IN PARTNERSHIP WITH:
CNRS

Ecole Centrale de Lille

Université des sciences et technologies de Lille (Lille 1)

Activity Report 2018

Project-Team DEFROST

DEFormable Robotics SofTware

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

RESEARCH CENTER
Lille - Nord Europe

THEME
Robotics and Smart environments

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Project-Team DEFROST

Creation of the Team: 2015 January 01, updated into Project-Team: 2017 November 01

Keywords:

Computer Science and Digital Science:

A2.3.3. - Real-time systems
A3.1.1. - Modeling, representation
A5.10. - Robotics
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.6. - Optimization
A6.4.3. - Observability and Controlability
A6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

B2.5.1. - Sensorimotor disabilities
B2.7. - Medical devices
B5.1. - Factory of the future
B5.6. - Robotic systems
B5.7. - 3D printing
B9.2. - Art

1. Team, Visitors, External Collaborators

Research Scientists

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2. Overall Objectives

2.1. Overall Objectives

The DEFROST team aims to address the open problem of control and modelling 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 robot: 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 to many cases in surgical robotics, the contact of the soft robot with the anatomy is permitted and it creates additional deformations on the robot.

3. Research Program

3.1. Introduction

Our research crosses different disciplines: numerical mechanics, control design, robotics, optimisation methods, 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 transversal 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 modelling soft robots with strong real-time constraints. To solve continuum mechanics equations, we will start our research with real-time 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...).
- Fulfill the new computational time constraints (harder than surgical simulation for training) and find better tradeoff between cost and precision of numerical solvers using reduced-order modelling techniques with error control.
- Exploring interactive and semi-automatic optimisation methods for design based on obtained solution for fast computation 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 from 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 intensity of the contact with the environment...
- 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 challenge here is to ensure / prove stability in closed-loop.

3.4. Objective 3: Modeling the interaction with a complex environment

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

- Setting up real-time modelling 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 sensor: 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 Robotic 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 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 the 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 example in order to improve the modelling and to demonstrate the concrete feasibility of our methods. On the other side, concrete applications will also feed the reflexions 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 highly diffused and is one of the ways put forward to maintain the level of competitiveness of companies based in France and to avoid relocation in cheap labor countries. Yet, in France, it is considered that the level of robotization is insufficient compared to Germany, for instance. One of the challenge is the high investment cost for buying robotic arms. In the recent years, it has led the development of "generic" and "flexible" (but rigid) robotic solution that can be produced in series. 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 need to be performed by a deformable robot: we would optimize the shape of its structure to create the set of desired motion . A second important aspect is the reduction of the manufacturing cost: It is often anticipated that the cost of deformable robots will be low compared to classical rigid robotics. 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 are particularly convenient as they provide a mass/carried load ratio several orders higher than traditional robots, highly decreasing the kinetic energy and so increasing the motion speed allowed in presence of humans. Moreover, the technology allows more efficient and ergonomic wearable robotic devices, opening the options for exo-skeletons. 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 environment. For some particular industry (chemistry, food industry...) this could also be an advantage compared to existing rigid solutions. For instance, the German company http://www.festo.com, key player in the industrial robots field, is experiencing with deformable trunk robot and we are working on their accurate control.

4.2. Personal and service robotics

The personal and service robotics are considered as an important source of economic expansion in the coming years. The potential applications are numerous and particularly 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 not comfortable. 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 textile (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 since years for cinematographic shootings, theater, amusement parc (Disney’s audio-animatronic) and performing arts. We believe that soft robots could be a good support for art. We are pursuing the collaboration with the artist Jonathan Pepe (see https://jonathan-pepe.com/Haruspices).

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Award from the Robotics Society of Japan

We received a best paper award from the *Robotics Society of Japan* for the paper entitled “Software toolkit for modeling, simulation, and control of soft robots” that have been published in the *Advanced Robotics* journal. This paper presents the SoftRobots plugin as a first unified software framework dedicated to modeling, simulation and control of soft robots.

5.1.2. Development of a New Open-Source Plugin for SOFA - Model Order Reduction

The plugin Model Order Reduction (MOR) was developed based on the work of the paper [11]. It allows to reduce a SOFA finite element model to gain simulation speed while keeping a good accuracy. It can be used in the SOFA community not only for robotics, but for any application where computational time is an issue, e.g. medical simulations. It is distributed under the GPL license and is available on github: https://github.com/SofaDefrost/ModelOrderReduction.

The plugin is a combination of C++ and Python Code. The user can define the reduction parameters using a python Script or a Graphical User Interface (GUI).

5.1.3. Echelon III: A compliant manipulator

We have participated to the grand challenge of RobotSoft conference that took place in Linorvo, Italy. We have build a robot dedicated to the manipulation competition and we got the 2nd place. A new version of the robot has been developed for the Inria Showroom, installed at Euratechnology in Lille. This version, equipped with a camera, demonstrates the ability of the robot to perform inspection tasks in a limited workspace. We plan to build a new version in 2019 to use it as a research platform, in particular to test planning and control algorithms.

