Editorial: Robotic Handling of Deformable Objects

I. Introduction

OBJECT handling and manipulation is a recurrent theme in robotics, moving progressively from simple rigid objects to articulated objects and then complex deformable objects. In recent years, there has been a growing interest in the development of robotic systems that are able to handle deformable objects, due to many potential applications in the industrial and domestic field but also in robotics in remote hostile environments. Despite the promising prospects, considering object deformation in grasping and manipulation poses significant challenges affecting almost all aspects of robotics: perception, modeling, planning, control and grasping. Some of the challenges are described next:

- Deformation is mainly perceived through vision and/or force. On the one hand, force or tactile measurements provide crucial information for grasping and manipulation, but this feedback is only available locally. Vision, on the other hand, offers a global picture of shape deformation, but it is subject to noise and occlusions. The comprehensiveness of visual data comes at the cost of a higher data processing complexity.
- The modeling of deformation is complicated by the diverse deformation characteristics of objects. For pure elastic objects, the deformation is expressed by a linear relation between stress and strain using Young's modulus. However, in many cases this relation does not apply or it is difficult to define (e.g., for previously unknown objects).
- The challenge of planning lies in the high-dimensional configuration space of deformable objects. Unlike rigid objects, whose configuration is specified by a six-degree-of-freedom pose, the configuration of deformable objects requires many more states to describe.
- Nonlinearity in the deformation modeling and high-dimensional configuration space together make controlling a deformable object a difficult task.
- Handling deformable objects also demands progress in gripper design, especially for fragile objects that could easily be damaged.

The Special Issue on Robotic Handling of Deformable Objects published by IEEE Robotics and Automation Letters is dedicated to addressing the challenges mentioned above. This article, authored by the Guest Editors of the Special Issue, serves as an introduction to it. The Guest Editors were also the organizers of two workshops that motivated this Special Issue: "Workshop on Robotic Manipulation of Deformable Objects" (RoMaDO) [A1] and "Workshop on Managing deformation: A step towards higher robot autonomy" (MaDef) [A2] both organized in conjunction with the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2020 on the topic of handling deformable objects. These workshops, held virtually, included presentations from 16 invited speakers, well-attended live sessions (over 100 participants jointly), and 15 contributed papers from all over the world, reflecting a wide interest in the topic from the robotics community.

Thirteen letters that report the latest advances in robotic handling of deformable objects were selected for the Special Issue after the review process. These papers focus on different aspects of handling deformable objects and demonstrate various tasks for robots, ranging from industrial applications such as routing cables to domestic ones such as cooking.

II. Guide to the Special Issue

In this section, we introduce the letters that form the Special Issue, framing our discussion around different salient topics, namely gripper design, simulation of deformable objects, dual-arm manipulation, machine learning, contact-based manipulation, and benchmarking.

Gripper design: Identification of different types of deformable objects will contribute to robustly grasping and manipulating them. To better classify deformable objects, Deng *et al.* [A3] propose an indenter layer for traditional microfluidic tactile sensors to increase their sensitivity and thus enhance the grasping task. This new design is integrated with a tendon-driven soft gripper for grasping different kinds of objects. Another challenge introduced by the deformation of the object is contact loss, which results in larger forces in the grasping and manipulation of the object. To remedy this, Han *et al.* [A4] present an innovative design including a gecko adhesive pad installed on the gripper to increase the adhesion between the gripper and the object, enabling grasping and manipulation with reduced forces.

Simulation of deformable objects: Simulation is an indispensable tool for robotics research. Although the simulators classically used in robotics can simulate rigid bodies, only a fraction of them can handle deformable objects. In this Special Issue, two letters consider the problem of simulating deformable objects. Huang *et al.* [A5] present a new open-source simulation system and an experimentally validated object grasp data-set with different performance metrics. The presented physics-based simulator allows computing the effects of contacts of robot grippers on arbitrary 3D deformable object models. To make simulated objects behave similarly to their real world counterparts, the parameters of the simulation usually require

Date of current version 8 July 2022.
Digital Object Identifier 10.1109/LRA.2022.3185539

careful tuning. Antonova *et al.* [A6] demonstrate a Bayesian simulation-based inference method addressing this issue. This method is able to estimate posterior distributions over relevant simulation parameters (elasticity, friction, scale) from few real-world trajectories. It can handle challenging, highly deformable objects including cloth and ropes.

