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Kinematic comparison of surgical tendon-driven manipulators and concentric tube manipulators

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ABSTRACT

Robot manipulators are increasingly used in minimally invasive surgery (MIS). They are required to have small size, wide workspace, adequate dexterity and payload ability when operating in confined surgical cavity. Snake-like flexible manipulators are well suited to these applications. However, conventional fully actuated snake-like flexible manipulators are difficult to miniaturize and even after miniaturization the payload is very limited. The alternative is to use underactuated snake-like flexible manipulators. Three prevailing designs are tendon-driven continuum manipulators (TCM), tendon-driven serpentine manipulators (TSM) and concentric tube manipulators (CTM). In this paper, the three designs are compared at the mechanism level from the kinematics point of view. The workspace and distal end dexterity are compared for TCM, TSM and CTM with one, two and three sections, respectively. Other aspects of these designs are also discussed, including sweeping motion, scaling, force sensing, stiffness control, etc. From the results, the tendon-driven designs and concentric tube design complement each other in terms of their workspace, which is influenced by the number of sections as well as the length distribution among sections. The tendon-driven designs entail better distal end dexterity while generate larger sweeping motion in positions close to the shaft.

1. Introduction

Manipulators or robot arms [1] are increasingly used in confined space applications. Typical examples include minimally invasive surgery (MIS), such as laparoscopic surgery, Single Port Access surgery (SPA), Natural Orifice Transluminal Endoscopic Surgery (NOTES) [2–6] and industrial endoscopic non-destructive inspection [7]. In these applications, the manipulator needs to access and/or operate in confined spaces where obstacles are abundant. Hence, the manipulator is usually snake-like, i.e., slender and has a large number of degrees of freedom (DOFs). This allows the manipulator to be able to access the target and have adequate maneuverability around it. For surgical snake-like manipulators, the cross-sectional dimension is typically in the order of 10^1 mm. These manipulators are placed on a robotic platform and their flexible bending sections are inserted into the surgical cavity via a trocar. The surgeons steer the manipulator to access to the surgical target and perform operations, such as viewing, cutting tissues, suturing, knotting, etc. [8].

Traditional snake-like manipulators are fully articulated serial robot arms with large number of joints. Each joint is actuated by

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one or two integrated motors [9], depending on the joint type. The consequence of this design is that the robot is large in size and it is complex in both mechanical structure and control. To actuate all the joints, another approach is to separate the actuators from the robot structure, such as the tensor arm [10]. In this design, the motors are placed at the robot base, and the motion is transmitted to the manipulator via tendons. Using this design, the dimension of the manipulator can be reduced to some extent but the number of tendons needed is large, which constrains the down scaling of the robot as well. The cross-sectional dimension of these snake-like robots is typically in the order of 10^2 mm. Miniaturization is required for them to be applied to MIS. However, to miniaturize the size of these robots, efforts needed is tremendous. As a result, this fully articulated design is uncommon in surgical manipulators. The SPRINT robot contains two arms and each arm has 3 fully actuated joints [11]. Rigorously, it is not snake-like. The i-Snake [12] is more snake-like. It has 7 controllable joints and the diameter is 12.5 mm. However, the payload of the iSnake is very limited. This greatly restricts its applications in MIS.

To reduce the number of actuators and simplify the control, underactuation could be adopted. In an underactuated system, the number of actuators is less than the number of DOFs. As seen from nature, it is not necessary that all DOFs be actively controlled to fulfill tasks. For example, human fingers are underactuated but they can grasp objects successfully. In the past two decades, quite a number of underactuated snake-like robots or manipulators have been developed. Examples include the Elephant Trunk Robot [13], OctArm [14], Air Octor [15], the wire-driven robot [16], etc. A common feature shared by these robots is that the number of actuators employed is generally much less than the robot's DOFs. For example, the wire-driven robot has 30 spherical joints but only six motors are used to actuate the manipulator [16]. The benefit of underactuation and moving the actuators out of the manipulator body is that both the mechanical structure and control become simpler. This alleviates the difficulty of miniaturizing the snake-like robots and pushes forward the application of snake-like robots to the field of MIS. Unfortunately, the consequence of underactuation is the reduced workspace and reduced dexterity of the manipulator, compared with full-actuated serial manipulators, which have been well studied in the literatures. Therefore, in this work, we focus on the comparison of the commonly used underactuated surgical manipulator designs.

From the literature, there are three prevailing designs for underactuated surgical flexible manipulators. The first type is the tendon-driven continuum manipulators (TCMs) [1,6,17–20], in which the backbone is a continuous structure, the actuators are placed at the base and the motion of the manipulator is controlled via tendons or cables or wires, which are similar and are all referred to as tendons in the rest of this paper. The second type is the tendon-driven serpentine manipulators (TSMs) [1,6,16,21,22]. Their structure is similar to the previous type, only the backbone structure is different. It is composed of a number of short links or vertebrae, with two successive vertebrae forming a joint. The large deformation of the backbone is generated from the small rotations of the multitude joints. To regulate the joints rotations, elastic components are required [16,23,24]. The third type is the concentric tube manipulators (CTMs), in which the backbone comprises of several nested pre-curved tubes. By rotating and translating the tubes, the shape of the backbone is controlled. In this design, the motors are also placed at the robot base [25–30]. One question arises immediately: How should we choose the design? In the literature, there are a number of comprehensive reviews on continuum robots, such as the review by G. Robinson[1], R.J. Webster[6], Burgner-Kahrs [5]. In these works, existing robot systems using these

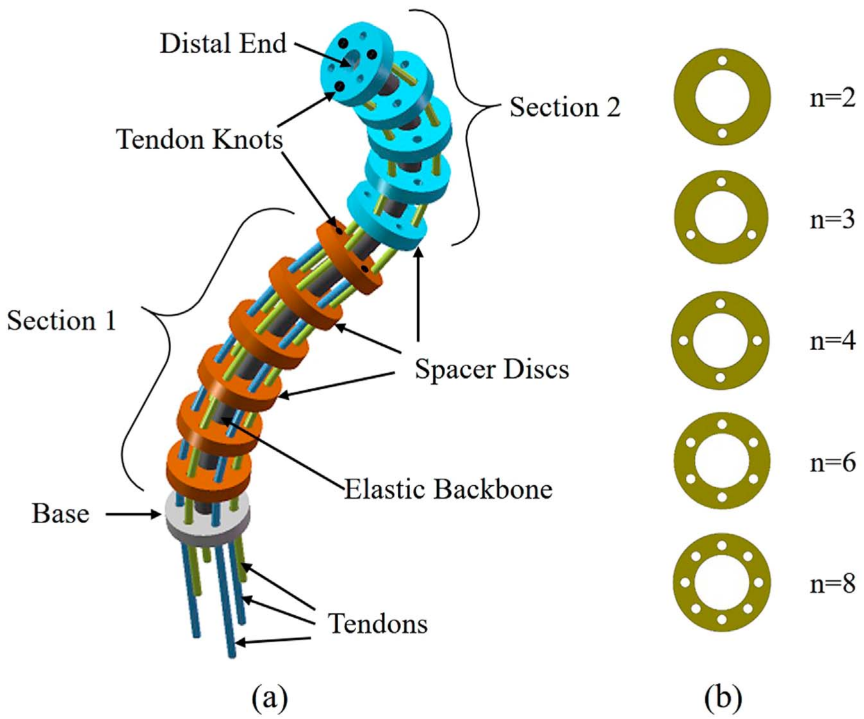

Fig. 1. An Example of Tendon-driven Continuum Manipulator: (a) structure and components; (b) typical tendon guiding pinholes on spacer disks.