pierre Berthet-Rayne, Christian Duriez.

Global demographic aging poses a major challenge to healthcare systems, intensified by the significant increase in medical needs specific to the elderly population. To address these increasing demands and minimize risks associated with medical vascular interventions, such as aortic valve stenosis pathology, prioritizing less invasive approaches has become imperative. In this context, Transcatheter Aortic Valve Implantation (TAVI) has emerged as a significant advancement, offering a less invasive alternative to traditional cardiac surgery. To optimize the precision and efficiency of this procedure, the use of a growing robot stands out as an innovative approach. Its ability to deploy from the inside ensures flexibility tailored to the unique morphology of each patient, thus reducing the risks of tissue perforation. Inspired by the work of Li et al., a cadaveric clinical test was undertaken, implementing an 8 mm diameter growing robot made from silicone-coated Ripstop Nylon and pressurized with an iodine solution. The results of these trials revealed difficulties in navigating through narrow anatomical areas such as stenosis. Consequently, a study on the compliance of growing robots was undertaken [28], exploring the use of various materials with different properties.(See Fig. 17)

9 Bilateral contracts and grants with industry

9.1 Bilateral grants with industry

9.1.1 Caranx Medical

Caranx Medical is a startup company focusing on surgical robotics. Their aim is to revolutionize surgery with novel ground-breaking surgical robots. We have started a PhD thesis in Feb 2022 through the CIFRE program. The phD is focused on the use of vine robots in surgical robotics. We are working on a new model for everything robots. We had a paper accepted to Robosoft this year

Participants: Christian Duriez, Jeremie Dequidt, Flavie Przybylski.

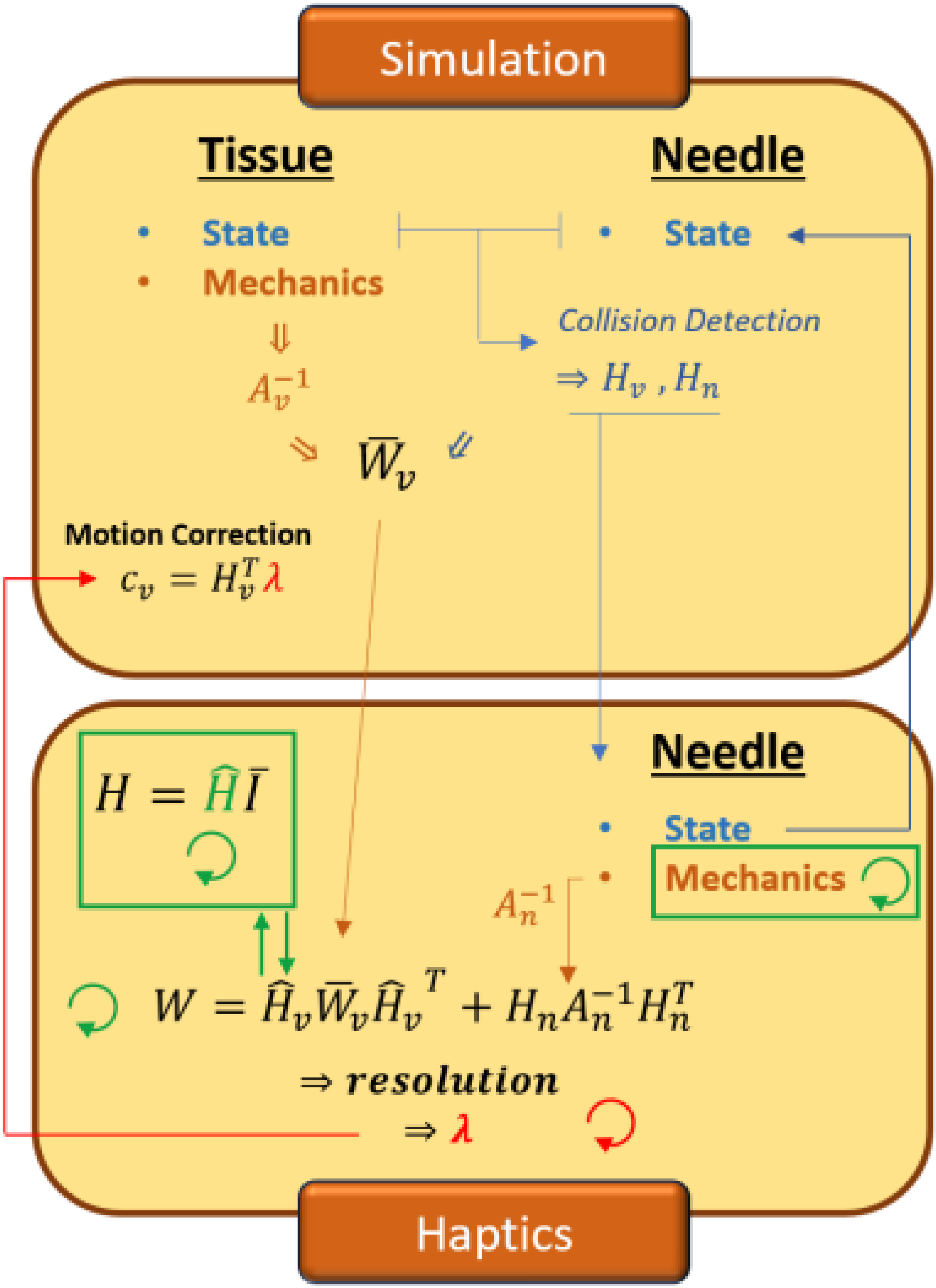

Figure 15: Organization of the simulation and haptic loops, and their communication.

