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A novel constrained wire-driven flexible mechanism and its kinematic analysis

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A B S T R A C T

Snake-like flexible manipulators are widely used in minimally invasive surgery (MIS), which require adequate dexterity in confined workspace. Typically, the design mechanisms of these manipulators include tendon-driven mechanism and concentric tube mechanism. Though, the workspace and dexterity of these designs are limited due to the lack of control in either the length of the bending section or the curvature of the bending section at the distal end. In this paper, we present a novel constrained wire-driven flexible mechanism (CWFM), in which both the length and the curvature of the bending section are controllable. The idea is to employ an active constraint to control the length of the bending section and use the wires to control the curvature of the bending section. Compared to the existing designs based on wire-driven flexible mechanism (WFM), CWFM has expanded workspace and enhanced dexterity while its size is not sacrificed. Additional benefits include much reduced sweeping area and controllable stiffness. Based on the computer simulation, on average, CWFM with the same size as WFM can improve the dexterity by 4.69 times and reduce the sweeping area to 20.5%.

1. Introduction

Minimally invasive surgery (MIS) brings benefits to millions of people each year and is becoming the trend of new generation of surgeries [1,2]. Compared to open surgery, MIS brings to patients shorter hospital stay, less blood loss, and better postoperative cosmesis. In traditional MIS, such as laparoscopy, the instruments have a rigid slender shaft, e.g. the HiQ hand instruments provided by Olympus. Manipulators with similar designs are also equipped by surgical robots, such as the *Da Vinci* robot developed by Intuitive Surgical Inc. [3]. The rigid chopstick-like tools allow a relatively large payload and precise motion control. However, they cause the surgical site occluded as they cannot bend. Also, safety is a major concern in MIS. Snake-like flexible manipulators (FMs) is more compliant, therefore can reduce the potential damage to the delicate tissues. Also, they can bend the backbone to access a wider space in the body, can provide better angulation, and are more dexterous than the rigid tools [4–9]. They are increasingly used in MIS, especially in single port access surgery (SPA) and natural orifice transluminal endoscopic surgery (NOTES)[10].

In FMs, the end effector is positioned and oriented by deforming the flexible body, or the backbone. From a mechanical structure point of view, the flexible manipulators can be categorized into serpentine flexible manipulators (SFMs) and continuum flexible

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manipulators (CFMs). In SFMs, the backbone comprises a plurality of vertebrae, with adjacent vertebrae forming a joint, which can be a revolute joint or a spherical joint. For SFMs with revolute joints, the backbone bending is planar, and for SFMs with spherical joints, the backbone bending direction is controllable. The bending of the backbone can be either fully actuated or underactuated. In fully actuated SFMs, such as the Tensor Arm Robot [11] and the modular snake robot [12], all the joints are controlled independently by cables or motors. As an SFM typically has a large number of joints, the structure and control of the fully actuated SFMs is complicated. In underactuated SFMs, the number of actuators is much less than the number of degrees of freedom (DOFs) in the backbone, such as the wire-driven robotic arm in [13], which has a total of 30 spherical joints and the motion is controlled by only six motors. In underactuated designs, the joints' rotations are often constrained and the actuators are arranged separately from the backbone. Hence, the manipulator body is compact. This made the underactuated SFMs well suited to MIS. The other category of flexible manipulators is the CFM, whose backbone usually comprises one or several continuum elastic tubes or rods, such as the continuum manipulators presented in [4,6,14–17]. The backbone of the CFM bends in a similar manner to that of the elastic beam. Theoretically, the number of DOFs in the CFM is infinite. Therefore, it is impossible to control all the DOFs of the CFM, which means that CFMs are intrinsically underactuated. They can also be viewed as the underactuated SFM with infinite number of joints. In underactuated flexible manipulators (UFMs), including underactuated SFMs and CFMs, the distal end is positioned and oriented by backbone bending. Each UFM has one or more serially linked bending sections and each section bends similarly. The bending section can be actively controlled via tendons [4,18], cables [5,17,19–22], wires [13,23], pneumatic artificial muscles (PAM) [24], shape memory alloys (SMA) [25], electro-active polymers (EAP) [26], concentric pre-curved tubes [6], etc. Tendon-driven, cable-driven, and wire-driven manipulators work in a similar way. In the following text, they are all referred to as wire-driven manipulators.

