An Overview of Modeling and Control Techniques for Soft Robots

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ABSTRACT

Soft Robotics' developments pose a promising advancement in key health care areas such as surgical interventions, medical therapies and rehabilitation. Some of the research work efforts are aimed to develop devices compliant to human, with a higher level of dexterity, autonomy and capable to reach complex body cavities and adapt to the environment, among other characteristics.

In order to be able to commercialize these devices for medical applications, a rigorous and comprehensive understanding of system behavior and performance, as well as an accurate design for controllability, is required to ensure that the devices will comply with the specified requirements and are safe to use.

Modeling and Control techniques capable of accurately describing the mechanical behavior of highly deformable devices (non-linear systems) that will operate iteratively with the environment is key to the successful realization of these devices.

This work presents an overview of recent research in modeling and control of Soft Robots, as well as a summary of main commonalities and challenges encountered.

Keywords

Modeling, Simulation, Control of Soft Robots. Soft Robotics in Medical Devices, Surgical Instruments.

1. INTRODUCTION

The field of robotics has emerged with new trends in the use of soft and compliance devices that utilize flexible or deformable materials and sources of power and sensing [5]. These devices pose higher dexterity levels, can reach complex areas of body [3] and are more compliant for human use. As stated by Duriez et al [2], the soft structures offer an infinite number of degrees of freedom (dof) and redundant actuation which provides additional benefits in maneuvering inside the body while interacting with soft organs and tissue, as is the case with medical and surgical robotics applications.

The motion of a soft robot is dependent on its deformation [6][2]. The modeling and control of a soft device or robot is complex because of the multiple degrees of freedom, highly deformable structure, non-linear behavior, redundant actuation and unpredictable interactions with the environment that will impose additional deformations and changes in the systems' intended motion or dynamics, among other constraints [1][2].

Therefore, research work to develop new and robust techniques is key to be able to accurately model and control the robot. This paper presents an overview of recent research related to methods and techniques in modeling and control of soft robots.

2. MODELING OF SOFT ROBOTS

Conventional modeling, control techniques and kinematic equations used in rigid mechanisms does not directly apply to soft robots**.** Continuum mechanics methods have been used to formulate the dynamic description of a continuum, particularly it is being used to study deformations and behavior of elastic non-linear systems. [7][2]. The constitutive laws of a continuum system describe the relations between forces applied (e.g. stress) and resulting deformation (e.g. strain) of the system [7]. Selecting the optimum constitutive law is key to be able to obtain a realistic model and adequate solution. Assumptions are required to simplify the model and they need to be accurate enough to guarantee the quality of the model.

Some of the constitutive equations as discussed in Misra et al [9] for soft materials such as tissue are for example Hook's law, which applies to linear elastic materials,

$$\sigma = C\colon \varepsilon$$

which represents a simpler method to model elastic materials. Another approach presented is the use of non-liner elastic model such as hyperelasticity model. In this case, as stated in [9] strain energy density function (W(F)), it is used to obtain the stress in the material as a result of deformation:

$$\mathrm{P} = \frac{\partial \mathrm{W(F)}}{\partial \mathrm{F}}$$

P is the First Piola – Kirchhoff stress tensor
F is the deformation gradient tensor.

Although simpler models like the ones governed by Hooke's law will increase computational efficiency, it will not accurately describe other more complex systems with non-linear behavior. Therefore, additional techniques are required for an accurate modeling of the system.

3. RECENT WORK

In recent works, different and combined techniques have been used to address some of these challenges.

In the work of Saunders et al [10], the locomotion of a highly deformable tobacco hornworm caterpillar, the Manduca Sexta, was modeled. The tobacco hornworm carterpillar can stretch and bend.

A reduced-order, planar, extensible-link model was utilized and various assumptions were made to simplify the model. One of the assumptions was that the caterpillar motion is quasi-static (inertial forces are negligible). Experimental data was acquired by the use of motion tracking systems and ground reaction forces were also measured. The motion tracking system was utilized to get the configuration parameters such as link length and orientation. To solve the sets of non-linear equations for the configuration parameters, an optimization method was used. Forces and torques on each link were computed by solving the 2D Newton Euler equations (inverse kinematics) and with the information obtained from the motion tracking system. A correlation coefficient was computed to compare ground reaction forces that were measured vs the ones computed with the model (91% correlation in the vertical direction and 76% in the horizontal direction).

Also, the quasi-static assumption was verified by taking into consideration the inertial forces in the model. It was confirmed that they were negligible in comparison with the external forces. The model can be utilized further to develop strategies for the locomotion control of soft robots similar to this model.

The model relies on obtaining experimental data to be able to solve for the inverse kinematic problem. Also, a quasi-static assumption is made, which limits the motion to low velocities.

