Elastic Mesh Braided Worm Robot for Locomotive Endoscopy

Thomas Manwell, Tomáš Vítek, Tommaso Ranzani, Arianna Menciassi, Kaspar Althoefer and Hongbin Liu*

Abstract— **This paper presents a new design of worm robot whose body is constructed using a novel crimped elastic mesh braid inspired by the earthworm. The proposed worm robot is intended for inspection within the human body via natural orifices. The design and fabrication procedure of the worm robot are given in the paper. The imitation of peristalsis, used by natural worms, is used to control the worm robot for the purpose of producing motion while causing minimal trauma to biological tissue. The forward locomotive function of the worm robot has been tested on both a flat surface and in a rubber tube. It is shown that the worm robot is capable of propagating forwards for both test conditions in a form similar to the earthworm. The test results indicate the proposed worm robot design has promising application for natural tube inspection, like the colon and the esophagus.**

I. INTRODUCTION

Colorectal cancer is the third most common cancer worldwide and the fourth most common cause of death, especially in the developed countries [1] [2]. Inspection of the large intestine via colonoscopy is an essential procedure for colorectal cancer diagnosis, but drawbacks including strain on the organ, strenuous for the surgeon and length of time it takes leave a space for technological advances. In order to improve traditional colonoscopy, a growing number of robotic solutions have been presented in recent years using a variety of actuation methods and movement algorithms.

Many of these solutions have been inspired by biological methods for locomotion, in particular peristaltic locomotion found in the earthworm (Oligochaeta). Advantages of imitating the mechanism of the earthworm are its cylindrical shape with all mechanical parts enclosed within a compact volume, requiring less space than other mechanisms, and it produces frictional gripping forces with its environment without needing to pinch [3] [4] [5].

It is the earthworm's two distinct muscle types, longitudinal and circumferential, alternatively contracting and relaxing, that enable the worm to achieve the locomotive functions [6]. During longitudinal contractions the segments become shorter and wider gripping the contact surface, while during radial contractions, segments become longer and narrower and are free to move. By controlling which segments are in an elongated state and which are in a compressed state, the worm transfers a 'wave' of contact points towards its rear end, progressing forwards.

Several of the prototype solutions based on the earthworm use pneumatics [7] [8] pressurizing discrete silicon or latex chambers in succession. These produce a larger circumferential change than elongation change. One also directed air externally to remove wrinkles in the colon tissue [9]. Shape memory alloys have been used to create artificial muscles that react to electrical signals imitating nature. This allowed for small dimensions and with the use of micro legs to achieve speeds similar to the earthworm [5]. Other solutions have been actuated using a combination of DC motors, worm gears and tendons [10]. Other approaches have made use of caterpillars for self-propulsion [12] and granular jamming to create stiffness controllable worm-like manipulators [11]. Robotic worms [13] [14] have also been developed for other applications including search and rescue [15] and in-pipe inspection [16] providing important theoretical insights, including the use of servo motors [17] and SMA combined with origami structures [18].

In this paper, we propose a new design of worm robot whose body is constructed using a novel crimped elastic mesh braid, Fig.1. This braid provides large ratio of longitudinal elongation over radial extension, thus providing effective locomotive function. Furthermore, the mesh braided worm body acts also as an extension spring, reducing the actuation complexity. In addition, the mesh-braided worm body is easy to be fabricated and minimized. Hence, the proposed worm robot is a promising platform for mounting a camera for the inspection of organs such as the colon and esophagus.

Figure 1. The developed worm robot using a crimped elastic mesh braid

II. DESIGN OF THE ELASTIC MESH BRAIDED WORM ROBOT

In order to imitate the earthworm's style of movement, we have attempted to replicate the mechanical means by which it achieves this. Where the earthworm has longitudinal muscles and radial muscles working together, this worm robot has a braided mesh as its core structural component,

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which changes in both length and width, antagonistically working against tendons pulled by a motor within each segment.