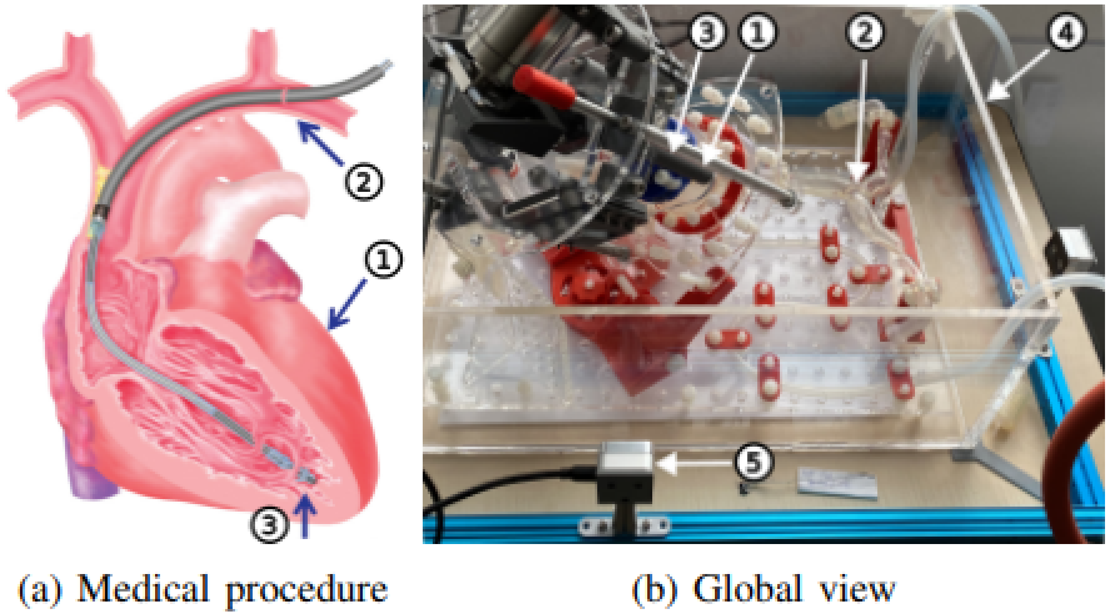

Figure 16: Soft robotic phantom for tool evaluation in pacemaker lead implantation. 1: Right ventricle, 2: Subclavian vein, 3: Ventricle Apex, 4: Water tank, 5: Vision-based measurement system.

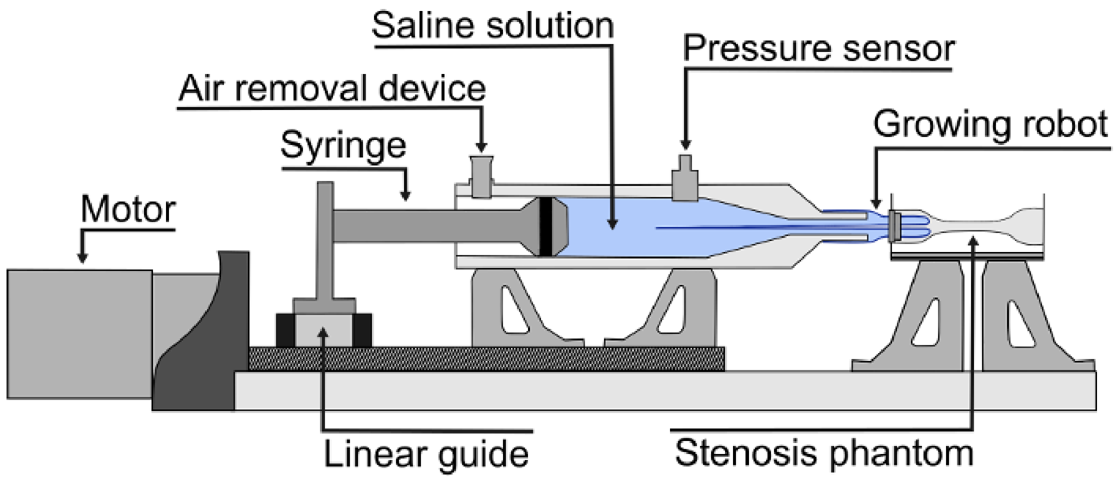

Figure 17: Experimental platform equipped with a pressurization system designed to execute the eversion of a robot through a rigid phantom simulating a stenosis.

10 Partnerships and cooperations

10.1 International research visitors

10.1.1 Visits of international scientists

Other international visits to the team

Xin LI

Status PhD

Institution of origin: Hong Kong Polytechnic University

Country: China

Dates: From March 2024 until August 2024

Context of the visit: Collaboration on the modeling and control of continuum robots.