5.1.4. Collaboration with Allison Okamura’s team at Stanford

This year we had a very close collaboration with the CHARM Lab directed by Allison Okamura at Stanford University. This collaboration resulted in two exchanges: A Stanford PhD student, Margaret Koehler came for 6 months from September 2017 to February 2018 in the team in Lille and Christian Duriez left 7 months of February to August 2018, (thanks to a Fulbright fellowship). We mainly investigated two projects: the haptic rendering on deformable interfaces (A publication in the RAL journal has just been accepted and will be published in 2019) and on the project “Vine Robot” (eversion locomotion). Our teams continue to work on these project. We have also applied to the “Equipe Associée” program.

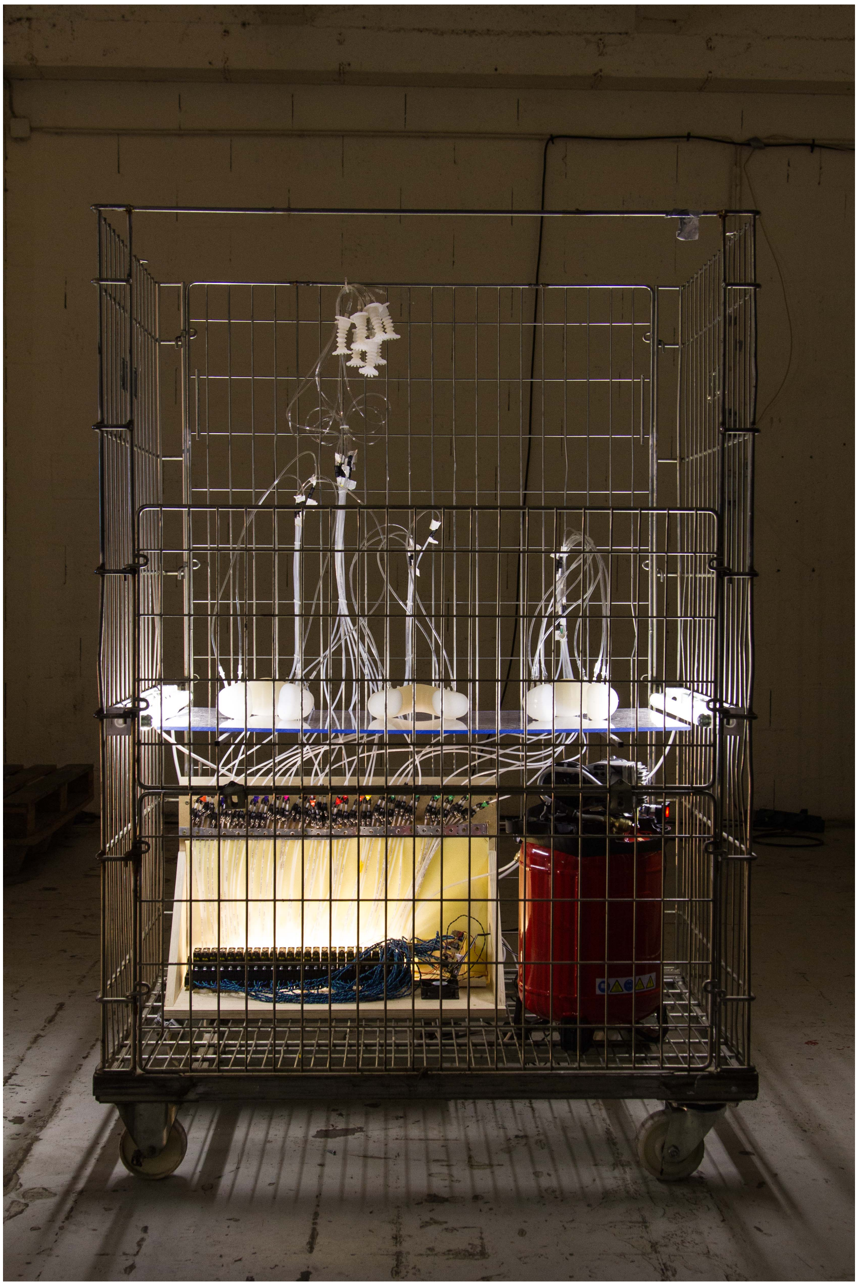

Figure 1. Exobiote project.

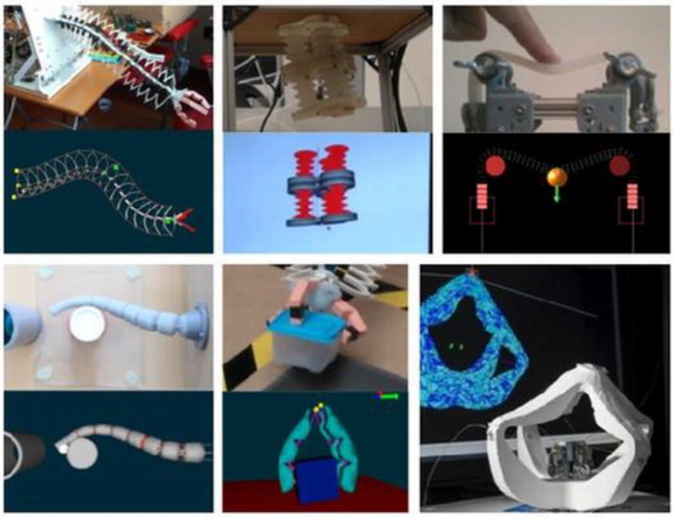

Figure 2. A unified software framework dedicated to modeling, simulation and control of soft robots [2].