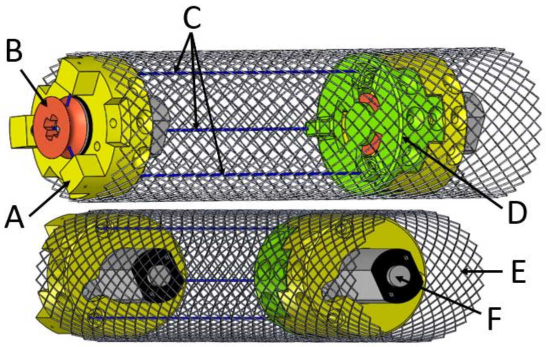


Figure 2. 3D model of a segment of the worm device components. A: Motor Housing, B: Tendon pulley, C: Tendons, D: Pulley Enclosure (tendons from next segment secured to this), E: Braided Mesh, F: DC Motor

The braided mesh (RS Components) is made of many helical plastic strands interwoven to form a cylindrical scissor mechanism that exhibits spring properties. The strands are coiled such that when the mesh is compressed, its radius increases and produces a compression spring force. This force then causes the segment to extend back to its rest position when the motor reverses. It was found that its default state could be shifted with the introduction of crimps. These were added in a similar way as [19], by compressing the mesh until buckling then heating with a hot air gun set at 300°C for a few seconds. To maintain spring characteristic the mesh was heat treated again in the fully elongated position.

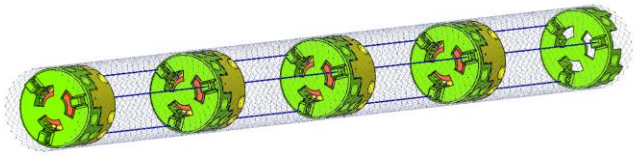


Figure 3. 3D CAD model of 4 segment worm device

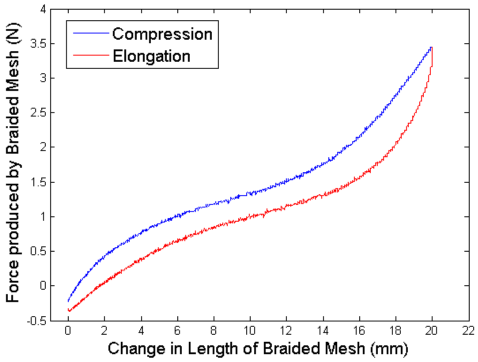


Figure 4. Force Displacement Relationship of braided Mesh

The braided mesh provides the worm body with a high elongation to radial expansion ratio, much like the earthworm, which will potentially lead to greater efficiency. With three crimps in the mesh braid, the worm body has 1.6 times longitudinal elongation and 70% radial diameter reduction in full extension stage. It has been shown in [19], the ratio of elongation to radial expansion increases with the increase of crimps of the mesh braid.

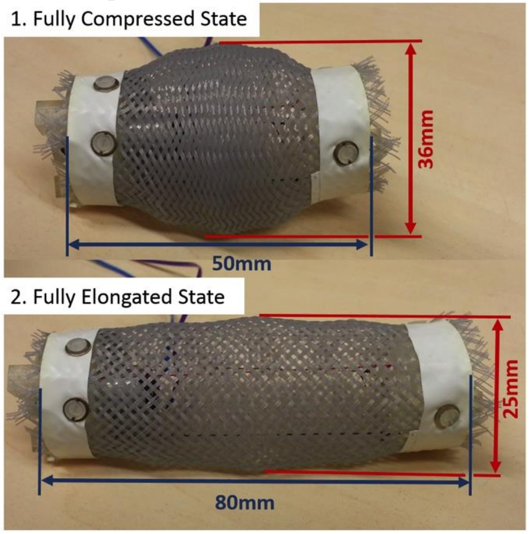


Figure 5. A single segment: (1) fully compressed, (2) At rest (fully elongated)

The tendons are wound onto a single pulley, which is turned by a single DC motor (rated 2.5V, Precision Microdrives™). Current feedback provided the controller with a closed-loop control system that didn't require additional sensors or cables. As the motors turn the pulleys and the threads pull each segment together, the mesh is compressed like a spring and the antagonistic force builds up somewhat linearly (See Figure 4). As this happens the motor draws more current, which when monitored by the control system can be used as indicator to see the state of the segment. Where our design deviates from being similar to the worm is using hard vertebrae segments. This is necessary to provide rigidity for the motor and pulley housing. Future designs may be entirely soft, but in this case we do not consider this to be a major drawback as they are small enough to fit into the target organ, the colon.