Mobility program/type of mobility: Research stay

10.2 European initiatives

10.2.1 Horizon Europe

euROBIN

Participants: Christian Duriez.

euROBIN project on cordis.europa.eu

Title: European ROBotics and AI Network

Duration: From July 1, 2022 to June 30, 2026

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- C.R.E.A.T.E. CONSORZIO DI RICERCA PER L'ENERGIA L AUTOMAZIONE E LE TECNOLOGIE DELL'ELETTROMAGNETISMO (C.R.E.A.T.E.), Italy
- PAL ROBOTICS SLU (PAL ROBOTICS), Spain
- KUNGLIGA TEKNISKA HOEGSKOLAN (KTH), Sweden
- INSTITUT JOZEF STEFAN (JSI), Slovenia
- FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV (Fraunhofer), Germany
- FUNDACION TECNALIA RESEARCH & INNOVATION (TECNALIA), Spain
- TECHNISCHE UNIVERSITAET MUENCHEN (TUM), Germany
- DHL EXPRESS SPAIN SL, Spain
- COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (CEA), France
- INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM (IMEC), Belgium
- TEKNOLOGISK INSTITUT (DANISH TECHNOLOGICAL INSTITUTE), Denmark
- UNIVERSITEIT TWENTE (UNIVERSITEIT TWENTE), Netherlands

- ASEA BROWN BOVERI SA (ABB), Spain
- ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE (EPFL), Switzerland
- MATADOR INDUSTRIES AS, Slovakia
- DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV (DLR), Germany
- IST-ID ASSOCIACAO DO INSTITUTO SUPERIOR TECNICO PARA A INVESTIGACAO E O DESENVOLVIMENTO (IST ID), Portugal
- UNIVERSITA DI PISA (UNIPI), Italy
- FUNDINGBOX ACCELERATOR SP ZOO (FBA), Poland
- UNIVERSITAET BREMEN (UBREMEN), Germany
- FONDAZIONE ISTITUTO ITALIANO DI TECNOLOGIA (IIT), Italy
- KARLSRUHER INSTITUT FUER TECHNOLOGIE (KIT), Germany
- EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH (ETH Zürich), Switzerland
- CESKE VYSOKE UCENI TECHNICKE V PRAZE (CVUT), Czechia
- OREBRO UNIVERSITY (ORU), Sweden
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (CNRS), France
- VOLKSWAGEN AKTIENGESELLSCHAFT (VW AG), Germany
- SIEMENS AKTIENGESELLSCHAFT, Germany
- SORBONNE UNIVERSITE, France
- UNIVERSIDAD DE SEVILLA, Spain

Inria contact: François Chaumette

Coordinator: DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV

Summary: As robots are entering unstructured environments with a large variety of tasks, they will need to quickly acquire new abilities to solve them. Humans do so very effectively through a variety of methods of knowledge transfer – demonstration, verbal explanation, writing, the Internet. In robotics, enabling the transfer of skills and software between robots, tasks, research groups, and application domains will be a game changer for scaling up the robot abilities.

euROBIN therefore proposes a threefold strategy: First, leading experts from the European robotics and AI research community will tackle the questions of transferability in four main scientific areas: 1) boosting physical interaction capabilities, to increase safety and reliability, as well as energy efficiency 2) using machine learning to acquire new behaviors and knowledge about the environment and the robot and to adapt to novel situations 3) enabling robots to represent, exchange, query, and reason about abstract knowledge 4) ensuring a human-centric design paradigm, that takes the needs and expectations of humans into account, making AI-enabled robots accessible, usable and trustworthy.

Second, the relevance of the scientific outcomes will be demonstrated in three application domains that promise to have substantial impact on industry, innovation, and civil society in Europe. 1) robotic manufacturing for a circular economy 2) personal robots for enhanced quality of life 3) outdoor robots for sustainable communities. Advances are made measurable by collaborative competitions.

Finally, euROBIN will create a sustainable network of excellence to foster exchange and inclusion. Software, data and knowledge will be exchanged over the EuroCore repository, designed to become a central platform for robotics in Europe.

The vision of euROBIN is a European ecosystem of robots that share their data and knowledge and exploit their diversity to jointly learn to perform the endless variety of tasks in human environments.

IRE

Participants: Jérémie Dequidt, Christian Duriez.

IRE project on cordis.europa.eu

Title: Intelligent Robotic Endoscopes for Improved Healthcare Services

Duration: From March 1, 2024 to February 29, 2028

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- REGION HOVEDSTADEN (REGIONH), Denmark
- INSIMO, France
- AMBU A/S, Denmark
- UNIVERSITEIT TWENTE (UNIVERSITEIT TWENTE), Netherlands
- KOBENHAVNS UNIVERSITET (UCPH), Denmark
- UNIVERSITE DE LILLE (UNIVERSITE DE LILLE), France
- UNIVERSIDAD REY JUAN CARLOS (URJC), Spain
- EBERHARD KARLS UNIVERSITAET TUEBINGEN (UT), Germany

Inria contact: Christian Duriez

Coordinator: KOBENHAVNS UNIVERSITET - UCPH

Summary: In Intelligent Robotic Endoscopes (IRE) for Improved Healthcare Services we envision creating intelligent robotics solutions, extending current endoscope technology with robotics control that is based on learning from currently collected human operator data, coupled with novel biomechanical modeling techniques, and sensory feedback as well as soft robotics phantom for training.