Figure 3. From a computationally intensive simulation to a surrogate version saving accuracy

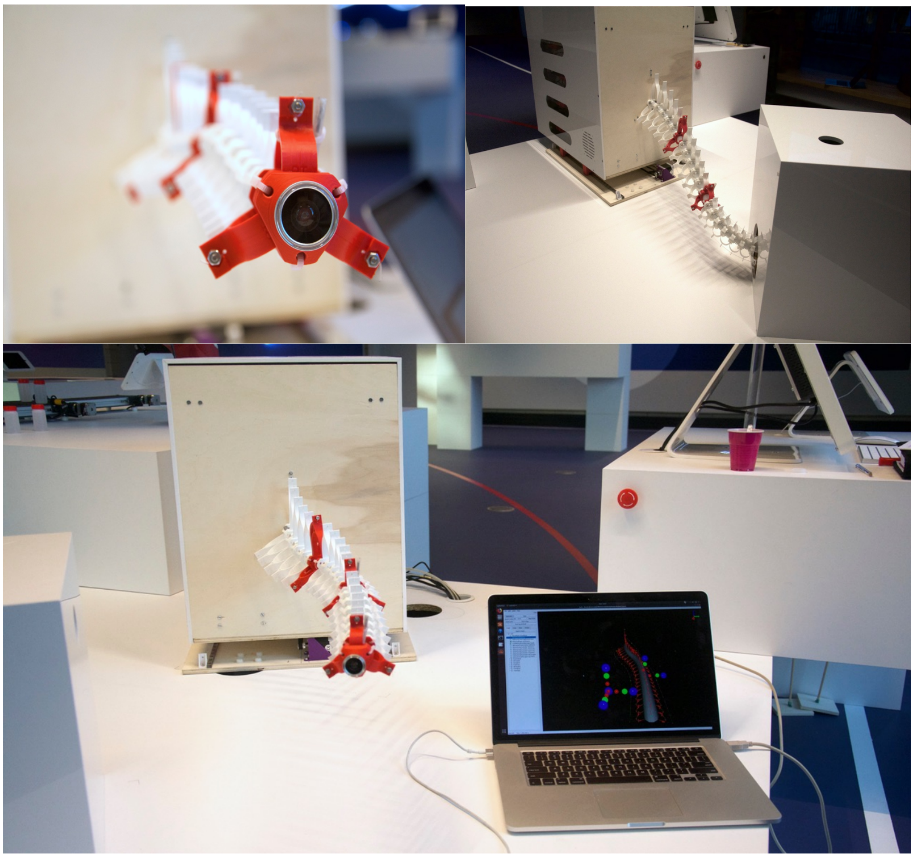

Figure 4. Echelon III in action

BEST PAPER AWARD:

[2]
E. COEVOET, T. MORALES BIEZE, F. LARGILLIERE, Z. ZHANG, M. THIEFFRY, M. SANZ-LOPEZ, B. CARREZ, D. MARCHAL, O. GOURY, J. DEQUIDT, C. DURIEZ. *Software toolkit for modeling, simulation, and control of soft robots*, in "Advanced Robotics", 2017, https://doi.org/10.1080/01691864.2017.1395362

6. New Software and Platforms

6.1. SOFA

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.

- Participants: Christian Duriez, François Faure, Hervé Delingette and Stéphane Cotin
- Partner: IGG
- Contact: Stéphane Cotin
- URL: http://www.sofa-framework.org

6.2. SoftRobots

SoftRobots plugin for Sofa
KEYWORDS: Numerical simulations - Problem inverse - Soft robotics
FUNCTIONAL DESCRIPTION: 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 https://project.inria.fr/softrobot/.

- Participants: Christian Duriez, Olivier Goury, Jérémie Dequidt, Damien Marchal, Eulalie Coevoet, Erwan Douaille and Félix Vanneste
- Contact: Christian Duriez
- URL: https://project.inria.fr/softrobot/

6.3. 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 FUNCTIONAL DESCRIPTION: This is the first version of the plugin.

NEWS OF THE YEAR: Publication using this plugin accepted dans IEEE Transactions on Robotics

- Participants: Olivier Goury, Félix Vanneste, Christian Duriez and Eulalie Coevoet
- Contact: Olivier Goury
- Publication: Fast, generic and reliable control and simulation of soft robots using model order reduction
- URL: https://project.inria.fr/modelorderreduction/

6.4. SoftRobots.Inverse

KEYWORDS: Sofa - SoftRobots

FUNCTIONAL DESCRIPTION: This plugin builds on the plugin SoftRobots (https://project.inria.fr/softrobot/). Inside the plugin, there is 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 a the closest possible configuration than 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.

- Partners: CNRS - Université de Lille - Ecole Centrale de Lille
- Contact: Christian Duriez
- URL: https://project.inria.fr/softrobot.inverse

7. New Results

7.1. Dynamic control of soft robots

The objective is to design a closed-loop strategy to control the dynamics of soft robots. We model the soft robot using the Finite Element Method, which leads to work with large-scale systems that are difficult to control. No unified framework exist to control these robots, especially when considering their dynamics. The main contribution of our work is a reduced order model-based control law, that consists in two main features: a reduced state feedback tunes the performance while a Lyapunov function guarantees the stability of the large-scale closed-loop systems. The method is generic and usable for any soft robot, as long as a FEM model is obtained. Simulation and real robots experiments show that we can control and reduce the settling time of the soft robot and make it converge faster without oscillations to a desired position. It can make the robot converge faster and with reduced oscillations to a desired equilibrium state in the robot's work-space. These results have been presented at the European Control Conference [24] and accepted for publication in Robotics and Automation Letters [8].