A more general approach is described by Thieffry et al [6]. In this work, offline simulation of robot movement under various parametric conditions was done. A snapshot matrix ("Snapshot-Proper Orthogonal Decomposition (POD") was compiled with robot's accelerations that serve to reduce the dynamic model of the structure. Also, the modes were obtained from the snapshot space using a singular value decomposition. A significant number of simulations were required in order to obtain a snapshot matrix that makes the model as accurate as possible. In this work 3360 snapshots of accelerations were obtained.

The control laws were based on Linear Time Invariant (LTI) reduce order model. This model does not depend on geometrical conditions. As described by Thieffry et al [6], the challenge of this model is to get an accurate snapshot matrix that will entail multiple offline gathering of information of robot simulation. Also, the contacts were not included in the model, therefore, collisions with the environment are not taken into account.

The method works as long as the robot trajectory remains around a previously defined equilibrium point since the reduction matrix obtained using the POD method as well as the linearization of the compliance matrix was done around the equilibrium point. Therefore, a limited working area is part of the challenges discussed on this work. The reductions methods presented in this work will allow for the application of conventional rigid robotics control techniques to control the robot.

In the work of Duriez et al [1], the FEM simulation computes the non-linear deformation of the robot in real time at interactive rates in the control algorithm. A soft silicone material is used to obtain experimentally the constitutive law of the silicone.

A reduced compliance matrix between actuators and end effector is obtained by the use of the FEM simulation and Lagrange multipliers. Constraints such as rigid or deformable obstacles were added and integrated in the control algorithm.

The final configuration of the soft robot, at the end of the time step, is corrected by using the value of the constraint response.

In their work, they found that more than one solution might exist due to actuator redundancy. Their method was validated on a real 3d soft robot made of silicone. As discussed in this work, one of the things that can be a future subject of study is to evaluate the quality of the solution obtained in the cases where several solutions were possible.

In the work of Lee et al [4], a more generic approach is presented, in which there is no need to obtain an analytical model for neither the system, nor the structural parameters, or understand in details the external environment of the robot. As discussed by Lee et al., [4] a generic control framework will learn the inverse model by utilizing a live motion tracking system to know where the state variable is at all times and this information is imputed into the control system to compute control commands based on real time information of the robot state space condition.

4. DISCUSSION

Soft structures mathematical models and resulting equations leads to complex numerical problems which are difficult to resolve.

The efforts in estimating the analytical model range from utilizing continuum mechanics approaches combined with the use of finite element analysis to estimate deformations and apply inverse modeling to get the internal forces required to achieve a desired deformation or movement.

In many of the research work reviewed, experimental studies were performed to gather information of structural parameters of the system, understand the kinematic behavior and being able to select the best constitutive laws. Also, experiments were conducted to compare the numerical solution to the experimental results and validate the accuracy of the model or obtain valuable information to adjust the model.

One of the common challenges in devices for medical applications such as those involved in surgical interventions is being able to account for unpredictable interactions with the environment (tissue and organs inside the body) which will impose additional deformations and deviations from the intended motion. These interactions with the external environment are difficult to model.

For this reason, the analytical model and/or control algorithms needs to account for these aspects in solving the inverse kinematic problem to obtain accurate solutions in which the required internal forces or commands necessary to control the performance of the device can be obtained.

Some of the approaches utilized interactive online Finite element modeling to be able to continuously iterate the modeling to accommodate the real-time changes and effects due to interactions within the device and the environment. Others rely on a nonparametric online learning framework with a motion tracking system to track the state variable and adjust the control system accordingly.

Also, some other challenges presented are around the use of optimization methods to get the best solution and managing actuators redundancy.

In the research work reviewed, the following common areas and related challenges were identified.

Table 1. Research Efforts Commonalities

Area	Challenges	Techniques
• Analytical Model – Constitutive laws	✓ Infinite Dofs ✓ Structural parameters of the system are not readily available ✓ Deformations are difficult to predict	✓ Experiment ✓ Finite Element Methods ✓ Optimize methods for model order reduction without sacrificing accuracy
• Global model • Robot Contact with environment (resulting in additional deformations or deviations from intended path)	✓ Structure geometry and parameters dependence	✓ Real time interactive model ✓ Non- parametric online modeling

5. CONCLUSION

As the Soft Robotics field continues to grow, advanced methods for modeling and control become important for the realization of these devices. In this review, different techniques are presented in which key research commonalties and challenges were identified as described in Table 1. Some of the commonalities in the research efforts are around methods to develop analytical model and accurately solve the inverse dynamic problem, the use of optimization methods to get the best solution, managing actuators redundancy, model reduction techniques and address the soft structure contacts with the environment.

Based on this review, some future efforts are aimed to being able to get global and accurate approaches that can simulate and control the locomotion of soft structures.

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