The challenge with colonoscopy is that the success rate of detecting cancer depends on the skills of the clinician that operates the endoscope. From a health and societal perspective, the number of colonoscopies is bound to increase as they are the only way to screen patients for early cancer detection. Many European countries have national screening programs. This is a very big market in need of improved technology.

IRE enables a new generation of intelligent robots that through data, simulation and learning can interact with the interior of a living human while communicating with a human operator. The huge variation of human anatomy and the dynamic effect of human physiology make it a complicated navigational task to use endoscopes. Entanglement, haemorrhage, and perforation risks create a critical and difficult environment to navigate autonomously in where even trained human operators meet challenges. We exploit one of the largest datasets on real-life colonoscopies with more than 2,000 operations to learn safe navigation, combined with simulated training on a population of biomechanical models of the abdominal region.

IRE boosts the design and configuration of the robotic endoscope using digital twins and simulation, and careful inclusion of clinicians will speed up the process of integration. IRE will raise the level of autonomy by building upon simulation, imaging, and learning to yield an increased interpretation and understanding of the complex real- world environments, capable of anticipating the effect of human motions, adapting and replanning to avoid entanglement.

10.2.2 H2020 projects

SimCardioTest SimCardioTest project on cordis.europa.eu

Title: Simulation of Cardiac Devices & Drugs for in-silico Testing and Certification

Duration: From January 1, 2021 to June 30, 2025

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- UNIVERSITE DE BORDEAUX, France
- UNIVERSIDAD POMPEU FABRA, Spain
- UNIVERSITAT POLITECHNICA DE VALENCIA, Spain
- SIMULA RESEARCH LABORATORY AS, Norway
- INSILICOTRIALS TECHNOLOGIES S.P.A., Italy and INSILICOTRIALS TECHNOLOGIES BV, Netherlands
- SORIN CRM SAS, France
- EXACTCURE, France
- BOSTON SCIENTIFIC SCIMED, United States
- VIRTUAL PHYSIOLOGICAL HUMAN INSTITUTE FOR INTEGRATIVE BIOMEDICAL RESEARCH VZW, Belgium

Inria contact: Christian Duriez

Coordinator: INRIA, Maxime Sermesant

Summary: IComputer modelling and simulation have the power to increase speed and reduce costs in most product development pipelines. The EU-funded SimCardioTest project aims to implement computer modelling, simulation and artificial intelligence to design and test cardiac drugs and medical devices. Scientists will establish a platform for running in silico trials and obtaining scientific evidence based on controlled investigations. The simulation of disease conditions and cohort characteristics has the potential to overcome clinical trial limitations, such as under-representation of groups. It also reduces the size and duration of human clinical trials as well as animal testing, and offers robust, personalised information. Leveraging in silico technology in healthcare will expedite product and drug certification and offer patients the best possible care.

10.3 National initiatives

ANR DOMINANTS:

Participants: Gang Zheng.

Dexterity-oriented methodology in optimized design and control of soft aerial manipulators. This is a 4-year project, supported by the ANR (French National Agency for Research) in the framework of PRCI, with administrative start date being 1 October 2024. The DOMINANTS project aims to develop a novel methodology for optimized design and fast control of SAM for the purpose of increasing dexterity so that it can reach a larger workspace with the ability to quickly grasp various types of static and dynamic objects in a complex and unstructured environment.

ANR ACCESS:

Participants: Yinoussa Adagolodjo, Christian Duriez, Alexandre Kruszewski, Gang Zheng.

Actively controlled electrode for soft surgery. This is a 42-month project, supported by the ANR (French National Agency for Research) in the framework of PRCE, starting from 1 November 2024. ACCESS is the continuation of the ROBOCOP project, and it aims to create an innovative biocompatible thin film electrode array (TFEA) integrating soft actuators to be coupled with the implanted stimulator, as well as the innovative controlled/automatic robotic insertion of this TFEA into the cochlea, where the surrounding anatomical structure will be considered. ACCESS project will help the surgeon, guarantee more effective implantation by reducing insertion trauma and achieving better hearing performance after surgery.

ANR SPECULAR:

Participants: Olivier Goury, Christian Duriez.

Radiofrequency ablation of liver tumors has become the procedure of choice for many patients. However, despite their many advantages, these percutaneous procedures require advanced skills from the practitioner, particularly for interventions involving soft and mobile organs such as the liver. The aim of this project is to develop a comprehensive virtual reality training system for these procedures. To achieve this, it is necessary to simulate the interactions between the needle and virtual organs fast and realistically, and to reproduce an immersive operating room environment. This includes realistic rendering, medical image generation and haptic feedback. The results of this project will accelerate the training of these alternative approaches, and could change the standard of treatment towards much less cumbersome and traumatic approaches for patients.