7.2. Vision-based force sensing for soft robots

This paper proposes a new framework of external force sensing for soft robots based on the fusion of vision-based measurements and Finite Element Model (FEM) techniques. A precise mechanical model of the robot is built using real-time FEM to describe the relationship between the external forces acting on the robot and the displacement of predefined feature points. The position of these feature points on the real robot is measured using a vision system and is compared with the equivalent feature points in the finite element model. Using the compared displacement, the intensities of the external forces are computed by solving an inverse problem. Based on the developed FEM equations, we show that not only the intensities but also the locations of the external forces can be estimated. A strategy is proposed to find the correct locations of external forces among several possible ones. The method is verified and validated using both simulation and experiments on a soft sheet and a parallel soft robot (both of them have non-trivial shapes). The good results obtained from the experimental study demonstrate the capability of our approach.

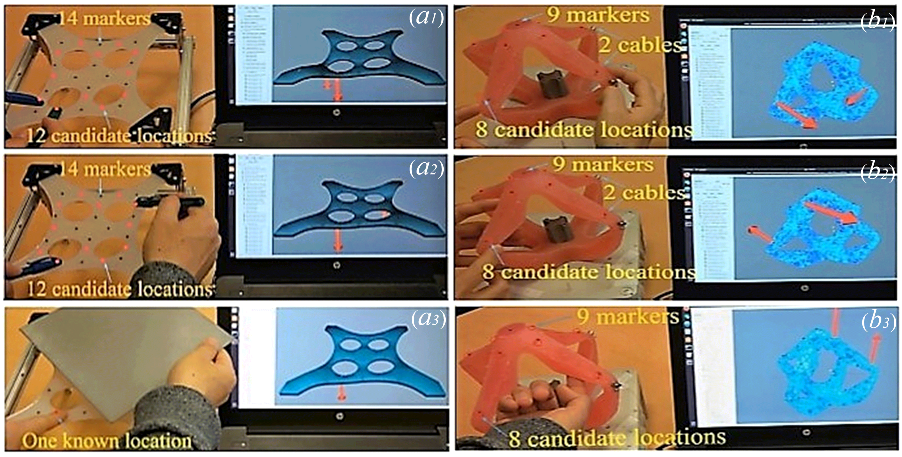

Figure 5. External force sensing for soft objects

7.3. Fast, generic and reliable control and simulation of soft robots using model order reduction

Obtaining an accurate mechanical model of a soft deformable robot compatible with the computation time imposed by robotic applications is often considered as an unattainable goal. This paper should invert this idea. The proposed methodology offers the possibility to dramatically reduce the size and the online computation time of a Finite Element Model (FEM) of a soft robot. After a set of expensive offline simulations based on the whole model, we apply snapshot-proper orthogonal decomposition to sharply reduce the number of state variables of the soft robot model. To keep the computational efficiency, hyper-reduction is used to perform the integration on a reduced domain. The method allows to tune the error during the two main steps of complexity reduction. The method handles external loads (contact, friction, gravity...) with precision as long as they are tested during the offline simulations. The method is validated on two very different examples of FE models of soft robots and on one real soft robot. It enables acceleration factors of more than 100, while saving accuracy, in particular compared to coarsely meshed FE models and provides a generic way to control soft robots.

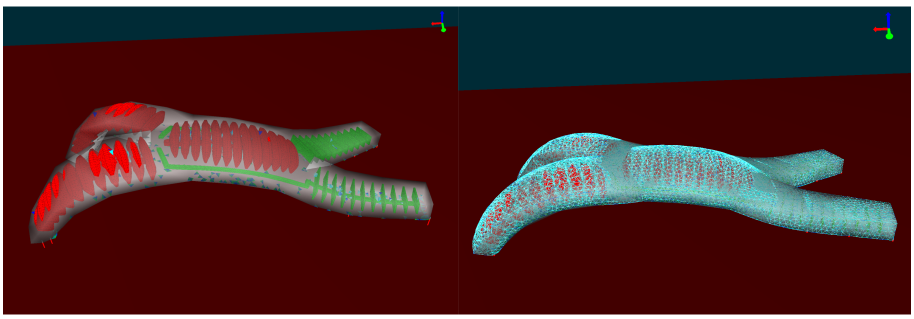

Figure 6. Pneumatic Soft Robot fine simulation versus its surrogate reduced representation manageable in real-time.

7.4. FEM-based kinematics and closed-loop control of soft, continuum manipulators

This paper presents a modeling methodology and experimental validation for soft manipulators to obtain forward and inverse kinematic models under quasistatic conditions. It offers a way to obtain the kinematic characteristics of this type of soft robots that is suitable for offline path planning and position control. The modeling methodology presented relies on continuum mechanics which does not provide analytic solutions in the general case. Our approach proposes a real-time numerical integration strategy based on Finite Element Method (FEM) with a numerical optimization based on Lagrangian Multipliers to obtain forward and inverse models. To reduce the dimension of the problem, at each step, a projection of the model to the constraint space (gathering actuators, sensors and end-effector) is performed to obtain the smallest number possible of mathematical equations to be solved. This methodology is applied to obtain the kinematics of two different manipulators with complex structural geometry. An experimental comparison is also performed in one of the robots, between two other geometric approaches and the approach that is showcased in this paper. A closed-loop controller based on a state estimator is proposed. The controller is experimentally validated and its robustness is evaluated using Lyapunov stability method.

