Real-time FEM based control of soft surgical robots

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1 Introduction

Surgical robots, such as the Da Vinci©, interact with delicate biological structures such as blood vessels or internal organs. However, they are made of rigid materials that limit their ability of moving through confined spaces without inducing excessive contact pressures and stress concentrations which could create new injuries. An alternative solution, potentially easier to produce and suitable for interventions where the highest precision (less than a few millimeters) is not necessary, is growing in the scientific community with the development of robots made of soft materials [1]. This type of robots allows for a safer contact with internal organs and displacement among them at the cost of an increase in the complexity of control. Indeed, soft robots can dissipate the energy of collision and comply with the shape of their environment through their internal deformation. However, their infinite number of degrees of freedom does not allow to compute inverse kinematics easily. Also, the idea of using a large number of actuators to simplify the control is countered by the fact that these actuators are coupled together through the whole deformation of the robot.

Although soft, these robots could still be used in situations where medical instruments need to stay in a fixed position, by rigidifying a robot filled with particles jammed through vacuum actuation [2] .

To address the problem of controlling these robots, traditional robotic methods cannot be used because the coupling between actuators and effectors is constantly modified through the deformation of the robot. This is why it is necessary to know the influence of applied forces on the structure while controlling it. In this purpose, we have developed a new method of control [3] based on the real-time inverse simulation with internal deformation computed through the use of Finite Element Method (FEM). It was coded in SOFA, an open-source framework that contains fast implementations of FEM as well as optimization methods for collision response and mechanical interactions with haptic feedback. This work has demonstrated its first proofs on various numerical examples but also on a real deformable robot made of silicone and actuated through cables.

2 Method

To model the large non-linear deformations undergone by the soft structure, a corotational volume FEM formulation [4] is used in this work. At each step i of the real-time simulation, the internal forces are linearized as follows:

$$\mathbf{f}(\mathbf{x_i}) \approx \mathbf{f}(\mathbf{x_{i-1}}) + \mathbf{K}(\mathbf{x_{i-1}})d\mathbf{x} \quad (1)$$

where $\mathbf{f}$ represents the volumetric internal stiffness forces at a given position $\mathbf{x}$ of the nodes, $\mathbf{K}(\mathbf{x})$ is the tangent stiffness matrix that depends on the actual position of the nodes and $d\mathbf{x}$ is the displacement of nodes between two steps $d\mathbf{x} = \mathbf{x_i} - \mathbf{x_{i-1}}$.

In a first approach, we want the model to be in static equilibrium state regarding internal and external forces, which is acceptable for quasi-static motions i.e for low velocities. The following equation has then to be solved:

$$-\mathbf{K}(\mathbf{x_{i-1}})d\mathbf{x} = \mathbf{p} + \mathbf{f}(\mathbf{x_{i-1}}) + \mathbf{J}^T\boldsymbol{\lambda}. \quad (2)$$

where $\mathbf{p}$ represents the external forces (e.g. gravity) and $\mathbf{J}^T\boldsymbol{\lambda}$ gathers the contributions of the actuators through a product between $\mathbf{J}^T$ and $\boldsymbol{\lambda}$ that are respectively the direction of the forces and their unknown intensities.

Then, we use the following algorithm :

- First, a free configuration is found by solving the previous equation with $\boldsymbol{\lambda} = 0$. We can then compute the violation of the desired positions before the appropriate actuation.
- Secondly, the following projection into constraint space is used :

$$\boldsymbol{\delta} = \underbrace{\left[\mathbf{J}\mathbf{K}^{-1}\mathbf{J}^T\right]}_{\mathbf{W}}\boldsymbol{\lambda} + \boldsymbol{\delta}^{\text{free}} \quad (3)$$

  where $\boldsymbol{\delta}^{\text{free}}$ and $\boldsymbol{\delta}$ are respectively the violations before actuation and the one after actuation i.e to be minimized by the control. A Gauss-Seidel iterative solver is used to find a solution for the couple ($\boldsymbol{\lambda}$,$\boldsymbol{\delta}$)
- Finally, the free configuration of the robot is updated according to the influence of the forces $\mathbf{J}^T\boldsymbol{\lambda}$ previously calculated to obtain the configuration under actuation.