ANR ROBOCOP:

Participants: Lingxiao Xun, Yinoussa Adagolodjo, Olivier Goury, Christian Duriez, Alexandre Kruszewski, Gang Zheng.

Robotization of Cochlear implant. This is a 5-year project, supported by the ANR (French National Agency for Research) in the framework of PRCE, starting from 1 October 2019 until 30 September 2024. ROBOCOP aims at creating a new prototype of cochlear implant, and robotize (i.e. actuate and control) its insertion process to facilitate the work of surgeon, to increase the success ratio, and to decrease the probability of trauma.

ANR COSSEROOTS:

Participants: Yinoussa Adagolodjo, Christian Duriez, Quentin Peyron, Gang Zheng.

Cosserat Rod Theory for Slender Robots. This is a 4 year project, supported by the ANR (French National Agency for Research) in the framework of PRC, starting from 1 November 2020 until 31 October 2024. The objective of COSSEROOTS project is to systematically investigate the relative parameterization modeling technique in order to create for the first time a toolbox dedicated to modeling and control of slender, flexible, continuous, bio-inspired robots that can undergo large, controlled deformations 7.1.5. See the associated GitHub project.

ANR Equipex+ TIRREX:

Participants: Christian Duriez, Damien Marchal, Gang Zheng.

TIRREX project aims to develop new emblematic platforms in robotics with a national coordination for their access and development. The project brings together all the major players in French academic research in robotics (CNRS, INRIA, CEA, INRAE) with 19 partners. It is structured around 6 thematic axes: Humanoid Robotics, XXL Robotics, Micro-Nano Robotics, Autonomous Terrestrial Robotics, Aerial Robotics and Medical Robotics, and transversal axes: Prototyping & Design, Manipulation, and open Infrastructure. Christian Duriez is co-responsible of the axis open Infrastructure, in particular for the development of digital twins.

PEPR-O2R:

Participants: Christian Duriez, Quentin Peyron, Jeremie Dequidt.

O2R is a national initiative that involves french major laboratories in robotics and will last 8 years starting from Jan. 2024. The focus of this ambitious program is to investigate three scientific challenges: Understanding determinants for social adaptation of robots and their links with robotic decisions and design choices; Creating integrated robot hardware and software architectures, to enable embodied intelligence and robustness faced with the complexity of their exercise and use environments; Endowing robots with capabilities for fluid interaction with humans, to favor social integration. Within this program, DEFROST is very active through two specific actions: the first one being material, architecture and embodied intelligence and the second one about simulation tools for multiphysics, multiscale robots.

10.4 Regional initiatives

CPER RITMEA:

Participants: Christian Duriez, Alexandre Kruszewski, Gang Zheng.

Design and development of soft upper limb exoskeletons. This is a 2-year project, co-financed by the region. The objective of this project is to design passive/active soft upper limb exoskeletons with the aim of simplifying the daily activities of the patient.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

General chair, scientific chair

- **Summer school "Deformations in Robotics 2024"**
  Location: Villeneuve d'Ascq, France
  Attendance: 40 international PhD students and young researchers, 18 reknown speakers
  Program: Lectures, practicals and keynotes
  Summary: The use of deformations in robotics is one of the most active fields of application and research. To train the next generation of researchers and engineers, the PEPR O2R, Inria, CNRS, Centrale Lille and the University of Lille are joining forces to organize a summer school. During one week, participants will attend lectures and practical sessions on the fundamental concepts (modelling, simulation and control) necessary for the use of deformable materials in soft robotics, continuum robotics, hybrid rigid/deformable robotics as well as in rigid robotics interacting with a deformable environment. Human sciences and art works related to deformable robotics will also be presented.

11.1.2 Scientific events: selection

Member of the conference program committees

- Quentin Peyron and Gang Zheng are associate editor for IEEE-Robosoft.

Reviewer

- Quentin Peyron was a reviewer for IEEE-ICRA, IEEE-IROS, and IEEE-RoboSoft conferences, and for the Hamlyn Symposium on Medical Robotics.
- Yinoussa Adagolodjo was a reviewer for IEEE-ICRA, IEEE-IROS, and IEEE-RoboSoft conferences.
- Christian Duriez was a reviewer for IEEE-ICRA and IEEE-RoboSoft conferences.

11.1.3 Journal

Member of the editorial boards

- Christian Duriez is associate editor of Robotics and Automation Letters (RAL).
- Gang Zheng is associate editor of IET Cyber-Systems and Robotics.

Reviewer - reviewing activities

- Quentin Peyron was a reviewer for IEEE-RAL, IEEE-TRO, Advances in Mechanical Engineering, and IJRR journals.
- Yinoussa Adagolodjo was a reviewer for IEEE-RAL, IEEE-TRO and Transactions on Haptics.
- Christian Duriez was a reviewer for IEEE Transactions on Medical Robotics and Bionics.

11.1.4 Invited talks

Yinoussa Adagolodjo:

- **Hong Kong Forum on Robotics and AI : March 26th – March 29th** (CAIR)
  Title of the presentation: Exploring the Frontiers of Deformable Robotics: from Physics-based Modeling and Real-time Simulation to Control and Contacts Handling.