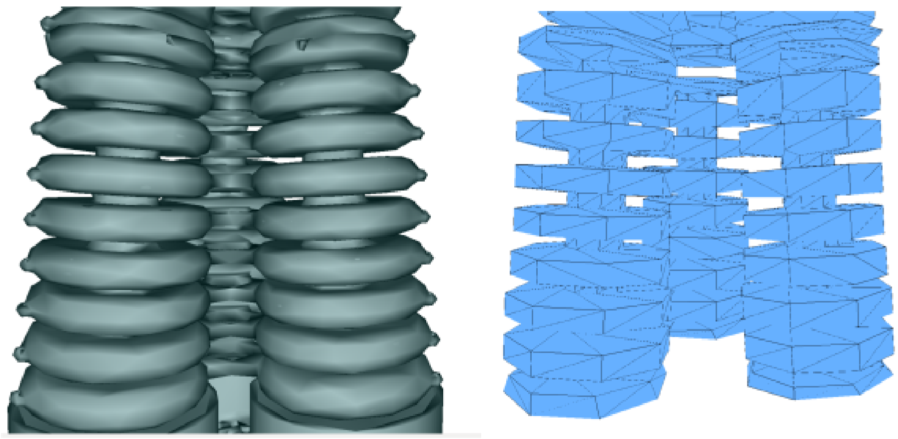

Figure 7. Visual model of the manipulator and the underlying finite element model.

7.5. FEM-based Deformation Control for Dexterous Manipulation of 3D Soft Objects

In this project, that was organize through a collaboration with Fanny Ficuciello from University of Naples and Antoine Petit from Mimesis team in Strasbourg we developed a method for dexterous manipulation of 3D soft objects for real-time deformation control, relying on Finite Element modelling. The goal is to generate proper forces on the fingertips of an anthropomorphic device during in-hand manipulation to produce desired displacements of selected control points on the object. The desired motions of the fingers are computed in real-time as an inverse solution of a Finite Element Method (FEM), the forces applied by the fingertips at the contact points being modelled by Lagrange multipliers. The elasticity parameters of the model are preliminarily estimated using a vision system and a force sensor. Experimental results were shown with an underactuated anthropomorphic hand that performs a manipulation task on a soft cylindrical object.

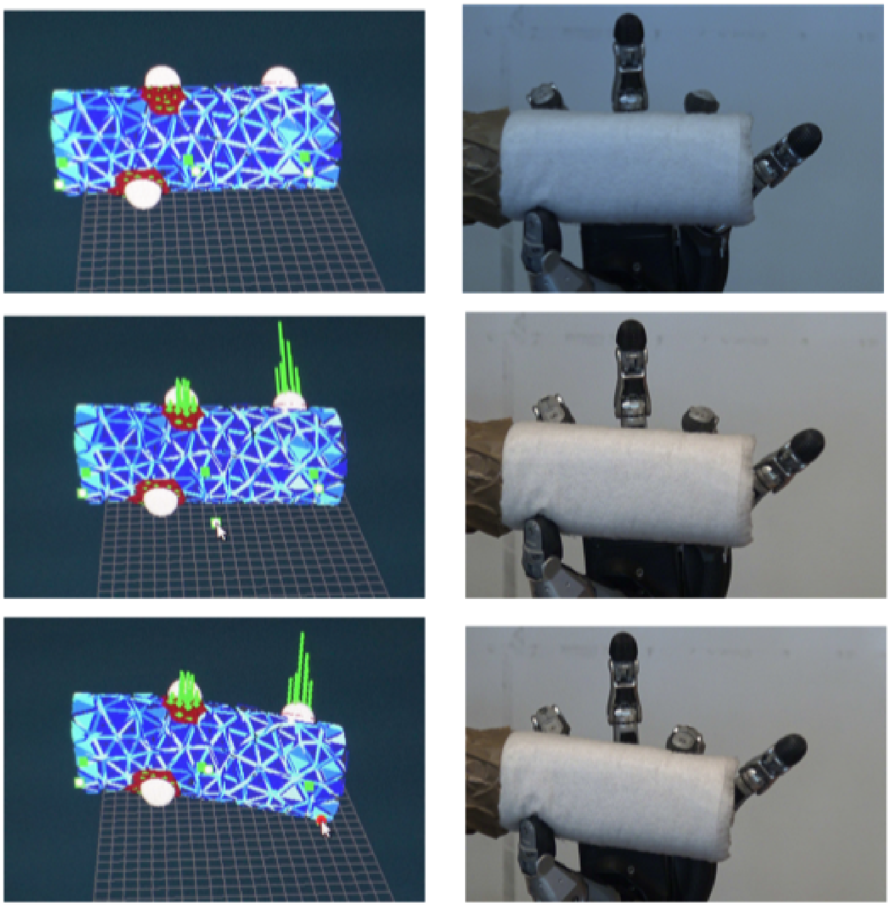

Figure 8. The manipulation of the 3D Soft Object inside the hand is driven by the inverse FEM simulation computed in real-time

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

TDR group is a robotics integrator specialized on optimizing production chains, usually multiplexing robots to perform several activities. Hence, their interest in graspers and the time invested in this activity has been growing within the last years. To improve this aspect, we have been developing together a concept of "universal grasper", based on soft robotics technology and capable of grasping an object with an arbitrary shape, and partially misplaced or misoriented. The prototype developed complies with the specifications and allows for scalability, with flexibility between grasping force and shape tolerance, and the ability for replacing objects without the need of an external vision system. Relying in SOFA for physical simulation, we have validated a prototype, and realize it. An industrial version of the prototype has been realized this year. It will be commercialized next year.

