Long and Thin Continuum Robot: Properties & Stabilization Mechanisms

Yannis (Yiming) He[1]

***Abstract*— In navigating and inspecting in complex environments, continuum robots can target positions that traditional robots cannot reach. In this application, long and thin continuum robots are desirable. However, withstand its self-weight and controlling such a robot is challenging. We proposed a tendon-driven continuum robot which is 710 mm long and 14 mm in diameter thin. We evaluated the real robot in different scenarios. The result of the study reveals that a continuum robot with a length-diameter ratio of over 50 can navigate through complex environments and hold payloads beyond 0.5 times its weight.**

I. INTRODUCTION

Robots are widely used in the process of industrial inspection and navigation[3] because they have high accuracy, efficiency, and trigger less human injuries. However, a conventional robot can hardly reach to complex environments due to their rigid body. A soft and continuum inspection robot is designed to have a long and thin joint-less body[1] to stably going through a complex environment.

Most of the current research on soft robotics focus on small scale invasive surgical operation[2]. However, the operation is hard to scale up due to the design of the pre-bend concentric tube. Moreover, because of the structural design of the long and thin, flexible body, such a robot cannot withstand its self-weight. This also leads to the difficulties of the controllability of a soft robot. Therefore, this research project aimed to understand basic properties of a long and thin continuum robot and suggest ways to stabilize the joint-less body in the process of inspection and navigation.

To ensure the testing result match with the real-life applications, a build-and-measure method is applied to this study. The researcher built a testing robot, whose body is 710 mm in length and 14 mm in diameter, using 3D printers: Formlab 2 and Ultimaker 3. (insert picture of the hamster 2.5). In the testing process, MicroScribe MX Digitizing Systems and a spring force sensor are used to capture the position of the robot and the force required by the actuation.

After the investigation for the structure of the robot, the study discussed two position-constraint methods to stabilize the robot. (1) sectional layer Jamming method allows the stiffness of each segment of a joint-less body to be controlled individually, which constraint the flexibility of a segment depend on its former segment. (2) Tripod method constraint the motion of a robot relative to its environment to achieve stability.

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[1]Yannis He is with Faculty of Applied Science & Engineering, Division of Engineering Science, University of Toronto, M5S 2E4 ON, Canada yannis.he@mail.utoronto.ca

II. METHODS

This section will introduce the construction of a robot, methods of the testing, and the production of the stabilizing mechanism.

A. *Construction*

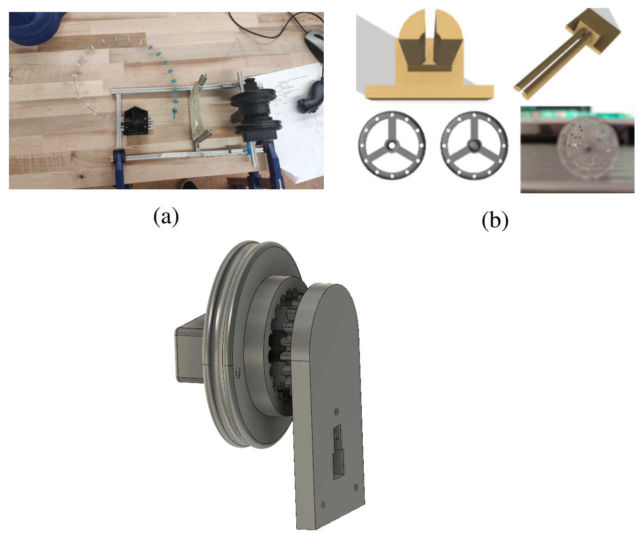

Fig. 1: (a) Prototype: *Hamster2.5*, a hand-actuated navigation robot. The soft body is freeze by the locking mechanism. (b) Alignment Tool used to assist the assembling process. (c) Two locking mechanisms are used to freeze the soft body to a non-equilibrium position, which ease the measuring process.

The robot (figure 1a) has two main parts: a deployable soft body and an actuation unit. For the deployable body, nitinol tube with 1.0 mm diameter was used as the backbone and disks were 3D printed in resin using *Formlab 2*. The 23 disks with 14.0 mm diameter and 2.0 mm thickness were connected to the backbone by super-glue. The robot is tendon actuated antagonistically; thus, four 0.1 mm steel fishing line going through each disk. To increase the stability and minimize twisting, an alignment tool (figure 1b) was designed to assist the assembling process.

The hand-actuation unit was built with customized components printed in tough PLA using *Ultimaker 3* and *Miniature T-Slotted Framing* with 100.0 mm^2 squared cross-section. Two dials with locking mechanism 1c are used to freeze the robot to any non-equilibrium position. This data provides a consistent result for the measuring process.

