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Study on the load capacity of a single-section continuum manipulator

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ABSTRACT

This paper presents a simplified method to establish a mathematical model for predicting the loaded posture of a single-section continuum manipulator with arbitrary shape and size of the cross-section. The method constructs a parameter of equivalent bending stiffness for the manipulator and later considers the single-section continuum manipulator to be an equivalent Euler-beam while discussing the symmetry of the cross-section. Thus, the tip position and posture of the manipulator under load are deduced using the large deflection theory and unit load method. The loading model of the single-section continuum manipulator is verified by experiment, and the result indicates that the error between the theoretical model and the experiment is no more than 6%.

1. Introduction

In recent years, the continuum manipulator has aroused extensive attention in many subject areas, such as disaster relief, medical aid, and fruit harvesting. Compared with the conventional manipulator, the continuum manipulator has an infinite number of degrees of freedom in theory, so it can move into complex environments where its body can conform to and interact with obstacles in a safe manner.

The primary types of continuum manipulator include the cable-driven manipulator [1], rod-driven manipulator [2], pneumatic artificial muscle manipulator and concentric tube manipulator. They have been studied widely in many special fields. The snake-like manipulator [3–6] for surgery on the throat was presented by the Nabil Simaan, Kai Xu, and Russell Taylor from Johns Hopkins University. Ian A. Grangne and Ian D. Walker presented an elephant's trunk manipulator [7,8] based on the movement principle of the trunk muscle. Christos Bergeles and Andrew H. Gosline presented the concentric tube manipulator [9] for minimally invasive surgery inside confined body cavities. The kinematics of most continuum manipulators has been established based on the different structures of the continuum manipulator. Workspace kinematic modeling has been built for the steel-wire continuum manipulator [10], and the kinematic models of the Oct.-Arm continuum manipulator have been derived [11]. A lumped-parameter modeling approach that allows for the inclusion of nonlinear effects including friction was studied, and the results show that the proposed approach significantly improves the simulation accuracy compared with the case in which friction was not considered [12]. Tobias Mahl and Alexander Hildebrandt proposed new variable curvature continuum kinematics for multi-section continuum manipulators with arbitrarily shaped backbone curves assembled from sections with three degrees of freedom [13]. Rahim Mutlua and Gursel Alici reported an effective method to estimate these actuators' whole-shape deflection by employing a soft manipulator approach to accurately solve the electro-active polymer actuators' inverse kinematic problem

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[14]. D. Caleb Rucker provided a new model for the statics and dynamics of continuum manipulators with general tendon routing paths, which was derived by coupling the classical cosserat-rod and cosserat-string models [15]. Roger E. Goldman proposed a modeling strategy for translating the unknown interaction forces into a generalized force in the configuration space of a continuum segment [16].

For functionalities of a continuum manipulator, it is ordinarily equipped with devices, such as a gripper, micro-camera or other tools, at its free end. These devices are the payloads, which affect the posture and the free end position of the continuum manipulator. Furthermore, for a multi-section continuum robot, a lower section is likewise considered a payload of its upper sections. Thus, it is necessary to analyze the characters of the single-section continuum manipulator under payload. The capacity model of a multi-section continuum manipulator had been built using the finite element theory of a pseudo rigid-body [17], whereas the large deflection theory had been used to establish a dynamic and vibration model of the backbone continuum manipulator that is driven by cables from the perspective of bending and shear deformation [18], and the spatial continuum models of rods undergoing large deformation and inflation are established by the finite element theory [19]. The literature [17–19] has focused on studies of the cable-driven continuum manipulator, in which the backbone is considered as an elastic rod. The bending, twisting, extension, and shear are synthesized for analyzing deformation. Enlightened by [17–19], this paper puts forth a concept of equivalent bending stiffness to establish the kinematic model for a rod-driven single-section continuum manipulator with a payload at its free end based on the large deflection theory. The difference between the rod-driven type and cable-driven type is that the rod-driven type can provide the backbone with both pulling and drawing forces, and the cable-driven type provides only pulling forces. Regarding this point and its base structure, the single-section continuum manipulator can be simplified into an equivalent Euler-beam. Thus, the presented method strongly simplifies the posture analysis and prediction of a loaded single-section continuum manipulator.