9. Partnerships and Cooperations

9.1. Regional Initiatives

- **INVENTOR** Innovative tool for soft robot design and its application for surgery. This project is financed by **I-Site ULNE EXPAND**, supported by "le programme d'Investissements d'Avenir" and "la Métropole Européenne de Lille". The objective of this project is to develop an innovative tool for the facilitation of soft robot design.
- **COMOROS** Control of deformable robots for surgery Duration april 2017 to march 2020

  Program: FEDER Coordinator: C. Duriez Abstract: Surgical procedures are often carried out using instruments made of stiff materials that interact with delicate biological tissues such as internal organs, blood vessel walls and small cavities. This incompatibility of stiffness is one of the sources of danger in many surgical procedures. The use of robots made of soft materials, also called soft robots, would limit such risks by reducing contact pressures and stress concentrations. Their intrinsic deformability would also increase the ability to manoeuvre in confined spaces. However, the promising concept of using soft robots for surgical procedures cannot be practically implemented, due to the lack of precise modelling and control methods for soft robots. This scientific obstacle, identified as a pending issue by major surveys in this field, becomes particularly challenging when interacting with an environment as complex as the human anatomy. Drawing on our background in soft tissue simulation, contact models, surgical applications and soft robotics, our ambition in this project is to:

  - Develop accurate and generic numerical methods for continuum mechanics, adapted to strong real-time constraints in order to demonstrate the ability to model soft mechatronics systems.
  - Reconsider parametrization methodologies of digital models of the patient anatomy through the observation of mechanical interactions with soft robots via embedded sensors and medical imaging
  - Rethink motion generation and teleoperation control with force feedback so as to be compatible with the large number of degrees of freedom of soft robots and be based on accurate, rapidly-computed deformable models and interaction models.

  The project also targets the development of software with the required performance and features, as well as the experimental validation of models and methods using prototypes in realistic environments.

9.2. National Initiatives

- **SIMILAR** Soft robotIc framework for modeling, simulation and control. This project is supported by **Inria ADT**, and the objective is to design new 3D interactive software to design soft-robots. This new software will be on the top of our existing software stack relying on SOFA for all numerical simulation aspects and 3D rendering aspects.
- **Tremplin ERC** Christian Duriez received a **ANR** grant "tremplin ERC" (150k€) given the result obtained last year on the ERC proposal (evaluated at "grade A"). The project has allowed to allocate new resources on the developments that were presented in this ERC.

9.3. European Initiatives

9.3.1. Collaborations in European Programs, Except FP7 & H2020

Meichun Lin was doing a project belonged to Interreg - 2 Seas Mers Zeeën on Cooperate Brachytherapy(CoBra), it is a 4 years project which gathers the experts from the countries between English Channel and southern North Sea aiming on finding an advance method for curing prostate cancer. The project is divided by several fields which are - MR compatible robot design, radiation dose measurement, needle design and virtual real-time training tool development. Meichun was working on developing virtual real-time training tool with Defrost team. By using SOFA framework to simulate the soft tissue's deformation and the interaction with needle under the real-time, also with the Image Modelling of MRI, Organs and tissue Modelling and so on and so forth, the 3D rendering became more like the real procedure of the brachytherapy and better for training purpose.

9.4. International Initiatives

9.4.1. Inria International Labs

Christian Duriez realized a geographical mobility as part of the program Inria @ SiliconValley. More details in the Highlights section.

9.4.2. Inria International Partners

9.4.2.1. Declared Inria International Partners

Collaboration with the group of Allison Okamura at Stanford University

Christian Duriez was awarded of a Fulbright Grant for going 7 months (February to August 2018) at Stanford University to work with the group of Allison Okamura. One of a phD student of Stanford, Margaret Koehler, has been awarded of a Chateaubriand Grant for coming 6 months (September 2017 to February 2018) in our Group in Lille. The collaboration was about 2 projects. The first project is haptic rendering with deformable robotics device. The second project is about the modeling and simulation of the "vine robot" that is currently being designed at Stanford.

9.4.2.2. Informal International Partners

- Collaboration with Massachusetts Institute of Technology:

  Maxime Thieffry spent a month in the Distributed Robotics Laboratory, CSAIL, MIT, for a collaboration with Robert Katzschmann and Daniela Rus. This work led to a submission to the soft robotics conference, RoboSoft 2019.
- Collaboration with Dipartimento di Ingegneria Elettrica e delle Tecnologie dell'Informazione, Napoli:

  The project was on the control of manipulation tasks. Using the SoftRobots.Inverse plugin we allowed the control of the shape of a deformable object manipulated by a rigid hand. In the paper [20] we demonstrate the feasibility of the method.

