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A framework for the automated design and modelling of soft robotic systems

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ABSTRACT

The introduction of collaborative robots is expected to have a positive impact on industrial assembly. In this respect, new generations of robots that can deform and yield in a collision, thus being less harmful, seem a promising supplement to traditional rigid-link robots. Recently, these so-called soft robots have received significant attention and are now beginning to unfold their potential in industrial automation. This paper presents a framework for a soft robot design and modelling tool that effectively combines finite element analysis, continuum robot modelling, and machine learning. To validate the proposed method, a soft actuator is designed, modelled, and tested.

1. Introduction

Researchers and manufacturers have long been struggling to devise robotic systems that are sufficiently safe to operate in close proximity to humans. The need for human-friendly robot systems is becoming ever more pressing, as many companies are facing a shortage of skilled workers—a development that is inseparable from ongoing demographic changes in most industrial countries. The lack of skilled workers, on the one hand, and the proliferation of product variants, on the other, have fuelled a surge in demand for viable solutions helping to promote safe human–robot interaction in industrial workplaces. Industrial assembly, in particular, is considered one of the main beneficiaries of recent advances in collaborative robotics. Given that only between 5% and 40% of industrial assembly tasks are carried out by machines, the introduction of collaborative workplaces may well lead to higher throughput than in manual assembly and more flexibility than in full automation [1]. Collaborative robots may not only empower humans to carry out tasks that are otherwise difficult to accomplish, e.g. overhead assembly of parts, but also relieve workers from repetitive and ergonomically challenging work. Additionally, collaborative robots tend to be less expensive than high payload machines and can therefore open up new application areas and create opportunities for cost reduction.

Irrespective of the commonly accepted potential of collaborative robotics, safety remains a major concern. In this context, robots that can deform and yield in a collision, and are therefore less harmful [2], seem a promising supplement to traditional rigid-link robots. In recent years, these so-called soft (material) robots have received wide attention from robotics researchers and are now beginning to unfold their potential in industrial handling processes [3]. The field of soft robotics has arisen from a paradigm shift in machine design and is motivated by novel insights about the impressive sensor-motor abilities of soft-bodied animals. The octopus vulgaris, one of the best-researched soft animals, can achieve highly sophisticated and flexible behaviours through softness. For example, it can squeeze its supple body through small orifices or manipulate objects with one of its many tentacles. Soft robotics research builds on these insights and tries to translate them into engineering principles.

Even though significant progress in the development of soft robotic systems has been made in recent years, comprehensive approaches and guidelines towards soft robotics design are still missing. This paper presents a framework for a soft robot design and modelling tool taking a more holistic approach towards the development process. The framework effectively combines finite element analysis, continuum robot modelling approaches, and machine learning schemes and integrates these into a tool that will facilitate the design, modelling, and control of soft machines. To validate the proposed method, a soft fluidic actuator is designed and modelled according to the framework and simulated using the implemented tool in Abaqus and MATLAB.

2. Soft robotics design and modelling framework

Research in soft robotics has mostly focused on finding individual solutions to problems that are currently beyond the scope of conventional rigid-link robots [4]. The majority of these solutions are as impressive as they are unique. However, only few works have been proposed with a view to establishing holistic design and modelling guidelines [5,6]. Due to this lack of generalization and formalization, research in soft robotics is mainly driven by experimentation rather than simulation. Even in those cases where the fabrication of a

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particular robotic system has been preceded or accompanied by simulation, the generalisability of the employed methods has been scarcely addressed. This issue is further exacerbated by the plethora of existing designs, each of which comes with its own constitutive and kinematic equations. Consequently, the methods used to describe these relations are similarly diverse.

Computer-aided design and optimization of soft robotic components has mainly been done using finite element analysis (FEA) [5,7]. Additionally, evolutionary algorithms have been employed on top of FEA simulations to automatically generate soft robotic designs [8]. Modelling of soft robotics systems has been achieved with a variety of methods, many of which are based on continuous mathematics. Among the most widely applied methods is the piecewise constant curvature (PCC) approach proposed by Webster and Jones [9]. It has been shown that several other kinematic representations for continuum robots such as the ones derived by virtual rigid-links, Frenet–Serret frames, integral representations, and exponential coordinates ultimately lead to a PCC model.

The authors firmly believe that the lack of systematic design and modelling tools is one of the major issues restraining the proliferation of soft machines in many application areas. In an effort to establish a holistic methodology, the authors propose a framework for the automated design and kinematic modelling of soft material robots. In this article, the kinematic modelling approach introduced in Ref. [10] is augmented with machine learning schemes, which allows for rapid computation and simulation of the kinematic models. A schematic diagram of the framework is given in Fig. 1. The framework effectively combines finite element analysis, kinematic modelling, and machine learning for soft robotic systems. Combination of these three methods gives rise to a tool chain that allows the user to simulate the highly nonlinear deformations inherent in soft robotic systems and incorporate these deformations in the kinematic model of a continuum robot. The following subsections discuss the last three modules of the framework, i.e. finite element analysis, PCC kinematics, and artificial neural networks (ANN) in more detail. The first module, i.e. the design and parametrization of a soft robotic segment, has been discussed in Ref. [10].

