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Research paper

Robust control of continuum robots using Cosserat rod theory

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ABSTRACT

In this paper we introduce the first robust control for continuum robots that are modelled by Cosserat Rod theory. Constituted from deformable elastic backbones, continuum robots are highly nonlinear and complex. Current control approaches tend to overcome this obstacle by adopting assumptions to the robot's structure aiming to develop models that are both accurate and applicable for real time control applications. The drawback of such approaches is that maintaining those modelling assumptions restricts the robots expected performance. Here, we overcome the drawbacks by utilizing a dynamic model based on Cosserat Rod that is free from those assumptions and capable of accommodating the backbone general deformations. This general model has not been used in robust control design before as it is computationally expensive to simulate and be used for real time control applications. In this paper, we solved the expensive computation problem by employing a sophisticated numerical method known as the Generalized-α method. For the control part, a robust controller is designed based on sliding mode. To avoid drastic changes in the actuating tension, control input saturation is considered in the design process. Simulation examples are included to verify the effectiveness of the proposed design.

1. Introduction

Continuum robots are a class of robotic manipulators that govern continuous deformability in their structure. Inspired from soft mobile structures in nature (i.e. elephants trunks), continuum robots are defined as continuously bending, infinite degree of freedom robots, with elastic structure [1]. Due to these properties, design architecture and actuation concepts of continuum robots differ substantially when compared to conventional rigid manipulators. Continuum robots aim to exploit their flexibility in manoeuvring and enveloping objects by deforming the whole robot structure, mimicking in that their biological counterparts and offer high level of compliance and dexterity [2]. Their actuating mechanisms include tendons, pressurized tubes, and shape memory alloys [3]. In the real world, continuum robots are utilized in the applications that requires delicate movements or within congested environment. This could be seen, for example, in rescuing missions [4], inspections [5,6], and medical surgeries [3,7].

To fully utilize the potential advantages that continuum robots present, these machines must be controlled throughout their operation. From modelling perspective, continuum robots are considered more complex than the traditional manipulators and exhibit nonlinear dynamic behaviour due to their elastic characteristics. In its general form, the kinematics of

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Nomenclature

P	Centerline positon vector
u	Spatial angular rate of change
w	Temporal angular rate of change
m	Internal moment
l	External moment
ρ	Density
J	Second area moment
G	Shear modulus
τ_i	Tension of tendon i
V_{des}	Desired velocity
J_{des}	Desired jerk
λ	Adaptation coefficient
σ	Sliding surface
R	Rotational matrix
v	Spatial linear rate of change
q	Temporal linear rate of change
n	Internal force
f	External force
A	Area
E	Young's modulus
r_i	Location of tendon i
P_{des}	Desired position
a_{des}	Desired acceleration
υ	Controller input
e	Error

continuum robots involves differential equations while its dynamics employ partial differential equations (PDEs) [8]. These representations in their general form intricate the task of real time control for continuum robots, requiring both sophisticated control algorithms and numerical methods to handle nonlinearity and partial differential equations. To this end, different approaches have been developed by researchers to overcome and simplify the control task in which assumptions are adopted depending on the robot's design and application.

Some approaches neglect the dynamic behaviour in the controlling process. This is justified when the robot is operating in a slow motion or if its slender in size as seen in medical applications. In these approaches, the kinematic model alone is utilized. From kinematics point of view, continuum robots are represented as curves in space [1]. For the kinematic model to be utilized, assumptions of constant curvature [9,10] or piecewise constant curvature [11] are usually employed to simplify the resultant kinematic model allowing for the Jacobian to be calculated. Other cases where explicit kinematic model is not available, estimation methods were used to build the Jacobian [2,12]. Static and steady state models have also been used for control design for both constant and variable curvatures [13,14].

Other cases where the dynamic behaviour must be considered, various method have been employed to derive the dynamic models. These resultant models in general are categorized as either discrete lumped parameter models or distributed parameter models [15]. Lumped models are a natural transition from the traditional manipulators dynamic modelling. In these models the continuum body is approximated by a finite combination of mass-spring segments. Then by using Lagrange dynamics and identifying the parameters, the model could be derived. This approach has been adopted in several pure bending, constant [16,17], or piecewise constant curvature [18,19] assumed robots.

In distributed parameter models, Hamilton's principle has been used to derive the dynamic models for pure bending robots resulting in a set of PDEs [8], or a set of ODEs [20,21], where constant curvature was assumed. Similar work have been done with Lagrange dynamics [22,23]. Finite elements method has been utilized in describing flexible structures [24,25], which has been employed in flexible structural topology optimization [26–28], and in controlling continuum robots under quasistatic conditions [29] and constant curvature [30]. Assuming no torsion, other efforts aimed to provide a sufficient energy based dynamic models for multi section variable length continuum robots, by approximating the robots kinematics with shape functions. Allowing for an accessible inverse kinematic model without singularities [31,32]. Cosserat rod theory was also employed to derive the dynamic model for continuum robots [33,34]. The model represented by set of nonlinear PDEs, was capable of encompassing general robot deformations such as bending, torsion, and extension. However this model was not used in control applications due to its expensive computations [1,35].

Controlling continuum robots is not a trivial task, in which current approaches require assumptions in the continuum robot design and motion. The downside of such approaches is that they confine the robots performance to assure meeting those assumptions such as light weight structure, constant curvature, and pure bending deformations, limiting the exploita-