Modeling and Simulation of Hybrid Soft Robots Using Finite Element Methods: Brief Overview and Benefits

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Abstract. Mathematical modeling of hybrid soft robots is complicated by the description of the complex shape that they undergone when subject to actuation and external loads. It might be noticed that several approaches have been used so far in robotics, and the problem is not yet fully solved. This short paper aims at presenting an overview of modeling and simulation approaches for soft robots based on finite element methods. Benefits and perspectives of future directions are also discussed.

Keywords: Soft robotics · Modeling and simulation · Finite element method

1 Introduction

In the recent years there is a growing interest in building robotic systems with internal compliance, which can be either concentrated at the joint level or distributed along the manipulator's structure. The literature refers to the first class of systems as soft articulated robots [1], while to the second category as soft–bodied robots [2]. Soft robots are becoming pervasive in several applications, including medicine, rehabilitation, manufacturing, inspection and maintenance, remote explorations. However, despite the recent progresses, most of existing applications are limited to laboratories. In order to further advance the use of soft robots towards real-world applications and the development of commercially available solutions, it is important to fully understand and control their

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mechanical behavior. As a matter of fact, modeling and simulation of soft robots is still an hot research topic in the community. Existing mathematical formulations are well–established for soft articulated robots [3]. Indeed, literature about soft–bodied robots and multi–link soft–bodied robots is less mature. With this respect, the current most accurate approaches are those based on continuum mechanics for finite deformations [4]. Such models require a numerical technique, as the finite element method, for space discretization and thus, numerical solution. In this brief work we consider four main aspects related to the use of finite element methods in soft robotics: the most used approaches for modeling; the available simulators; the benefits of using finite element–based modeling techniques and simulation tools; a generic discussion about the open issues. To the best of the authors' knowledge, the present paper is the first attempt to provide a survey on the topic.

2 Finite Element Modeling for Soft Robotics

The mechanics of a soft robot is formulated as a nonlinear structural problem. In structural analysis, two major sources generate nonlinear behaviors: geometry and material. Geometric nonlinearity refers to a nonlinear relationship between displacements and strains. Indeed, material nonlinearity arises when the constitutive equations between internal stresses and strains are nonlinear: this means that the material behavior depends on the current deformation state and past history.

Finite element methods foresee the discretization of the mechanical structure using mono–dimensional, bi–dimensional and three–dimensional finite elements. By referring to classic robotic structures, the finite element discretization process involve the use of: (1) beam elements, when one dimension of the geometry is predominant over the two others (as in the case of slender continuum robots for minimally invasive surgery [5]); (2) shell elements, when two dimensions are comparable and the third is negligible (as in the case of robotic fishes with tiny structures [6]); (3) solid elements, when the three dimensions are comparable.

Regarding the mechanical approaches used for description of large displacements and deformations, two approaches are mainly adopted in the literature: (i) corotational frame (CF) formulation [7,8]; (ii) inertial frame (IF) formulation [9,10]. The approaches differ from the coordinate frames used to formulate the equations of motion. In CF formulations, a corotational frame is defined for each finite element, and it follows a mean rigid body motion of the component. Here, strains and stresses are measured from the corotated configuration whereas a fixed configuration is used as reference for measuring rigid body motions. Indeed, in IF formulations (also called geometrically exact finite element formulations) a global inertial frame is used as reference frame for all motions. Here, the exact representation of the rigid body motions is achieved by deriving frame invariant deformation measures from continuum mechanics. Since the motion of a component is viewed as a whole, without a priori decomposition into a mean rigid body and a superimposed flexible motion, the formulations based on the geometrically exact theories are the most general and accurate to account for flexibility [11].

Examples of using the CF formulation for soft robotics applications can be found in the works by Duriez et al. [12,13]. Indeed, the use of IF formulations for soft robots is available in [14].

3 Finite Element Simulators for Soft Robotics

Simulators in robotics provide assistance for robot analysis, testing of control algorithms, motion planning and interaction with the environments. General platforms such as V–Rep [15] and Gazebo [16] mainly provide simulation of articulated rigid robots. They are based on physics engine such as ODE [17] and Bullet [18], which are not currently optimized for deformable bodies. The gold standard approach for analysis of soft robots is the use of commercial finite element solvers for nonlinear structural analysis; in this respect, the current most adopted software is ABAQUS[1] (Dassault Systèmes, Vélizy–Villacoublay, FR). As an example, ABAQUS has been largely used in modeling and simulation of soft pneumatic actuators [19,20]. One simulator which is gaining attention is SOFA [21,22], an open source framework for physics simulation of deformable bodies. Initially devoted mainly to medical simulation, SOFA is today one of the most used simulators for soft robots, also thanks to the development of the SoftRobots plugin,[2] used for interactive simulation and control of soft robots. SOFA allows developing meshes with mono–dimensional and three–dimensional elements, and it offers multiple material models and solvers. Recently, the SimSOFT simulator [14] has been developed for dynamic simulation of soft–bodied and soft articulated robots. It describes a soft–bodied robot as a nonlinear beam element and it implements kinematic joints for their multi–link connection.