The single-section continuum manipulator in this study has a length of 800 mm, composed of five fiberglass rods with a diameter of 2.5 mm and eight identically cross-shaped tendon-guides. The tendon-guides are formed of aluminum alloy for light weight. One of the five fiberglass rods serves as the backbone, and the other four serve as a steering-rods. Each tendon-guide has five eyelets, of which one is center eyelet in the center for the backbone, and the others for steering-rods are equally dispersed on the brink. Rubber tubes of the same length are installed between tendon-guides along the backbone for serially arranging the tendon-guides in the space. The first tendon-guide at the free end of the manipulator is bonded together with the backbone and the four steering-rods by tightening bolts. The last tendon-guide on the bottom of the manipulator is bonded only with the backbone. Hence, the backbone is fixed with all tendon-guides and has a constant length, whereas the steering-rods around the backbone can slide through their corresponding pilot eyelets except for the free end ones. The manipulator is driven by four independently driven sets, each of which drive one steering-rod. Fig. 1 shows the proposed manipulator, and its detail is illustrated in Fig. 2. For driving the four steering-rods in harmonious actions, a PLC hard-core is developed to control them.

Fig. 3 (a) sketches the steering-rods. For the sake of easy explanation, the steering-rods are numbered 1 to 4. Here, steering-rods 1 and 2 are elongated by pushing them up by AC motors, whereas steering–rods 3 and 4 are shortened by drawing them down as shown in Fig. 3 (a), and the manipulator will bend to the right, illustrated in Fig. 3 (b). In a similar way, to elongate

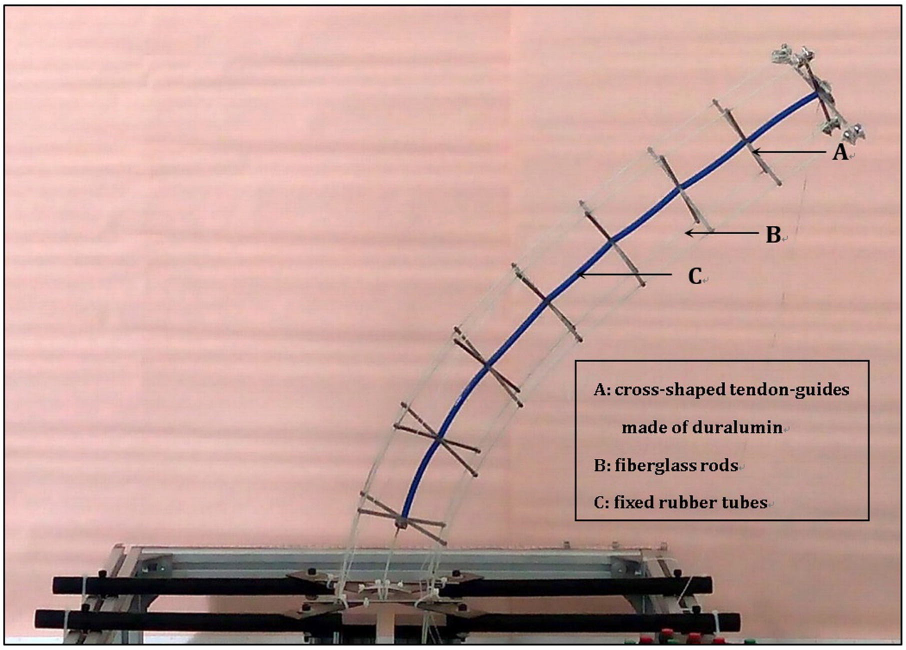

Fig. 1. Physical manipulator.