- **The Journées Scientifiques Inria Chile 2024 : Dec 4th – Dec 6th** (Journées scientifiques 2024)
  Title of the presentation: Bridging the Gap: From Biomechanical Simulations to Adaptive Surgical Robotics.
- **The Latin American Summer School on Robotics : March 9th – March 13th** (LACORO)
  Title of the presentation: Bridging the Gap: From Biomechanical Simulations to Adaptive Surgical Robotics.

Christian Duriez :

- **Workshop at Eurohaptics Conference** *Title*: Modeling, Sensing and Control of Deformable Robot: Application for Haptic Device.
- **Workshop ICRA** *Title*: Simulation and model-based control of continuum manipulators.
- **Inauguration PEPR O2R** *Title*: Robotique souple, bio-inspiration et relation à l'humain.
- **IMSD Keynote & SOFA America Workshop** *Title*: Control of soft robots by real-time mechanical computation of their deformable structure.
- **HCERES evaluation of CRIStAL** : *Title*: Contrôle des robots souples par calcul mécanique en temps réel de leur structure déformable.
- **Semaine de la robotique à Nancy** : *Title* : Quand la robotique devient souple (bientôt en ligne).

11.1.5 Scientific expertise

- Gang Zheng is member of the evaluation committee of CSS-MISTI of INRAE.
- Christian Duriez was evaluator for ERC proposals.

11.1.6 Research administration

- Gang Zheng is member of Ecole Doctorale MADIS in the domain of AGITSI.
- Gang Zheng is member of CER of Inria Lille.
- Damien Marchal was head of the Jury of the nationwide Concours Interne CNRS (BAP-E, IE).
- Damien Marchal is elected member of the "commission recherche" at the University of Lille Faculty of Science.
- Christian Duriez is co-director of the PEPR O2R.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

Teaching administration

- Jérémie Dequidt is the head of the International Relations at Polytech Lille.
- Alexandre Kruszewski is in charge of the Embedded and Cyberphysical system major of Centrale Lille.
- Yinoussa Adagolodjo is the first-year supervisor in the Industrial Engineering program at Polytech Lille.

Teaching activities

- Engineering cycle: Paul Chaillou, Automatic control and embedded systems, 64h, level L2, L3 and M1, Centrale Lille.
- Engineering cycle: Alexandre Kruszewski, 14 modules (Automatic control, numeric control, embedded systems, robotics, etc.), ≈250h, level (L3, M1, M2), Centrale Lille
- Engineering cycle: Jeremie Dequidt, 6 modules (Programming, Software Engineering, Embedded Systems, Databases, Medical Simulation, etc.), ≈350h, level (L3, M1, M2), Polytech Lille
- Master: Christian Duriez, Soft robotics, 24h, M2, Graduate degree en intelligence artificielle à l'Ecole Polytechnique (Palaiseau)
- Engineering cycle: Yinoussa Adagolodjo, 10 modules (Computer science, Robotics, Automation, Optimization, Industry 4.0, Introduction to research, Industrial logic, Modeling of production systems, Learning monitoring, Test and Maintenance), ≈230h, level (L3, M1, M2), Polytech Lille, IMT Nantes
- Engineering cycle: Etienne Ménager, Programming Software Engineering, ≈64h, level (L3,M1), Polytech Lille
- Engineering cycle: Quentin Peyron, Automatique IE3 and IE4, Modélisation et commande de systèmes, ≈ 30h, level (L3,M1), Centrale Lille.
- Engineering cycle: Quentin Peyron, Introduction to soft robotics, module Cobotique et Haptique, ≈ 19h, level (M1), IMT Atlantique Nantes.
- Engineering cycle: Damien Marchal, C++ for robotics, 8h, level(M2), JUNIA Engineering school.
- Master: Damien Marchal, Option "Enjeux Environmentaux et Société", 2x24h, level(M2), University of Lille.
- Engineering cycle: Tanguy Navez, (Programming, Software Engineering, Databases), 64h, level L3 and M1, Polytech Lille.

11.2.2 Supervision

PhD students:

- Paul Chaillou, Développement d'un système de robotique souple permettant de guider le système d'analyse moléculaire in vivo temps-réel SpiderMass pour l'aide à la chirurgie des cancers (SnakeMass), supervised by I. Fournier, A. Kruszewski and C. Duriez.
- Tanguy Navez, Contributions to the Concept of Embodied Intelligence in Soft Robotics through Control and Design Co-Optimization [32], supervised by O. Goury and C. Duriez.
- Luis Maldonado, Eco-design of parallel continuum robots using bio-sourced raw materials, supervised by Q.Peyron, S. Briot and C. Duriez.
- Antoine Alessandrini, Design of new control methods to maintain compliance of deformable robots while giving them good performance, supervised by L. Hetel, A. Kruszewski and C. Duriez.
- Weize Liu, Design and control of a flexible endoscope, supervised by G. Zheng, I. Fournier and Y. Adagolodjo.
- Xin Li, Design, modeling and control of origami mechanisms, supervised by G. Zheng and F. Boyer.
- Azouaou Ouyoucef, Control of soft parallel robots, supervised by G. Zheng, Q. Peyron and F. Boyer.
- Agneyan Dileep, Fault-diagnosis and lifetime prognosis of soft robots, supervised by Q. Peyron and V. Cocquempot.