The constraint on the terminal actuator is set by assigning its three directions of displacement (x, y and z) and forcing $\boldsymbol{\lambda}$ at zero, as a non-directly actuated point. This formulation of the problem allows for various actuators to be modeled by taking into account their physical characteristics (directional of actuation, unilateral (e.g pulling cable)/bilateral actuation, limited stroke) through the use of bilateral or unilateral constraints. Pneumatic actuation can also be used via normal constraint applied to selected faces of the deformable cavity.

3 Coupling with soft-tissue models

When using FEM, it is usual to impose the load and get the displacements (or deformations), which could be considered as a direct mechanical model in robotics. On the contrary, what the algorithm presented here does is a novel use of FEM to obtain an inverse mechanical model. However, taking into account all degrees of freedom of the model would be too much expensive for the algorithm to be real-time. This is why a compliance matrix $\mathbf{W}$ condensed in the constraint space is used. This matrix holds only the modeling of the mechanical coupling between each actuator and effector (or other actuators) so that it can be used in the inverse algorithm computed fast enough to be efficient.

With very small changes in the algorithms, [5] uses the method for parametrization of soft-tissue models by inverse simulation. It is applied to semi-automatic registration for adaptive radiotherapy. Indeed, the same condensation strategy is used to find the parameters and the boundary conditions (physics-based external loads) that provide the displacements that are observed on the images. This strategy is very important in the context of the navigation of a surgical soft robot interacting with the soft-tissue environment of the patient (see figure 1)

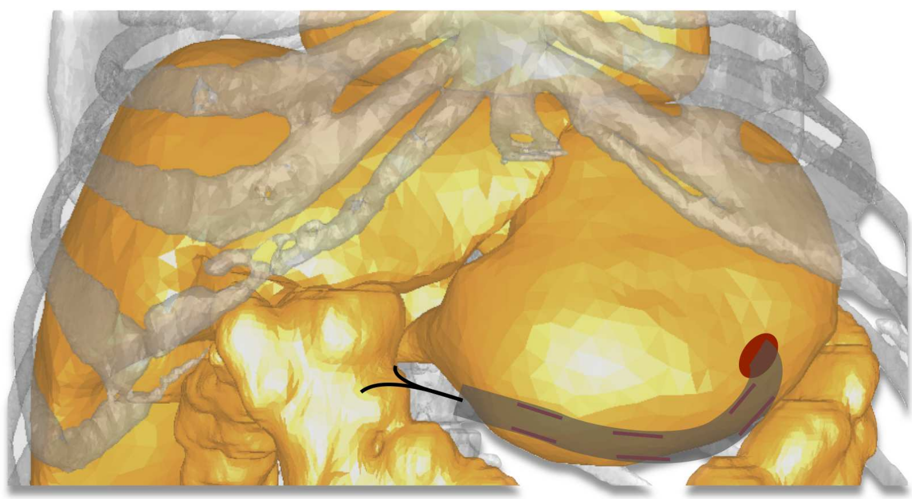

Fig. 1. The concept of a soft laparoscopic robot. Thanks to its flexibility, the robot can access difficult areas, while preventing hard contact stress with the wall of the soft tissues. Both patient anatomy deformations and soft robot would require FEM inverse method

The presentation will show how we envision to couple this inverse FEM method to provide online both control of the robot and registration of a physics-based model of the patient.

4 Conclusion

This work presents the use of a FEM inverse model, computed in real-time to control the motion of the soft robot. We also show that this inverse model strategy can be used to parametrize the modeling of the soft tissues of a patient by registration of the deformations. From these works, we can consider the development of a real-time simulation that could be used during a surgical intervention to control a soft robot that could navigate among organs whose positions and properties would be updated and taken in consideration while choosing how to plan the movements of the robot and how to actuate it. Another possible application is the control of soft robotic organs for realistic surgery training.

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