Design Optimization of Soft Robots

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The past few years have seen a significant increase in research activities that focus on the use of active or passive compliance in robotic systems. The emerging field, generally known as *soft robotics*, promises robotic systems that are safer, more resilient to damage, richly sensorized, and more adaptable than conventional rigid-bodied robots, emphasizing the importance of soft and deformable structures. Several unique aspects can characterize soft robotic systems, such as their elastic and deformable bodies, the large number of degrees of freedom, the viable use of unconventional material, the involvement of intrinsic passive mechanical dynamics, and the display of proprioception and exteroception.

The last few years have also seen the emergence of a modern view of intelligence, known as *embodied intelligence* or *morphological computation*, that leverages the properties of soft robots. Embodied intelligence emphasizes the importance of the codesign, or coevolution, of the brain (controller) and morphology (shape, size, and materials) of a machine to best fit the environment in which it operates. From the perspective of this view of intelligence, optimizing the design of the soft robot is, therefore, of great importance. Such design optimization can be led by machines and/or humans, or it can take inspiration from the coevolutionary processes of biological systems.

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The goal of this special issue is to provide an overview of the state of the art in the design optimization of soft robots and identify common perspectives and challenges, shared scientific goals, and high-impact applications. The accepted articles were carefully selected for novelty, thoroughness, and clarity.

In the first article, Liu et al. present an integrated mobile benthic platform and a soft manipulator that can be used for seafloor exploration, marine samples collection, and other underwater tasks. The benthic platform consists of a six-legged, crab-inspired robot, and the manipulator consists of a four-fingered soft gripper that can perform delicate grasping. Both systems are designed and optimized separately to serve as general-purpose underwater robots with locomotion and manipulation capabilities. The benthic platform is designed to have a payload for instruments, sensors, or a robot arm, and the soft arm is designed to be mounted on underwater vehicles. Based on the integrated platform, the authors experimentally employ spatial manipulation with inverse kinematics specifically for collecting tasks in a natural underwater environment. They show that the soft manipulator's workspace can be significantly extended by adding a benthic legged robot as a mobile base. Furthermore, they find that the designed system can approach objects precisely and effectively and perform dexterous grasping tasks, including retrieving objects from deep apertures in overhang environments.

In the second article, Chen and Wang provide a comprehensive review of the state of the art in the design of soft robots. They refer to "design optimization" as the broad innovations in any design aspect that lead to better performance by soft robots, including algorithms for solving a formulated mathematical problem related to design. The survey considers the design optimization of soft robots as a process to improve material/structure and properties/performance relations. The article not only covers nearly 100 references in modeling, simulation, and computational optimization but, more importantly, also connects them in a much more detailed manner than previous surveys have. For example, the article categorizes geometry, material, and actuation as the three areas where design variables may be identified for modeling soft robots, with the acknowledgment that the boundaries between those variables may change. It also describes simulation methods based on spring–mass models, finite elements, kinematic geometric transformation, and a nonsmooth Newton approach. Finally, the authors provide a high-level comparison of optimization methods, including gradient-based algorithms, evolutionary computation, and bio-inspired design. In the end, the survey identifies three main challenges in the design of soft robots.

1) Present models are usually simple, restrictive, and customized for a particular class of tasks, providing only limited insights into design problems.
2) An effective, efficient, and robust simulation tool that allows rapid

performance evaluation of a design candidate is lacking.
3) Reliable and robust optimization algorithms are yet to be developed.

It also highlights four areas where future work may be done by modeling material and robot dynamics, simulation, and optimization algorithms.

In the third article, Terryn et al. present a healable soft gripper and soft hand whose flexible membranes are composed of Diels–Alder polymer networks. The authors argue that soft robotic actuators based on their approach are able to recover their performance after severe damage at room temperature without the need for an externally applied stimulus. They also argue that this healing ability can help reduce the over dimensioning of systems and optimize designs based on function instead of on potential damaging conditions. The healing process can take seconds or up to a week, depending on the location and extension of the damage. As an extreme case, after cutting the actuator in two parts, it took seven days to heal without the need for any external heat stimulus, and the actuator performance recovered, too.

Next, Pagoli et al. present the design optimization of a robotic finger with a sliding, rotating, and soft bending mechanism. The novelty of the mechanism is its potential larger workspace compared to prior robots with soft appendages. The finger can rotate 300° about its axis, and the mechanism consists of three actuators: two stepper motors for sliding and rotating motion along the longitudinal axis and an air pump for bending. The design optimization relies on the nondominated sorted genetic algorithm II to find optimal values for seven geometric parameters of the soft joint and thus maximize the bending angle and minimize joint dimensions (i.e., length and diameter) under a given pressure. A prototype fabricated after the optimal design is evaluated for different bending angles and tip forces.

Finally, Lee at al. propose the design of pouch motors with geometric constraints that result in versatile and repeatable patterns of bending deformations with a controllable force. The pouch motors rely on the inflation of thin hollow pockets instead of material stretching. The authors describe a system of four pouch motors with geometric constraints allowing the actuator to produce a programmable bending deformation. They suggest that the proposed pouch pattern can be adapted to both soft robotic fingers and soft robotic joints. To demonstrate the efficacy of their approach, they assembled a soft robotic arm with three degrees of freedom and show that it can perform pick-and-place operations and change its stiffness for safe operation around humans. They also build a larger soft robotic gripper for grabbing larger objects.

We hope that the articles presented in this special issue provide new or better insights in the field of soft robot design and inspire the design of a new generation of adaptive, compliant, and reliable soft robots.

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