From the motion point of view, the bending section of the UFMs can be divided into three categories. In the first category, the length of the bending section is fixed while the curvature of the bending section is controllable. The wire-driven UFMs belong to this category. In the second category, the length of the bending section can be controlled but the curvature of the bending section is uncontrollable, such as in the concentric tube robot the curvature of the distal section is fixed. In these two types of UFMs, the distal end position and orientation are coupled, i.e., for a single bending section, the orientation can be solved from the distal end position or vice versa. This restricts the workspace of the manipulator. For a UFM with one bending section and immobile base, the distal end can only move on a surface. In the third category, both the length and the curvature of the bending section can be controlled. Examples include the PAM-/EAP-actuated UFMs, such as the OctArm [24,27,28]. For UFMs with same dimensions, the one in the third category has the largest workspace and is most dexterous. Also, it can potentially reduce the sweeping area during the motion. Such a manipulator is favored in confined space applications, especially in MIS where the environment is filled with sensitive organs. The reduced sweeping motion can avoid interfering with the surrounding organs and improve the safety. However, the size of the PAM-/EAP-actuated UFMs are often too large for surgical applications, for example, the outer diameter of the OctArm IV is 45 mm [24]. The HARP robot [29] also belongs to the third category. It comprises two concentric cable-driven snakes. However, its motion is quite slow as it is operated by the alternate "stiff mode" and "limp mode" of the two snakes. This restricts the application of the HARP. A UFM that is in the third category, is small in size, and can have quick movement is in demand. The development of such an UFM requires a new mechanism.

In this paper, we present a new mechanism based on our biomimetic wire-driven mechanism [13,23] and is named the constrained wire-driven flexible mechanism (CWFM). In the CWFM, the length of the bending section is controlled by an active constraint and the curvature is controlled by the wires. Compared to the existing surgical arms, which don't have the constraint, CWFM has a larger workspace and is more dexterous while retaining the same size. Also, it is operated just like the existing flexible manipulators, which move much faster than the HARP robot. The rest of the paper is organized as follows. The design of the CWFM is presented in Section 2. In Section 3, the kinematics model is developed. The workspace and dexterity analysis of the CWFM are presented in Sections 4 and 5, respectively. Section 6 shows the simulation examples and discussion, and finally, Sections 7 contains the conclusions.

2. The constrained wire-driven flexible mechanism

2.1. The work principle of the CWFM

The idea of the CWFM is to take advantage of the underactuation nature of the UFM. From our previous study, for UFMs, the workspace can be expanded by employing active constraints [30]. This principle is also reflected in concentric tube robots (CTR). The CTR is composed of a number of nested pre-curved tubes. They can translate and rotate w.r.t each other. Typically, the translation of the outer tube is smaller. Therefore, the inner tube is segmented into two parts by the outer tube. The proximal section is overlaid with the outer tube. Its curvature is determined by the stiffness ratio and the relative rotation of the tubes. Since the inner tube is softer, the outer tube functions as an active constraint to the inner tube. On the other hand, the curvature of the distal section of the inner tube cannot be controlled. It is pre-determined by metallic treatments. The lengths of the proximal section and distal section are controlled by the relative insertion of the tubes. This inspired the idea of integrating a translational constraint tube to the existing wire-driven flexible manipulator (WFM). In our previous work, two types of WFMs were developed. One is the serpentine WFM [23], and the other is the continuum WFM [31]. In this work, a rigid translational constraint is added to the WFMs and is used to control the length of the bending section. The backbone of the CWFM can also be serpentine or continuum. In this paper, only the serpentine design is detailed as the continuum design is similar. Also, a single-section CWFM is sufficient to illustrate the design and principles, hence, a multi-section CWFM is not presented in this paper.

Fig. 1 shows the work principle of the CWFM. In the serpentine WFM with one bending section, the flexible backbone contains a plurality of vertebrae with adjacent vertebrae forming a joint. By applying a pure bending moment, the flexible backbone will bend to