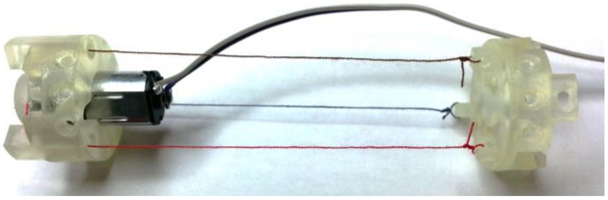
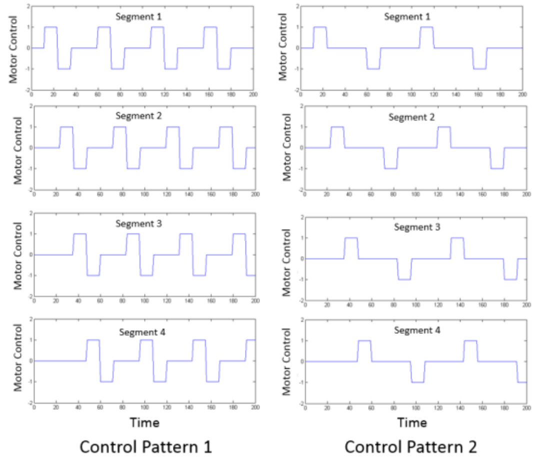


Figure 6. The mechanism within each segment shown without the mesh

Our prototype uses polyester sewing thread as tendons to pull the vertebrae together. Using three threads ensures stability in the antagonistic mechanism and therefore prevents buckling associated with using a single thread. The pulley design helps to avoid thread tangling. The motor wires trail from the rear of the worm to prevent interference with its motion and can also be used to retrieve the worm in an emergency. In the totally elongated state, with 4 segments, the worm robot is approximately 320 mm and in totally compressed state is approximately 200 mm. The proposed design has few mechanical parts, allowing for quick and inexpensive fabrication.

III. EXPERIMENTAL EVALUATION OF THE WORM ROBOT

The forward locomotion of the worm robot has been tested on a flat surface and inside a rubber half-pipe (bicycle inner tube) of diameter approximately 32 mm. Two control algorithms were evaluated, Fig. 7; both similar to the motion of an earthworm. These algorithms were coded and run on the Arduino™ platform and were tested with an open loop control system, without the current feedback, instead using selected motor speeds and run times.



Control Pattern 1

Control Pattern 2

Figure 7. Control algorithms used on the worm robot

Control algorithm 1: Sequential segment wave

This controller elongates ('opens') a segment while simultaneously compresses ('closes') the previous segment.

Control algorithm 2: Entire worm wave

This controller sequentially closes all segments with no overlap; then proceeds to open all segments in the same order.

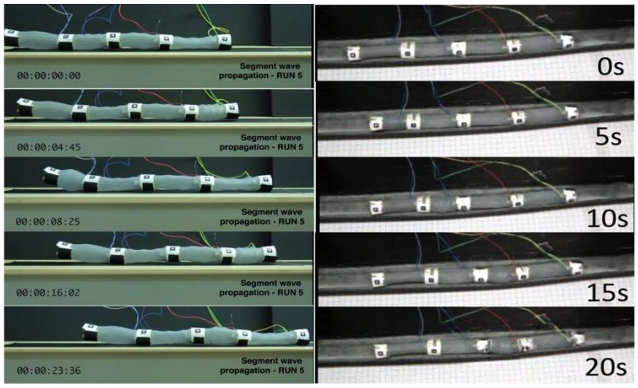


Figure 8. Video stills from (left) flat surface test and (right) rubber half-pipe test

During tests, marks were attached to the worm body and the motion of the worm was filmed, Fig. 8. Image tracking was carried out to investigate the motion of the worm. Figs 9 and 10 show the motion of the rear part of the worm robot and the relative motion of a single segment, respectively. It can be seen that, the worm can rapidly move forward with the control inputs of algorithm 1. Similarly, the worm is also able to move forward with the control pattern 1 when tested inside the tube, shown in Fig. 11 and 12. It was found that the worm robot was not able to produce forward motion as effectively with the control pattern 2. Table 1 summarizes the motion of the worm robot for two different test environments.

Test	Flat-surface, Algorithm 1	Flat-Surface, Algorithm 2	Half-pipe tube, Algorithm 1
Mean speed	5.6 mm/s	3.2 mm/s	2.1 mm/s
Mean segment frequency	0.44 Hz	0.14 Hz	0.25 Hz

Table 1. Motion of the worm robot using both control patterns on flat and in half-pipe with control algorithm 2.