- Congjian Gao, Design of parallel continuum robots with simple input ouput laws, supervised by Q. Peyron and S. Briot.
- Lingxiao Xun, Modeling and control of active cochlear implant [33], supervised by A. Kruszewski and G. Zheng.
- Yiru Guo, Design and analysis of flexible mechanisms, supervised by G. Zheng and A. Polyakov.
- Zitong Zhang, Control of rigid-flexible coupled mechanism, supervised by G. Zheng and A. Polyakov.
- Sizhe Tian, Simulation of needle insertion into a bio-inspired active prostate phantom: Application to biopsy and brachytherapy, supervised by J. Dequidt and Y. Adagolodjo.
- Flavie Przybylski, Simulation of eversion robots, supervised by J. Dequidt and C. Duriez.

Apprentices:

- Coralie Sion (Fives ECL - Ronchin),
- Nicolas Deplanque (Fives ECL - Ronchin),
- Sofian Mertens and Hamed Rezapoor (ArcelorMittal France)

are supervised by Y. Adagolodjo.

Interns:

- Wei Ziyi, Expérimentation de mécanismes de bases sur des matériaux anisotropes, supervised by T. Navez and Y. Adagolodjo.
- Antoine Alessandrini, Soft robot force-position control, supervised by A. Kruszewski and C. Duriez.
- Yoan Arnaud, Soft robot modeling, supervised by Q. Peyron.

11.2.3 Juries

- Gang Zheng is the reviewer for the PhD of Oscar F. Gallardo Luna defended on December 17th 2024 at University Polytechnique Hauts-de-France.
- Yinoussa was a jury member of the individual thesis monitoring committee of Mr. Thuc Lang Ha (Computer Assisted Needle Therapies).
- Alexandre Kruszewski reviewed the PhD thesis of N. Testard, defended on October 2nd 2024 at Centrale Nantes.
- Christian Duriez reviewed the PhD thesis of Azad Artinian defended on Februrary 1 at Sorbonne Université.
- Christian Duriez reviewed the PhD thesis of Nariman Khaledian defended on June 12 at Université de Lorraine.
- Christian Duriez reviewed the PhD thesis of Lionel Fliegans defended on September 17 at Ecole des Mines Saint-Etienne at Campus Aix-Marseille-Provence.
- Christian Duriez reviewed the PhD thesis of Andrea Gotelli defended on December 9 at Ecole Centrale de Nantes.
- Christian Duriez was the commitee president for the PhD defense of Loïc Mosser, on June 24, at University of Strasbourg.
- Christian Duriez was the commitee president for the PhD defense of Quentin Boyer, on December 6, at Université Grenoble Alpes.

- Christian Duriez was Jury member of the PhD defense of Pasquale Ferrentino on July 2 at Vrije University of Brussels, Belgium.
- Christian Duriez reviewed the Habilitation thesis (HDR) of Vincent Lebastard defended on January 2 at IMT Atlantique.
- Christian Duriez was Jury member of the Habilitation defense (HDR) of Redwan Dahmouche on June 27 at Université Bourgogne Franche-Comté (site FEMTO Besançon).
- Christian Duriez was a member of the committee for a full professor position in (soft) robotics at Sorbonne University.

12 Scientific production

12.1 Major publications

[1] Y. Adagolodjo, F. Renda and C. Duriez. 'Coupling numerical deformable models in global and reduced coordinates for the simulation of the direct and the inverse kinematics of Soft Robots'. In: *IEEE Robotics and Automation Letters*. IEEE Robotics and Automation Letters 6.2 (7th Apr. 2021), pp. 3910–3917. DOI: 10.1109/LRA.2021.3061977. URL: https://hal.science/hal-03192168.

[2] E. Coevoet, Y. Adagolodjo, M. Lin, C. Duriez and F. Ficuciello. 'Planning of soft-rigid Hybrid arms in Contact with Compliant Environment: application to the transrectal biopsy of the prostate'. In: *IEEE Robotics and Automation Letters* 7.2 (18th Feb. 2022), pp. 4853–4860. DOI: 10.1109/LRA.2022.3152322. URL: https://inria.hal.science/hal-03729071.

[3] E. Coevoet, T. Morales Bieze, F. Largilliere, Z. Zhang, M. Thieffry, M. Sanz Lopez, B. Carrez, D. Marchal, O. Goury, J. Dequidt and C. Duriez. 'Software toolkit for modeling, simulation and control of soft robots'. In: *Advanced Robotics* 31 (23rd Nov. 2017), pp. 1208–1224. DOI: 10.1080/01691864.2017.1395362. URL: https://hal.inria.fr/hal-01649355.

[4] C. Duriez. 'Control of Elastic Soft Robots based on Real-Time Finite Element Method'. In: ICRA 2013 IEEE International Conference on Robotics and Automation. Karlsruhe, France, 2013. URL: https://hal.archives-ouvertes.fr/hal-00823766.