9.5. International Research Visitors

- Prof. Shunjie LI from Nanjing University of Information Science and Technology (China) visited the team from May 10, 2018 to June 30, 2018.

9.5.1. Visits of International Scientists

9.5.1.1. Internships

Margaret Koehler, phD student at Stanford University, has been awarded of a Chateaubriand Grant for coming 6 months (September 2017 to February 2018) in our Group in Lille.

9.5.2. Visits to International Teams

9.5.2.1. Sabbatical programme

This year, Christian Duriez realized a geographical mobility, since he was invited for 7 months in the team of Allison Okamura (Stanford University). He worked on two projects: the creation of deformable haptic interfaces and the mechanical modeling of the "vine robot" (https://www.vinerobots.org). The trip was funded in part by a Fulbright scholarship.

In addition, a doctoral student of their team, Margaret Koehler, makes a stay of 6 months paid by a Chateaubriand Fellowship.

These exchanges are part of the program Inria @ SiliconValley. See the interview of C. Duriez and the interview of M. Koehler.

9.5.2.2. Research Stays Abroad

- Gang ZHENG has visited Nanjing University of Science and Technology (China) for two weeks in July 2018.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- Gang Zheng is a vice-chair of the IFAC Technical Committee "Social Impact of Automation", International Federation of Automatic Control, TC9.2
- Gang Zheng is co-chair of the working group "Commande et pilotage en environnement incertain" of GRAISYHM

10.1.1.2. Member of the Organizing Committees

- Gang Zheng, Associate Editor, SIAM CT19, Chengdu, China (SIAM Conference of Control & Its Applications 2019)

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- Gang Zheng is IPC member of SIAM-CT19, ICSRT 2019, ICFCTA 2019.

10.1.2.2. Reviewer

Kruszewski:

- ICRA
- ECC
- ACC

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Gang Zheng is the member of Editorial Board, Journal of Control Science and Engineering.
- Christian Duriez is member of Editorial Board of IEEE Transactions on Haptics

10.1.3.2. Reviewer - Reviewing Activities

Kruszewki:

- Systems & Control Letters
- Fuzzy Sets and Systems
- IEEE TFS
- Automatica
- IET Control Theory & Applications
- IEEE TCST
- IEEE Transactions on Industrial Informatics
- Nonlinear Analysis: Hybrid Systems

Olivier Goury:

- IEEE Robotics and Automation Letters

Christian Duriez:

- IEEE Robotics and Automation Letters
- IEEE Transactions on Robotics
- ACM Transactions on Graphics
- Computer Methods in Applied Mechanics and Engineering

Thor Morales Bieze:

- MDPI Actuators
- IEEE Transactions on Robotics
- Soft Robotics
- IEEE Robotics & Automation Magazine

10.1.3.3. Tutorials

- A tutorial on the Soft-Robotics plugin for SOFA was presented at the IEEE International Conference on Soft Robotics (Robosoft 2018) in Livorno.
- Tutorials about SOFA Plugins *BeamAdapter*, *Soft-Robots* and *Model Order Reduction* were presented during the 1st International SOFA week 2018 in Strasbourg.

10.1.4. Invited Talks

Christian Duriez:

- Stanford Robotic Seminar
- Harvard School of Engineering
- University of Madison Department of Mechanical Engineering
- Tufts University, Soft robotics seminar
- MIT CSAIL
- Toyota Research (Los Altos, California)
- Séminaire de Robotique, Université Jules Verne d’Amiens

10.1.5. Leadership within the Scientific Community

Christian Duriez has been invited to participate to the NSF-NIST-DARPA- workshop on “Simulation and Machine Learning in Robotics”. The outcome was to have an impact on the future calls of research projects in the field.

10.1.6. Scientific Expertise

Christian Duriez has been expert for evaluation of ANR Projects and is an evaluator of the European project (FET) Hybridheart. Damien Marchal has been expert for evaluation of HCERES.

10.1.7. Research Administration

A. Kruszewski and C. Duriez are members of the Laboratory council (CRIStAL). C. Duriez is vice-president of the “Commission des Emplois de Recherche” of Lille. O. Goury is an elected member of the “Comité de Centre” of Inria Lille.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Ingénieur: Kruszewski, Start & Go Metallophone, 15h, niveau L3, Centrale Lille, France

Ingénieur: Kruszewski, Start & Go Robotique, 46h, niveau L3, Centrale Lille, France

Ingénieur: Kruszewski, Start & Go Conception et environnement, 6h, niveau L3, Centrale Lille, France

Ingénieur: Kruszewski, Modélisation et commande de système: application à la robotique, 17h, niveau L3, Centrale Lille, France

Ingénieur: Kruszewski, Projet recherche, 12h, niveau M1, Centrale Lille, France

Master 2: Christian Duriez, Simulation physique interactive, 24h, Université de Lille

10.2.2. Supervision

PhD in progress: Thieffry, Modélisation et contrôle de robots déformables à grande vitesse, 01/09/2016, C. Duriez, T.M. Guerra, A. Kruszewski

PhD in progress: Zhang, New methods of visual servoing for soft-robots, 01/10/2015, C. Duriez, J. Dequidt, A. Kruszewski

PhD in progress: Coevoet, Méthodes d’optimisation pour la robotique déformable, 01/05/2017, C. Duriez

