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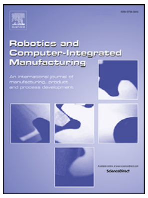

Workspace analysis of cable-driven continuum manipulators based on static model

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ABSTRACT

Cable-driven continuum manipulators are widely used in confined space applications, e.g. minimally invasive surgery. Different from conventional rigid manipulators, their end-effectors are positioned by deforming the flexible backbone. Existing workspace analysis of cable-driven continuum manipulators is based on kinematic modeling, in which the piecewise constant curvature assumption is adopted and the effect from external payload is fully neglected. In this work, we propose a method of analyzing the workspace using static analysis, which takes into account the internal cable tension, the external payload and the gravity force. Experiments are made through a continuum manipulator that is 90 mm in length and 7 mm in diameter to validate the proposed static model. Root-mean-square errors (RMSEs) are used to evaluate the differences between modeling and experiment. Results show that the average RMSEs along axial and lateral directions are 0.8 mm and 1.1 mm for the horizontal experimental layout, 0.4 mm and 0.1 mm for the vertical experimental layout. Based on the experimentally validated static model, workspace of a cable-driven continuum manipulator is analyzed. Results show that the workspace is much affected by the external axial force and lateral force, while is not affected by a pure bending moment. This indicates that the statics has to be considered in workspace analysis of continuum manipulators.

1. Introduction

Continuum manipulators are featured by positioning the end-effector with the large elastic deformation of the continuum flexible backbone. They comprise of one or multiple continuum backbones, without rigid links or joints as in conventional manipulators. Due to their unique feature, they have demonstrated a wide range of applications in the past few decades. One example is mimicking bionic limbs, such as the octopus tentacles [1,2], snake bodies [3,4], elephant trunks [5,6], fish tail [7] and flapping wings [8]. Another more important application is minimally invasive surgery (MIS), which is becoming the standard of care. Compared with traditional open surgery, the MIS has advantages in less blood loss, less postoperative pain, shorter hospital stay, better cosmetic effect, etc [9,10]. With the help of a robot, the MIS could be performed with better precision, less operating time and teleoperation capacity [10,11]. However, the surgical site of MIS is small and confined. This restricts the wide adoption of conventional articulated manipulators. Among various robotic systems targeting on MIS [12], the Da Vinci surgical system by Intuitive Surgical is the most successful one. However, one of the drawbacks is that the system is very bulky. This is due to the surgical manipulators are composed of a rigid shaft and an endowrist. To reposition the endowist, the surgical manipulator needs to pivot around the trocar. The robot arm that holds the surgical manipulator needs to move a large range due to the fulcrum effect.

Continuum manipulators show great potentials in robot-assisted MIS [13]. Its end-effector is repositioned by bending the backbone, without pivoting arounds the trocar. This could not only reduce the space requirement of the robot but also improve the workspace and dexterity. Generally, from the backbone structure, continuum manipulators can be categorized into three types. In the first type of continuum manipulators, they have a backbone made by a single elastic tube/rod/beam. The backbone deformation is controlled by a set of wires/cables/tendons (In the following, they are all referred to as cables since they work in a same manner). Examples include [14–18]. Secondly, some continuum manipulators have multi-backbone structures, where several parallel elastic tubes/rods/beams running through the whole manipulator. The backbone deformation is controlled by the push-pull of the slim tubes/rods/beams, such as the robots in [19–21]. The third kind of continuum manipulators are composed by several nested concentric tubes

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with different pre-curvatures. The overall manipulator shape is controlled by the tubes' insertion and rotation, such as the robots presented in [22–24]. Among all the three types, the most common continuum manipulator is perhaps the cable-driven single backbone continuum manipulator. This paper takes the single backbone continuum manipulator as an example to stress the modeling, experiment and analysis. However the proposed method can be extended and applied to any other kind of continuum manipulators.

The workspace of continuum manipulators can be defined as a set of points that can be reached by the end-effector of the manipulators. For applications such as MIS, end-effectors are usually clamps, scissors, hooks, cameras, etc. The distribution of these reachable points is vital for operations during MIS. Therefore, workspace is an important index to evaluate the performance of continuum manipulators. Previous literatures on this issue are usually based on the kinematic model of continuum manipulators [25–28]. In this classic kinematic model, the piecewise constant curvature assumption (PCCA) is made, i.e. the bending curve of the manipulator forms an ideal arc whose curvature is constant for each bending section [29–34]. This method totally neglects the statics of the manipulator, i.e. the effects of gravity and external loads are missed. In fact, due to the compliance of the structure, the bending profile of the continuum manipulator cannot be an ideal arc under the effect of gravity and external loads. So kinematic modeling with PCCA is not accurate, and static model of the continuum manipulator should be studied to find out how gravity and external loads affect the workspace of the continuum manipulator.