4 Advantages

According to the authors' point of view, finite element modeling techniques and simulation tools bring the following advantages for soft robotic applications.

Serial/Parallel Kinematic Chains. Finite element approaches allow modeling and simulation of serial and parallel kinematic topologies within the same framework, since after discretization the model comprises a series of elements connected through nodes with special boundary conditions. This is of great interest for the soft robotics community, where also parallel structures are showing great potentials. As an example, for surgical applications, parallel robots offer a design which is easy to miniaturize and can achieve multi degrees–of–freedom motion in confined spaces [23].

Library with Rigid and Soft Bodies. Finite element solvers use mathematical formulations that can accommodate the simulation of rigid elements, considered as special cases of elements with zero internal deformations. Regarding continuum

[1] https://www.3ds.com/.
[2] https://project.inria.fr/softrobot/.

bodies, finite element simulators offer the possibility to mesh a robotic structure with beam, shell or solid elements.

Library with Multiple Kinematic Joints. Finite element methods treat also connection between bodies. Existing commercial software for nonlinear structural analysis (i.e. ABAQUS) are connected with multibody dynamics packages (as SIMPACK, always from Dassault Systèmes) for performing analyses with multiple bodies. Different finite element solutions as SOFA or SimSOFT, indeed, have built–in joint models for connecting multiple bodies.

5 Discussion and Open Issues

Advancements in the domain of finite element modeling and solvers for soft robots have been relatively slow. Two major reasons can be identified: (i) computational power of the current machines; (ii) lack of reliable and universal recognized theoretical models. From this literature analysis, we can state that, in order to facilitate the design and development of effective soft robotic systems, three grand challenges remain in the development of: (1) conceptual design tools; (2) model–based controllers; (3) integrated tools for design, analysis, control and virtual simulations.

1. Conceptual Design Tools. The available simulators for soft robots usually deal with analysis and verification of systems, when a detailed computer–aided–design (CAD) model is already available. This strategy can result in wasted time and effort for detailed designs which may not work. A special effort is worth to be made towards the development of computer aided conceptual design tools specifics for soft robots. Indeed, model–based conceptual design tools might speed up the development of effective soft robots, by providing non–experts key design parameters of the systems according to their specific application.

2. Model–Based Controllers. Model–based control is barely popular for soft robotic systems. Few applications are related to simple models for continuum robots [24] or model order reduction techniques, which use heavy offline stages [13]. A great effort should thus be pursued in the direction of purely invertible models for soft–bodied robots, such that all the model–based controllers used for rigid robotics can be applied also for soft robots.

3. Integrated Tools for Design, Analysis, Control, Virtual Simulations. Simulators for soft robots should foresee a unique software environment where the integration of geometry and analysis of soft mechanisms is natural. As a soft robot usually works in its deformed configuration, it is necessary to have an environment where the CAD geometry follows the real physics behavior of the manipulator during the working trajectories. Such integrated environment should provide multiple material models, multibody dynamics, computational mechanics and (eventually) computational fluid dynamics capabilities (the latter is required for flying and underwater soft robots). Furthermore, effective virtual prototyping tools for soft robots should foresee the possibility to test control algorithms and different input trajectories. To this end, models specifically developed for control purposes and not only for simulation purposes are required. Interactive and real–time virtual simulation tools, together with advanced interfaces might allow engineers and users to moving closer to a better model viewing, manipulation and feedback on the design and practical usage of soft robots. To do that, the following features are needed: (i) rapid computational mechanics tools based on efficient dynamic models; (ii) integration of graphics and mechanics; (iii) interfaces with mapping algorithms able to control a distributed system as a soft robot with a limited set of inputs. Another topic which is worth to be investigated is the development of a unique product design representation of soft robots.

As a lesson learned from this preliminary literature review, it is worth highlighting the fact that we are still far away from an integrated software environment for conceptual design, analysis and control of hybrid soft robots.

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