[5] S. Escaida Navarro, B. Hein, S. E. Navarro, S. Nagels, H. Alagi, L.-M. Faller, O. Goury, T. Morales Bieze, H. Zangl, B. Hein, R. Ramakers, W. Deferme, G. Zheng and C. Duriez. 'A Model-based Sensor Fusion Approach for Force and Shape Estimation in Soft Robotics'. In: *IEEE Robotics and Automation Letters* 5.4 (2020), pp. 5621–5628. DOI: 10.1109/LRA.2020.3008120. URL: https://hal.inria.fr/hal-02882039.

[6] O. Goury and C. Duriez. 'Fast, generic and reliable control and simulation of soft robots using model order reduction'. In: *IEEE Transactions on Robotics* 34.6 (2018), pp. 1565–1576. DOI: 10.1109/TRO.2018.2861900. URL: https://hal.archives-ouvertes.fr/hal-01834483.

[7] H. Li, L. Xun and G. Zheng. 'Piecewise Linear Strain Cosserat Model for Soft Slender Manipulator'. In: *IEEE Transactions on Robotics* 39.3 (2023), pp. 2342–2359. DOI: 10.1109/TRO.2023.3236942. URL: https://inria.hal.science/hal-03913430.

[8] E. Ménager, P. Schegg, E. Khairallah, D. Marchal, J. Dequidt, P. Preux and C. Duriez. 'SofaGym: An open platform for Reinforcement Learning based on Soft Robot simulations'. In: *Soft Robotics* (2022). URL: https://hal.inria.fr/hal-03778189.

[9] T. Morales Bieze, A. Kruszewski, B. Carrez and C. Duriez. 'Design, implementation and control of a deformable manipulator robot based on a compliant spine'. In: *The International Journal of Robotics Research* (May 2020). DOI: 10.1177/ToBeAssigned. URL: https://hal.archives-ouvertes.fr/hal-03028723.

[10] M. Thieffry, A. Kruszewski, C. Duriez and T.-M. Guerra. 'Control Design for Soft Robots based on Reduced Order Model'. In: *IEEE Robotics and Automation Letters* 4.1 (Jan. 2019), pp. 25–32. DOI: 10.1109/LRA.2018.2876734. URL: https://hal.archives-ouvertes.fr/hal-01901031.

[11] F. Vanneste, O. Goury, J. Martinez, S. Lefebvre, H. Delingette and C. Duriez. 'Anisotropic soft robots based on 3D printed meso-structured materials: design, modeling by homogenization and simulation'. In: *IEEE Robotics and Automation Letters* 5.2 (Jan. 2020), pp. 2380–2386. DOI: 10.1109/LRA.2020.2969926. URL: https://hal.inria.fr/hal-02475589.

[12] L. Xun, G. Zheng, S. Ghenna, A. Kruszewski, E. Cattan, C. Duriez and S. Grondel. 'Modeling and control of conducting polymer actuator'. In: *IEEE/ASME Transactions on Mechatronics* 495-506 (Feb. 2023). DOI: 10.1109/TMECH.2022.3211091. URL: https://hal.science/hal-03852494.

12.2 Publications of the year

International journals

[13] H. Li, L. Xun and G. Zheng. 'Global Control of Soft Manipulator by Unifying Cosserat and Neural Network'. In: *IEEE Transactions on Industrial Electronics* 71.9 (2024), pp. 10944–10954. DOI: 10.1109/TIE.2023.3331109. URL: https://inria.hal.science/hal-04325359.

[14] M. Li, A. Polyakov and G. Zheng. 'On Generalized Homogeneous Leader-following Consensus Control for Multi-agent Systems'. In: *IEEE Transactions on Control of Network Systems* 11.1 (2024), pp. 558–568. DOI: 10.1109/TCNS.2023.3290429. URL: https://hal.science/hal-04390600.

[15] T. Navez, E. Ménager, P. Chaillou, O. Goury, A. Kruszewski and C. Duriez. 'Modeling, Embedded Control and Design of Soft Robots using a Learned Condensed FEM Model'. In: *IEEE Transactions on Robotics* (2025). URL: https://hal.science/hal-04991852. In press.

[16] A. Ouyoucef, Q. Peyron, V. Lebastard, F. Renda, G. Zheng and F. Boyer. 'Duality of the Existing Geometric Variable Strain Models for the Dynamic Modeling of Continuum Robots'. In: *IEEE Robotics and Automation Letters* 10.2 (Feb. 2025), pp. 1848–1855. DOI: 10.1109/LRA.2024.3524898. URL: https://hal.science/hal-04893096 (cit. on p. 17).

[17] S. Wang, H. Duan, G. Zheng, X. Ping, D. Boutat and A. Polyakov. 'Homogeneous Control Design Using Invariant Ellipsoid Method'. In: *IEEE Transactions on Automatic Control* (2024), pp. 1–8. DOI: 10.1109/TAC.2024.3384844. URL: https://hal.science/hal-04615967.

[18] K. Wu, G. Zheng, G. Chen and S. Awtar. 'A Body-frame Beam Constraint Model'. In: *Mechanism and Machine Theory* 192 (2024), p. 105517. DOI: 10.1016/j.mechmachtheory.2023.105517. URL: https://inria.hal.science/hal-04325275.

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