Modularization of medical robotic manipulator for adapting soft robotic arms with varying numbers of DOFs

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INTRODUCTION

Medical robotics systems are widely used nowadays and gaining more and more attention from both research societies and surgeons, providing new solutions to different minimally invasive surgeries. Despite higher costs, hospitals are embracing the new technology for reasons like providing more dexterity than traditional laparoscopy and better ergonomics, which relieve the surgeon's mental burden[1, 2]. Most of the designs of currently available medical robots consist of rigid parts not suitable for interventions such as flexible endoscopy. The tips of flexible endoscopes are usually actively steered by tendons while their bodies are passively flexible and will bend with the surrounding lumen.

The Bio-Inspired Technology group (BITE) at Delft University of Technology is designing new mechanical solutions that allow instruments to navigate through vulnerable anatomic surroundings and get to hard-to-reach locations. Inspired by nature, innovative soft robotic arms with varying numbers of steerable segments were designed and manufactured with 3D printing technology [3], allowing rapid manufacture and easy adjustment for different clinical needs. However, to build robotic actuators for these varying designs is time consuming, especially when a new design has to be changed according to the required number of degrees of freedom (DOF) that has to be controlled. Modular actuation has a strong advantage on addressing this issue as modular actuators can be easily duplicated and stacked for different DOF to make them suitable for new designs. Therefore, in this paper, a miniature soft robotic arm controlled by modularized actuation segments is proposed. These segments can work independently and/or together to steer the soft robotic arm. This study aims to investigate whether the proposed design is able to steer a cable-driven soft robot and is suited for designs with different numbers of steerable segments (DOF).

MATERIALS AND METHODS

The proposed manipulator design is modular with respect to the number of actuation segments in the soft robotic arm. These modularized actuation units correspond to the number of steerable segments required, each unit being able to steer one steerable segment. In each unit, we used four stepper motors (NEMA17, 17HS4401) with drivers (DRV8825, AZDelivery) connecting to one microcontroller (ATmega328P, Arduino UNO) with shield circuit (Arduino CNC shield v3). Mechanical supports and parts are identical in each segment. The stepper motors connect to the soft robotic arm by tendons and are arrayed with offset angles in order to minimize the space required for each motor. Microcontrollers in different segments are connected via I2C, the first leading microcontroller being the master and the others serving as slaves. To prove the concept, a soft robotic arm with two steerable segments (4 DOFs) is used. The 1st to 32nd microsteppings are used to increase resolution of the movement of the tip. A manipulator with two modularized actuation segments is built and employed with two control strategies. The first strategy consists of simply using two independent joysticks to steer two deflection angles of their corresponding segments. The second strategy is the follow-leader-control, meaning the first leading segment is remotely controlled by a joystick. When the deflection of the first tip is being determined by the user, the following part will then move the same way as the leading one by a feedforward control strategy.

RESULTS

The 4 DOF soft robotic arm manipulator that was built is shown in Figure 1. The dimensions of the modularized actuation part are 300x200x100mm. Two modules were assembled and connected to the soft robotic arm, which possesses 2 steerable segments with an outer diameter of 8 mm and a total length of 85 mm. The manipulator can successfully control the movement of each segment by two joy sticks as shown in Figure 2.

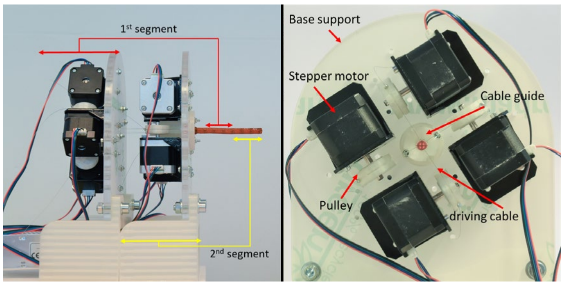

Figure. 1. The left figure shows the assembly of two modularized actuation segments together with a 4 DOF soft robotic arm. The right figure shows the actuation elements in one actuation module.