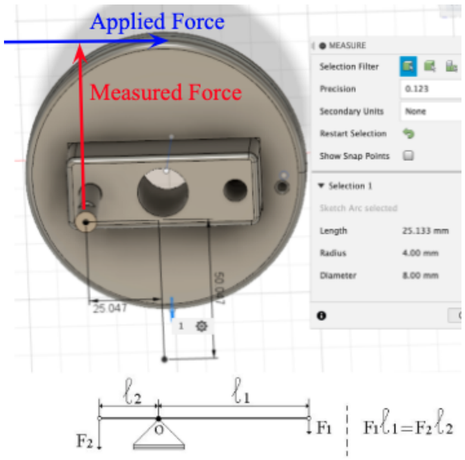

Fig. 2: Design in the actuation unit to indirectly measure the actuation force. The measured force was pulling perpendicularly to the rectangular block as the dial was turned.

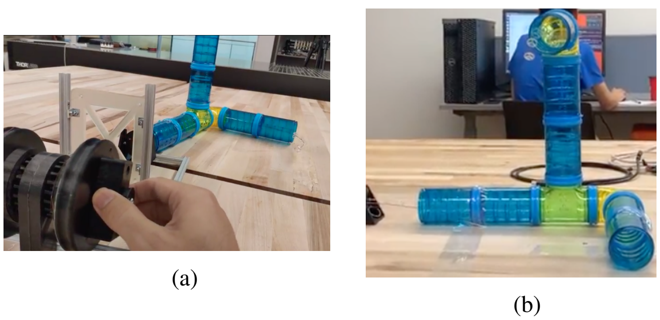

Fig. 3: (a) The robot was deployed straight in and then turned 90° to the right. (b) The robot was deployed straight in, then turn 90° up, turned 90° to the right at the top.

B. Testing

3D configuration, ability to load, and navigation were tested.

For the 3D configuration testing, initial position (straight), extreme bending position, abilities to bend to certain angles, as well as the tip's 3D workspace were measured using *MicroScribe MX*. Actuation was tested by measuring forces required to bend to different angles and the ability to carry loads using a spring force sensor. Due to the difficulty of pulling the tendons directly using the spring force sensor from the actuation unit, indirect method (figure 2) was used and the conversion is calculated as

$$F(applied\ to\ a\ tendon) = 0.5439 \times F(measured) \quad (1)$$

For the navigation testing, hamster pipes (figure 3) were used to simulate the environment, where the robot be deployed.

C. Stabilizing Mechanisms

Two design approaches were considered for designing a stabilizing mechanism for a long and thin continuum robot.

The first approach was built with sectional layer jamming. To maximize the stability and controllability, a deployable

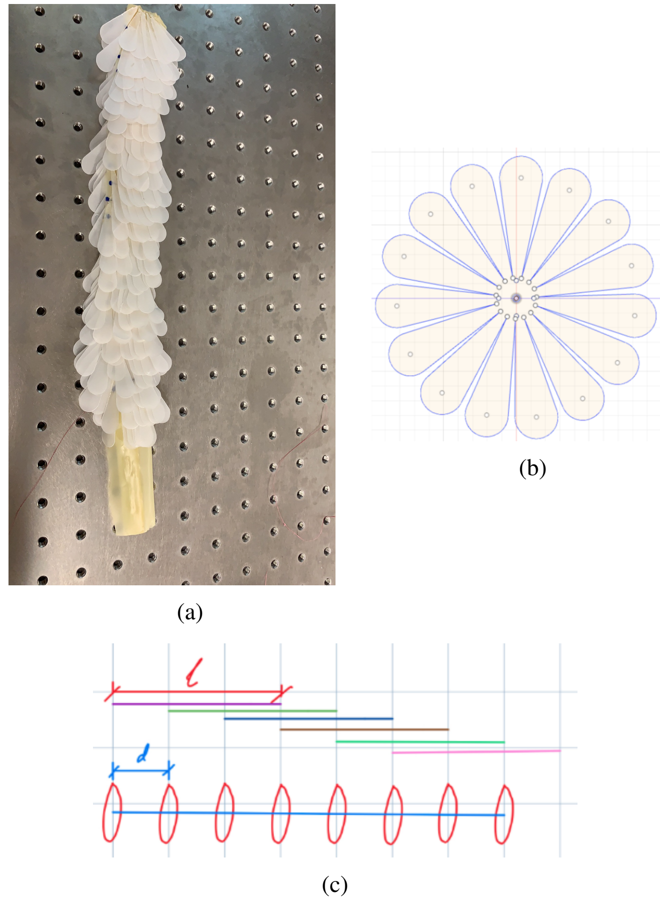

Fig. 4: (a) Petal-shape layers were connected to the rubber sheet by super-glue. There is another layer of rubber sheet, which is not shown in the figure, wrapping around to form an airtight chamber (b) The CAD design of the petals. (c) except for the first 2 disks, everywhere else has 3 layer of petals.

body can be divided into multiple segments and the sectional layer jamming can control the stiffness of the robot independently for each segment. Thus, a segment is stiffened when its position reaches the desired location. Therefore, the deployable body can be stabilized by minimizing the deviation caused by the flexible backbone. To reduce the fabrication time, a flower layer jamming, which was suggested by the former Continuum Robotics Laboratory colleague, Volker, was pursued instead of a traditional layer jamming approach[4]. Volker suggested that we could glue the petal-shape layers to the membranes (figure 4a, which is used forms the airtight chamber, instead of manually sewing the traditional layer. In the material selection process, translucent paper with 0.1 mm thickness was used as the "petals" (figure 4b) for the flower jamming, and stretchable natural rubber sheet with thickness of 0.15 mm thickness was used as the membrane. The length of the petals, l, was designed (figure 4c) to be 3 times longer than the distance between each disk, d, to ensure the number of layers, which is 3, is the same throughout the deployable body.