PhD in Progress: F. Vanneste, Design and simulation of Soft Robots made of mesostructured materials, 01/12/2018, C Duriez, O. Goury

PhD in Progress: Walid Amehri, Property analysis of soft robots, G. Zheng, A. Kruszewski

10.2.3. Juries

Christian Duriez a participé aux jurys suivant:

PhD: Yinoussa Adagolodjo, Couplage de La robotique et de la simulation médicale pour les procédures automatisées, Université de Strasbourg, septembre 2018, M De Matelin et H. Courtecuisse (président du jury)

PhD: Inderjeet Singh, Curve Based Approach for Shape Reconstruction of Continuum Manipulators, R. Merzouki (examinateur)

PhD in progress: Camille Krewcun, Simulation personnalisée de l’implantation de stent à partir de la géométrie coronaire acquise en imagerie OCT, phD start: 1er octobre 2016 , encadrant(s): Laurent Sarry, Émilie Péry

PhD in progress: LAGNEAU Romain, Data-driven models for dexterous manipulation of robots, Maud MARCHAL, Alexandre KRUPPA

10.3. Popularization

- Damien Marchal, Olivier Goury and Christian Duriez participated in “Fête de la science: Opération Chercheurs itinérants”, which involves giving scientific lectures in middle and high schools.
- Olivier Goury presneted a tutorial for the “Journée de l’Enseignement de l’Informatique et de l’Algorithmique (Journée JEIA)”, which is an event for high school teachers willing to learn more about computer science.
- Olivier Goury et Thomas Morzadec took part in the “Journée RIC (Recherche - Innovation - Créativité)”, happening at IMT Lille Douai. A demonstration was made for students of engineering schools and the university of Lille.

10.3.1. Interventions

- National events: Fête de la Science: participations à l’opération “chercheur itinérant”.

10.3.2. Creation of media or tools for science outreach

Développement du site hands-soft-robotics. http://handsonsoftrobotics.lille.inria.fr/

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Major publications by the team in recent years

[1] E. Coevoet, A. Escande, C. Duriez. *Optimization-based inverse model of soft robots with contact handling*, in "IEEE Robotics and Automation Letters", 2017, vol. 2, n^{O} 3, pp. 1413–1419

[2] *Best Paper*
E. Coevoet, T. Morales Bieze, F. Largilliere, Z. Zhang, M. Thieffry, M. Sanz-Lopez, B. Carrez, D. Marchal, O. Goury, J. Dequidt, C. Duriez. *Software toolkit for modeling, simulation, and control of soft robots*, in "Advanced Robotics", 2017, https://doi.org/10.1080/01691864.2017.1395362.

[3] C. Duriez, E. Coevoet, F. Largilliere, T. Morales Bieze, Z. Zhang, M. Sanz-Lopez, B. Carrez, D. Marchal, O. Goury, J. Dequidt. *Framework for online simulation of soft robots with optimization-based inverse model*, in "SIMPAR: IEEE International Conference on Simulation, Modeling, and Programming for Autonomous Robots", San Francisco, United States, Proceedings of SIMPAR 2016 conference, December 2016, https://hal.inria.fr/hal-01425349

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[6] F. Largilliere, E. Coevoet, M. Sanz-Lopez, L. Grisoni, C. Duriez. *Stiffness rendering on soft tangible devices controlled through inverse FEM simulation*, in "International Conference on Intelligent Robots and Systems - IROS 2016", Daejeon, South Korea, October 2016, https://hal.inria.fr/hal-01386787

[7] T. Morales Bieze, F. Largilliere, A. Kruszewski, Z. Zhang, R. Merzouki, C. Duriez. *FEM-based kinematics and closed-loop control of soft, continuum manipulators*, in "soft robotics", 2018, https://hal.archives-ouvertes.fr/hal-01745625

[8] M. THIEFFRY, A. KRUSZEWSKI, C. DURIEZ, T.-M. GUERRA. *Control Design for Soft Robots based on Reduced Order Model*, in "IEEE Robotics and Automation Letters", 2018

[9] Z. ZHANG, J. DEQUIDT, A. KRUSZEWSKI, F. LARGILLIERE, C. DURIEZ. *Kinematic Modeling and Observer Based Control of Soft Robot using Real-Time Finite Element Method*, in "IROS2016 - IEEE/RSJ International Conference on Intelligent Robots and Systems", Daejeon, South Korea, October 2016, https://hal.inria.fr/hal-01370347

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[11] O. GOURY, C. DURIEZ. *Fast, generic and reliable control and simulation of soft robots using model order reduction*, in "IEEE Transactions on Robotics", 2018, https://hal.archives-ouvertes.fr/hal-01834483

[12] Z. KADER, G. ZHENG, J.-P. BARBOT. *Finite-time and asymptotic left inversion of nonlinear time-delay systems*, in "Automatica", April 2018, https://hal.archives-ouvertes.fr/hal-01781561

[13] K. LANGUEH, G. ZHENG, T. FLOQUET. *Impulsive fixed-time observer for linear time-delay systems*, in "Journal of The Franklin Institute", May 2018, vol. 355, n° 7, pp. 3354 - 3366 [*DOI :* 10.1016/J.JFRANKLIN.2018.02.019], https://hal.archives-ouvertes.fr/hal-01932968

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