Editorial

Soft Robotic Modeling and Control: Bringing Together Articulated Soft Robots and Soft-Bodied Robots

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Editorial: Soft Robotic Modeling and Control: Bringing Together Articulated Soft Robots and Soft-Bodied Robots

Welcome to this special issue of *The International Journal for Robotics Research* on the topic of Modeling and Control of Continuum and Articulated Soft Robots. The proposal for this special issue came out of discussions during the workshop titled "Soft Robotic Modeling and Control: Bringing Together Articulated Soft Robots and Soft-Bodied Robots" at the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). The vibrant discussions at the workshop highlighted the need to create more bridges between the various separate sub-fields of soft robotics. This special issue aims at taking a further step in this direction.

With the aim of getting closer to animals' performance, elastic elements are purposefully introduced in the mechanical structure of soft robots. Animals can indeed move quite differently from rigid robots, perform dynamic tasks efficiently, and interact robustly, compliantly, and continuously with the external world through their body's elasticity. Inspiration from nature has been a common origin for the current research on modeling and control of articulated and continuum soft robots. Multiple approaches emerged at different times and grew separately. This special issue has the objective to enhance understanding and stimulate further discussion on the similarities and differences in modeling and controlling robots with inherent compliance.

Achieving the desired effective and efficient motion for compliant control systems is challenging. Model-based control of *articulated soft robots* has been growing as a research field. There are theoretical and experimental results showing how soft robots can outperform classical rigid robots in various applications. However, many problems remain unsolved, for example how to properly design feedback controllers without altering the natural softness of the robot, or how to efficiently excite the robot's natural dynamics. The control of *continuum soft robots* is further challenged by the difficulties in deriving an accurate and tractable dynamic model of the system and its environment. While the lack of tractable models prevents the direct application of classical control theory to the control of these kind of robots, it also pushes researchers to find innovative solutions to control soft-bodied robots.

Notably, in recent years great progress has been made in developing dynamic models that approximate the behavior of continuously deformable soft robots. We believe that these mathematical formalizations are generating a common ground between the two worlds, allowing for a better understanding of the challenges in representing soft robot dynamics, and providing inspiration to develop new control approaches.

The 25 papers of this special issue have been divided into five areas: *design*, *modeling*, *model-based control*, *machine learning*, and *experimental evaluation*. When papers covered multiple areas, we decided to categorize those based on the area those works mostly contributed to.

1. Design

Several accepted papers present new robotic designs and demonstrate how to render those controllable for various robotic tasks.

Amanov et al. present the design of a tendon-driven continuum robot with extensible sections showing an additional degree of freedom (DOF) compared with previous designs. The robot is characterized experimentally. The robot is controlled via model-based control and performs better in median and maximum path deviation than compared with the state of the art.

Rozen-Levy et al. design a caterpillar-inspired soft robot that climbs tree branches and similar structures. The robot is a tethered system and has the (currently) fastest locomotion for such robots using crawling gait.

Roozing et al. analyze a compliantly actuated 3DOF leg with bio-inspired tendons through simulation and evaluate it via an experiment. The energy consumption is reduced significantly compared with state-of-the art series-elastic actuator configurations.

Hussain et al. show how to tune soft material properties using different interpenetrating phase composites. Their experimental validation uses a tendon-driven soft–rigid gripper with task-specific soft joint stiffnesses.

Robertson et al. describe the design, fabrication, and experimental analysis of a modular pneumatically driven origami-inspired actuator. The authors developed a sophisticated design with electronic connectors for plug-and-play re-configurability.

2. Modeling

The largest number of accepted papers present modeling techniques for articulated soft or soft continuum robots.

Tutcu et al. couple a kinematic model with a quasi-static equilibrium solution for more accurate modeling of the end-effector of a growing-type soft-continuum robot.

Komatsu et al. introduce a modeling approach to analyze the computational properties of soft materials based on an algebraic method using an input–output equation. This morphological computation approach is motivated from systems biology. It is useful for the analysis of computational capabilities of soft materials and the design of the input force to a soft devices to generate a target behavior.

Sedal et al. compare various models for fiber-reinforced elastomeric enclosures (FREEs) using experimental data. Neural networks were prone to overfitting while for other model types a better mathematical structure would have helped to accurately represent the experimentally observed behavior.

Camp et al. develop a fluidic actuator model and a design for a hand rehabilitation robot that is piston activated. A predictive model is presented and validated that has a superior volume–strain relationship.