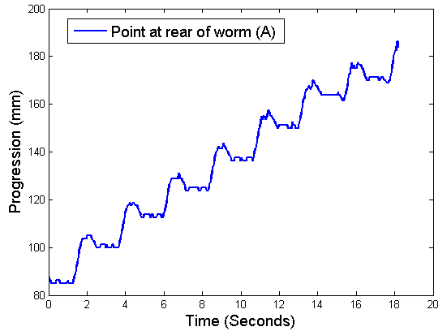


Figure 9. Progression of a point at the rear of the worm robot tested on a flat surface using control algorithm 1

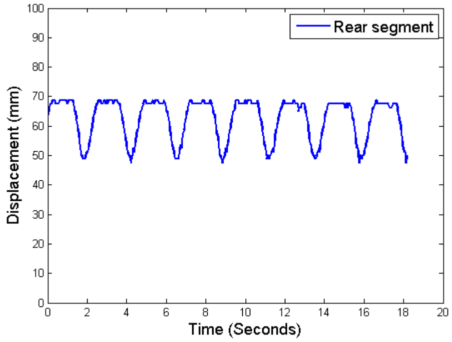


Figure 10. Motion of one segment relative to the next when worm tested on a flat surface using control algorithm 1

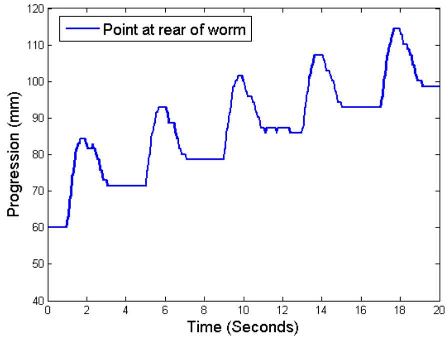


Figure 11. Progression of a point at the rear of the worm robot tested inside a rubber half-pipe using control algorithm 1

It was observed that the motion of one segment Figure 10, Figure **12** correlate with their input signal of control pattern 1. The contact for frictional anchor points is taking place not only at intended contact point of the mesh's widest point but also between the motor housing and the environment due to the weight of the motor. A design improvement would be to shift the weigh distribution to segments' center points. Slip was also observed when segments are shifted backwards in our results. It was found there was more slip in the rubber tube test because of increased friction on elongated segments from the walls of the tube. The progression takes place when segments have less contact with the surroundings, meaning there is less kinematic friction. This characteristic is potentially useful for avoiding trauma to biological tissue.

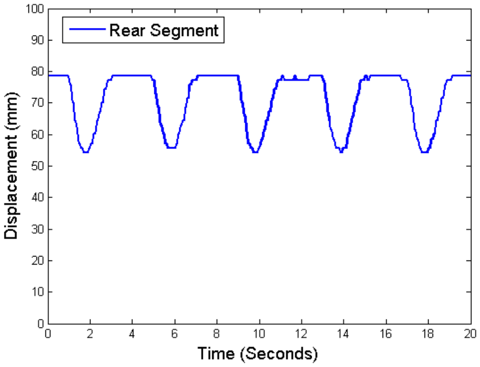


Figure 12. Motion of one segment relative to the next when worm tested inside a rubber half-pipe using control algorithm 1

IV. CONCLUSION AND DISCUSSION

We have shown a novel device that closely imitates the movement style of the earthworm, producing a similar locomotion. Experiments have shown that the worm robot was able to propagate forward on both flat surfaces and inside a rubber tube. This indicates that the developed semi-soft worm robot has great potential as a way to move inside the human body for observation and therapy, with its reach, compliancy and locomotion without pinching.

Two models were trialed; a version with separate pieces of mesh for each segment with the motor's wires coming out of the sides and another with a continuous piece of mesh with motor wires contained within the worm and exiting out the rear of the worm. The first was able to move without mechanical obstruction but could not fit inside the rubber tube for testing. The second was more robust but it required more effort to compress the segments because of the motor cables and so took longer. As the braided mesh provides structure and a spring force our design consists of small number of parts and yet achieves the intended motion and the movement style, which will lead to an efficient and safer alternative for human endoscopy. The device can be further developed to be waterproof and sterilized after use, or because of its simplicity with few mechanical parts and straightforward to manufacture as a device that can be disposed of after use, without great cost.

While this design has 4 segments, the worm has several hundred. A large number of segments would be difficult to achieve but would enhance friction. This is a significant difference between the earthworm and the presented worm robot. The earthworm creates a contact area comprised of many compressed segments, which at times amounts to the majority of its total length.

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