In view of robotics, the continuum manipulator can be modeled as an under-actuated serial robot with hyper-redundant degrees of freedom. Thus, the statics is coupled with the kinematics, where gravity effect, external loads, actuating cable tensions should be considered together. This makes the static modeling of continuum manipulators more complicated. A lot of efforts has been done on this issue. Static analysis of a multi-backbone continuum manipulator is presented in [35], in which system static equilibrium is derived using elliptic integrals. Based on the Cosserat-rod theory, static models of continuum manipulators are proposed in [36,37]. Static analysis of a single backbone continuum manipulator is made in [17], where the static model is proposed based on the principle of virtual work. A new mechanics-based linear model for the forward and inverse kinematics mapping between tendon displacements and beam configuration is proposed in [14], where the mechanical interactions of the compliant tendon-beam system are fully considered. However, workspace analysis considering manipulator statics has not been achieved in literatures.

This research develops a general method for the workspace analysis of continuum manipulators. The proposed method is based on the static model of the manipulator. During the static modeling, gravity effect, external loads, actuating cable tensions are all taken into consideration. Furthermore, a group of experiments are made to validate the theoretical model. Based on this, workspace of the manipulator is calculated. The effect of external loads on the workspace is analyzed. At the same time, results are also compared with those obtained by the classical kinematic model. Through the comparison, it is revealed that static model should be considered in the workspace analysis, especially non-negligible external forces exists.

This paper is organized as following. The static modeling of continuum manipulators is detailed in Section 2. Then, experimental validation of the static model is made in Section 3. Based on the static model, workspace of the continuum manipulators is analyzed in Section 4. Finally, conclusion is made in Section 5.

2. Statics modeling

This section addresses the static modeling of the continuum manipulators taking a single backbone continuum manipulator as an example. However, the proposed model can be applied to a more general class of continuum manipulators, such as multi-backbone manipulators [35] and pneumatic driving continuum manipulators [38].

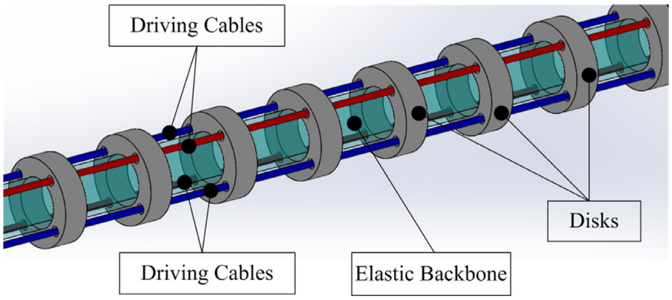

Fig. 1. A general structure of continuum manipulators.

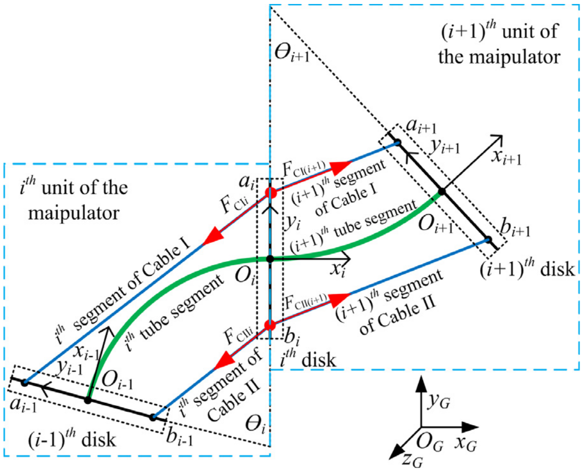

Fig. 2. Schematic of two adjacent units of the continuum manipulator.

The general structure of a single backbone continuum manipulator is illustrated in Fig. 1. As is shown, an elastic tube locates at the center, which performs as the central core of the manipulator. Along the center tube, a serial of disks with guiding holes are mounted, which divide the manipulator to several units. These disks are also used as cable guides. A group of driving cables pass through the guiling holes, and cables can move along the disk holes. By changing the lengths and/or tensions of the driving cables, the structure can achieve a desired bending. Inside the tube, various materials can pass through, such as the electric wires, controlling cables, etc. Moreover, various kinds of end-effectors can be integrated at the end of the manipulator. This structure makes the continuum manipulator extensible to different tasks.

Fig. 2 shows the diagram of two adjacent units of the continuum manipulator, where the green curves represent the tube segments, the black dot rectangles represent the cross sections of the disks, the black solid lines represent the middle planes of the guiding disks, and the blue lines represent the driving cable segments. Local frames Ro_{i-1}, Ro_i and Ro_{i+1} are fixed on the $(i-1)$th, ith and $(i+1)$th disks, respectively. Cable I and II provide the actuating forces. The following assumptions are made.

- The elongation along the axial direction of the tube is ignored;
- The deformation of the elastic tube is pure bending;
- The elastic tube can be simulated by an Euler–Bernoulli beam;
- Profile of the elastic tube between two adjacent disks is approximated to an arc;
- Profile of the driving cable between two adjacent disks is straight lines.

Similar assumptions can also be found in some previous researches, such as [14,19,29]. One significant characteristic of the assumptions in this research is that each profile of the elastic tube segment between