Olson et al. present a quasi-static analytical model of soft arms bent with longitudinal actuators. The model is based on equilibrium principles and assumes an unknown neutral axis location. The model is a generalizable framework and works for N fluid-driven actuators, a subset of which are pressurized to induce a bend with a certain curvature and direction. They are able to model load on the actuator that is thus not bending with constant curvature.

Sholl et al. perform a study on fiber-reinforced actuator modeling. They present mathematical theory and experimental evaluation of actuator modeling that can predict the shape of the actuator even under load.

Naselli and Mazzolai introduce the softness distribution index for easier model selection of soft robots. This work is a step towards a unified framework for modeling soft actuators.

Vignali et al. present the development of four constitutive models that include the contribution of collagen fiber families into material hyperelasticity and anisotropy. A minimal parameter model was fitted using *ex vivo* specimens and successfully applied to the simulated positioning process of an aortic valve using a soft robot.

3. Model-based control

Five of the accepted works make use of analytical models to derive effective controllers for soft continuum and articulated soft robots.

Franco and Garriga-Casanovas propose a controller for soft continuum manipulators using adaptive energy-shaping for the single-segment planar case, with in-plane disturbances. Validation is performed in both simulation and experimentally. They that their algorithm is slower but smoother than a model-free PID controller when using the same tuning parameters.

Tang et al. devise a model-based online learning adaptive control algorithm, to be used with a continuously soft rehabilitation glove for stroke patients. The controller is tested experimentally, showing its ability to accurately track the patient's hand position.

Trumić et al. propose an adaptive controller, for simultaneous control of position and stiffness in articulated soft robots actuated with pneumatic actuators. The result is a closed-loop algorithm that is robust to model uncertainties and for small changes in reference stiffness and also to actuator uncertainties.

Sadati et al. introduce an open-source Matlab package for simulating continuum soft robots. The package is called TMTDyn and can be used for designing and testing control algorithms. The software can handle hybrid articulated-continuum structures, therefore contributing to bridging the gap between the two worlds of articulated soft and soft-bodied robots.

Mengacci et al. identify a class of articulated soft robots for which motion and stiffness can be regulated independently. The identified characteristics of this class are used to generalize torque profiles learned through a proposed iterative learning controller and are applied to control the stiffness and motion profiles of variable stiffness robots.

4. Machine learning

Three of the accepted papers use machine learning techniques to control soft robots.

Surovik et al. propose to use reinforcement learning for deriving locomotion strategies for tensegrity robots. These systems can be regarded as a middle ground between articulated and continuum soft robots. Symmetry and dimensionality reduction lead to an application of guided policy search that are easily generalized.

Hamaya et al. introduce a framework for user–robot exoskeleton interaction design using machine learning. An active learning framework based on Gaussian process regression was used for deriving a non-parametric model of pneumatically actuated articulated soft robots. The proposed framework was tested on volunteers using a robotic arm with two joints and four actuators.

Hao Jiang et al. propose a hierarchical control system that allows a Honeycomb Pneumatic Networks Arm to perform interaction tasks without force sensors or models of the environment. The hierarchical control system has a low-level motion controller to move the tip, a mid-level controller to perform primitive motion behaviors, and a high-level planner choosing behaviors according to the desired task. Motion control is shown with a Q-learning-based feedback control method, whereas training data is increased by setting virtual goals.

5. Experimental evaluation

Four of the accepted papers focus on the experimental validation and testing of soft robotic designs and control strategies.

Picardi et al. present experimental results with a single-leg underwater hopping robot. Increasing the size of the robot's head showed increased hopping stability. In environments with predominantly shape dependent forces, morphological changes can solve certain control problems.

Gong et al. test a fully functional underwater robot with attached soft gripper arm for seabed harvesting. Design, fabrication, and kinematic control of the soft manipulator with an opposite bending and stretching structure (OBSS). Using an inverse kinematic model-based controller as well as real-time closed-loop stereo vision feedback, several objects were picked and placed with the gripper.

Best et al. present an experimental analysis of model-based controllers for simultaneous stiffness and position control of pneumatically actuated soft robots. Sliding mode control (SMC) and model predictive control (MPC) are analyzed on a single joint setup and than transferred to a multi-joint setup.

Jeong et al. developed a lifetime model for tendon-driven soft actuators. The model was validated extensively through experiments under various levels of actuation stresses.

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