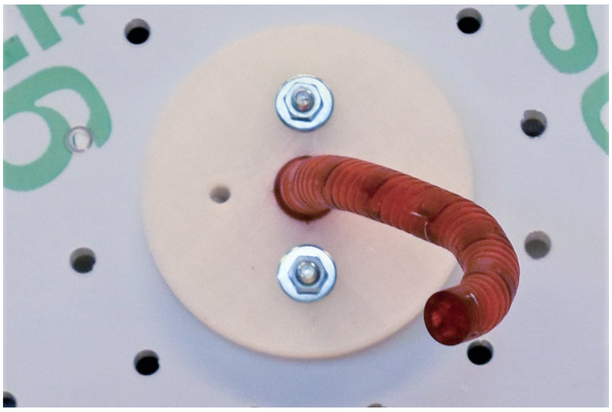

Figure. 2. Front view from the manipulator showing robotic arm being driven by two-joystick.

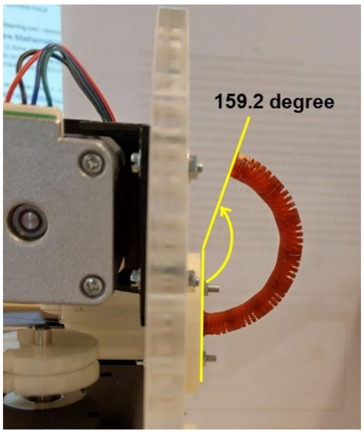

Figure. 3. Side view from the manipulator showing the maximum deflection it can achieve.

The resolution of tip movement and the maximum deflection of both steerable segments together are 0.38° and 159.2°, respectively, as measured with a digital camera and image processing software. In Figure 4(A)-(F), the follow-the-leader strategy is shown from the top view. The second segment can approximately follow the position of the first leading segment in large steps, however, its positioning in small steps is not smooth. While the control model assumes the tendons are routed parallel to the axis of the catheter, the tendons actually follow a very steep helical path, leading to small errors . Backlash was observed between actuator pulleys and tendons when the actuator reversed direction to steer the tip in the opposite direction.

CONCLUSION AND DISCUSSION

The modularized actuation unit can successfully drive a steerable segment of a tendon-actuated soft robotic arm independently and also together with other segments. Follow-the-leader control is achieved but with displacement error in the tip and in the following segment. With an improvement of the utilized mathematical model as well as the use of tendon force monitoring to compensate for actuator backlash, the error is likely to be reduced. To steer a multiple-segment soft robotic arm, a controller other than two joy sticks should be designed to have a better ergonomics since human operators are not used to control more than two segments at once. The advantage of a modularized actuation unit is its expandability and flexibility in adapting to robotic arms with varying DOFs. In the presented manipulator, it is proven that a robot with modularized actuation can be easily extended to more segments. Ignoring the physical limits on the maximum overall size of an actuation unit, the theoretical maximum number of controllable segments would be 128, as dictated by the maximum number of 7-bit addresses on an I2C bus. Further research will focus on decreasing the number of required actuators, miniaturization of the system, adding sensors that provide position and force feedback to reduce errors and also on the control model of the soft robotic arm.

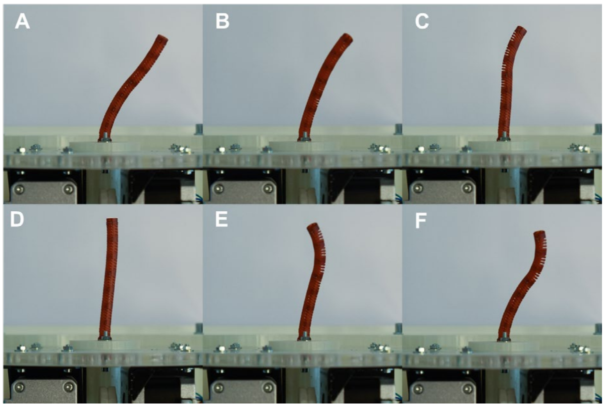

Figure. 4. Top view of follow-the-leader motions in different steps. From (A) to (C), the leading segment was steered to the right, and followed by the second segment. From (D) to (F), the leading segment was steered to the origin and followed by the second segment.

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