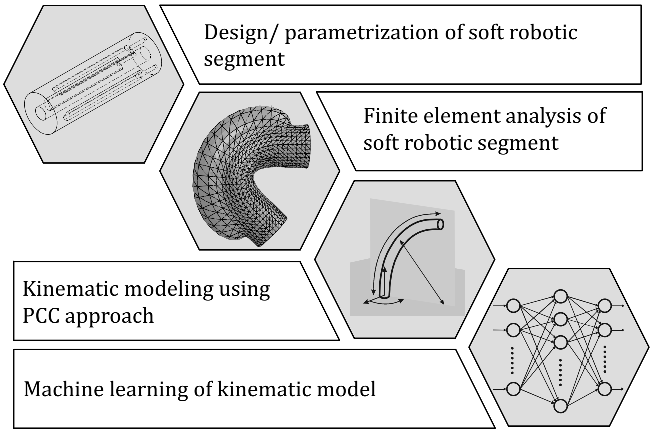

Fig. 1. Design and kinematic modelling framework for soft robotic systems.

2.1. Structure-mechanical simulation using finite element analysis

FEA simulations have proven very effective for modelling the highly nonlinear deformation of soft robotic modules of various designs [5]. In fact, it has been shown that finite element simulations can in part replace time-consuming experiments [7]. Another major advantage of FEA is that it can easily be adapted to different geometries. By contrast, analytical modelling of elastic structures is rather cumbersome and, as mentioned above, the constitutive and kinematic equations are highly dependent on the particular design and the load conditions. Modelling the highly nonlinear deformation of soft segments using FEA therefore seems a promising solution.

However, finite element simulation comes at the cost of a high computational burden. As finite element modelling does not lend itself well to real-time applications, machine learning methods are applied in a subsequent step to learn the nonlinear kinematics/kinetics of a soft robot's segments (see Section 2.3).

2.2. Kinematic modelling using PCC approach

The next step in the proposed framework comprises the kinematic modelling of a soft robot segment using the PCC approach. In principle, alternative methods may well be applied to solve the kinematics of non-constant curvature robots and they can potentially be integrated in the framework. Where applicable, however, the PCC approach constitutes a powerful and modular method.

As pointed out above, the PCC approach represents a unification of previous kinematic approaches. In Ref. [9] Webster and Jones demonstrated that seemingly different kinematic and differential kinematic representations lead to the same result for PCC forward kinematics. Since constant curvature allows for simplifications in kinematic modelling, it is often considered a desirable characteristic. Whereas variable curvature elastic structures are described by integral functions, PCC robots can be represented by a finite number of curved links. The particular advantage is the modularity of the kinematic transformations that the PCC assumption entails. This allows the kinematic transformations to be decomposed into two separate mappings: one from actuator space to configuration space, the other from configuration space to task space (see Fig. 2).

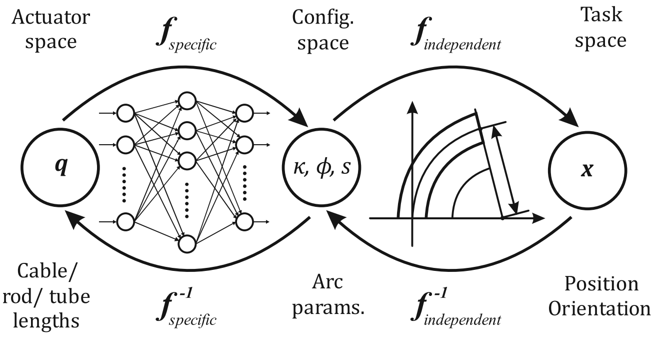

Fig. 2. Mappings in constant curvature kinematics.
Adapted from Ref. [9].

Actuator variables $\mathbf{q}$ can be, for example, lengths of cables, pressures, or displacements in flexible push rods. They influence the configuration of a robot in different ways, depending on its design. The configuration of a robot is described by three curve parameters, where s denotes the arc length, κ the curvature, and ϕ the rotation angle of the plane containing the arc. The mapping $\boldsymbol{f}_{\text{specific}}$ from actuator space to configuration space is robot specific, as it is highly dependent on the hardware realization of a particular robot. By contrast, the mapping $\boldsymbol{f}_{\text{independent}}$ between configuration space and tasks space is the same for all systems for which the PCC assumptions holds. It is therefore robot independent. The position and orientation of a robot's tip are described by task space coordinates $\mathbf{x}$. The forward kinematic transformations from actuator space to task space are summarized in Eq. (1). Here, the robot independent mapping is further decomposed in two mappings: one, $\boldsymbol{f}_1$, that links arc parameters and Denavit–Hartenberg (D–H) parameters θ, d, and another, $\boldsymbol{f}_{\text{D–H}}$, relating D–H parameters to task space variables $\mathbf{x}$.

$$q \xrightarrow{f_{specific}} \kappa, \phi, s \xrightarrow{f_1} \theta, d \overset{f_{independent}}{\xrightarrow{f_{D-H}}} x \tag{1}$$

In the proposed framework, the robot independent relationship between configuration space and task space is derived using PCC kinematic relations. The inverse kinematic mappings $\boldsymbol{f}^{-1}$[41_TD $DIFF] can be used for motion control of a robot segment or arm.

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