Dual-arm manipulation: The use of multiple arms provides more inputs to manage the high-dimensional configuration of deformable objects and achieve complex manipulation tasks. Dual-arm manipulation is featured in six of the letters. The transportation of different kinds of deformable objects is considered by Cui *et al.* [A7], who generalize the Dynamic Movement Primitives formulation to the scenario of dual-arm deformable object manipulation. A novel adaptive term is introduced to capture the object's deformability using a mass-spring-damper model. Alternatively, Liu *et al.* [A8] study an extremely challenging bimanual task: cooking with stir-fry. The authors propose a novel Structured-Transformer network for coordination of the bimanual movements. Robot motions are automatically adjusted given the visual feedback on the semi-fluid objects in the cooking pan. Dehio *et al.* [A9] analyze high-speed bimanual tasks that generate high impacts. The authors not only modify the robots' end-effectors with deformable soft pads that absorb these impacts, but they also integrate their deformation dynamics into a constrained model-predictive control strategy for safe robot operation. A common industrial task that requires a dual-arm setup is cable manipulation, which is considered in several letters. Wang *et al.* [A10] address a bimanual cable shaping task using machine learning, whereas Jin *et al.* [A11] propose a cable routing framework consisting of high level planning based on spatial representation and low level motion execution with manipulation primitives. Finally, Huo *et al.* [A12] model a linear object as a kinematic multibody system, encoded by a sequence of keypoints. Then, they design two movement primitives to both control the object's shape and establish desired contacts.

Machine learning: The impact of machine learning approaches, which are powerful tools for addressing a large set of problems, continues to be very significant in robotics research. Several papers in the Special Issue apply machine learning techniques. Imitation learning is well suited for tasks where expert (usually human) demonstrations can be easily obtained. In particular, expert demonstrations were collected for cable manipulation [A11] and for cooking with stir-fry [A8]. Alternatively, neural networks are exploited for various purposes. In the work of Tuomainen *et al.* [A13], Graph Networks-based Simulators (GNS) are used to learn a model of particle interactions that encapsulate the dynamics of a manipulation task. For accurate learning of cable deformation dynamics, a Graph Neural Network is combined with a residual model in [A10]. Neural network models are also used for encoding the state of deformable objects in [A6], [A12].

Contact-based manipulation: Contact in the environment can be utilized to constrain degrees of freedom of deformable objects for easier manipulation. However, the combined treatment of object deformability and controlled contacts is challenging and demands specific approaches. One prominent example of contact-based manipulation is cable routing, addressed in [A11], [A12]. As mentioned above, in these two papers manipulation primitives are designed for contact handling. In other tasks the placement of the object-environment contacts is not prespecified. For these cases, Han *et al.* [A14] report a new algorithm that enables a robot to autonomously select an optimal contact point to perform a desired deformation control task. Thus, the authors present a two-stage approach that first obtains the contact point and then controls the deformation.

Benchmarking: One underdeveloped topic in the research of robotic manipulation of deformable objects is benchmarking, not only for making more reliable comparisons among different methods but also for sharing standardized tools and data-sets for the scientific community. Garcia-Camacho *et al.* [A15] provide a public data-set of sensor data in cloth manipulation tasks. They categorize these types of tasks and the protocols to test them. Moreover, a simulated data-set focused on grasp evaluation is provided in [A5] along with a code repository allowing researchers to test and benchmark grasp strategies.

Acknowledgment

The Guest Editors wish to acknowledge the essential contribution of the anonymous reviewers to the success of this Special Issue. We also wish to express our gratitude to the Editorial Board at IEEE Robotics and Automation Letters for their assistance and support throughout the editorial process.

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Appendix
Related Articles

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