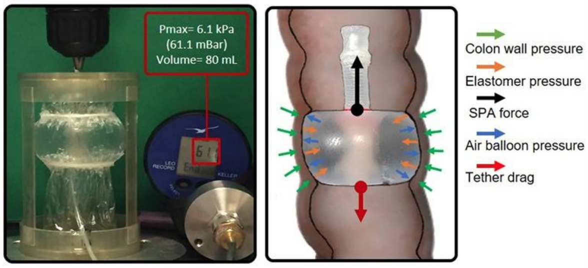

Fig. 5: External support that stably fixes the robot in the environment, designed by the University of Dundee.

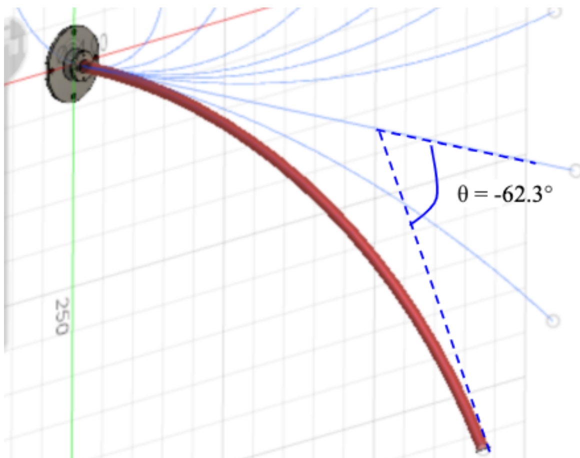

Fig. 6: The robot cannot withstand its weight. The natural bending angle without any actuation is -62.3°.

The second approach was called Tripod Approach, which was inspired by tripod stands used for photography. Instead of holding a robot's weight by its backbone, the robot can stabilize itself by external support, an airbag (figure 5), for instance. However, during the developing process, a paper [5] with a similar idea was published by the University of Dundee. Therefore, no further investigation was done on this approach.

III. Results

A. 3D Configurations

The initial position, natural bending position, extreme bending position to the top and sides, and 3D workspace of the tips were recorded using 3D measurement tools. As expected, this long and thin continuum robot, without actuation, does not withstand its weight. The angle, θ, between the initial position and the tangent line at the tip was -62.3° (figure 6). The ability to go to other bending angles (figure 7) was also measured. With different amount of forces applied to the actuation unit, the robot could go up to 360° (figure 7i). In the actual measurement, the flexible backbone without external supports was highly unstable and led to the difficulty to measure exact data. Figure 8 shows the difference of data measure from bending up without support and bend to right with support from the table.

B. Actuation

Forces required to go to different angles under the effect of gravity in the vertical plane were measured and displayed in figure 9. Since the limit of the spring force sensor is 10.0 g, the measurement was not able to continue to more than 180°. However, figure 9 shows that the angle raised is linearly proportional to the forces applied. Thus, the forces required can be estimated using the linear relationship.

Forces required to lift loads to the horizontal level is shown in figure 10. From the observation of the measurement process, the robot was highly unstable when the load reached 3.6 g. Moreover, the shape of the long body does not follow the constant curvature model anymore after this load (figure 11). Additionally, some thresholds were observed in the actuation. The robot did not react to the applied forces until the threshold was passed.

C. Navigation

As mentioned in the Methods section, the robot was able to travel through the hamster pipe without issues. With practices, it could go through two 90° turns within 14 seconds. Nevertheless, as the complexity of the environment increase, the robot started to have difficulty to navigate because the soft body is hard to be pushed in. After the second 90° turns, the robot can only bend in one way, which is the direction it bent to at last, because the high torque was applied to the flexible body and the disks started to twist. Moreover, when the robot was arranged to certain irregular shapes, the movement of the robot did not react to the applied force linearly as well. Once the applied force passed a threshold, the robot will have a sudden turn. This phenomenon was also observed in the actuation of a concentric tubular robot, known as snapping [6].

IV. Discussion

Based on the testing results, we believe that continuum robots built for navigation need a light-weighted stabilizing mechanisms. Without the stabilizing mechanism, the robot does have basic functions, but it is hardly controllable while carrying payloads. Moreover, flexibility affects the deployment of the robot and causes the twisting. Any small movement of the body causes a drastic movement at the tips because the body is too long.

The discovered issues with layer jamming, in general, were as follows. The airtight chamber was hard to seal. Once the chamber was leaking, the entire chamber needed to be replaced. Besides, the weight of each segment still depends on its previous segment. Hence, snapping would occur before and after the stiffening, which is hard to be simulated.

For the tripod approach, the weight of each segment depends only on its surroundings. Therefore, except for the section that is operating, other sections can have no relative movement with the environment. Nevertheless, further investigation needs to be done to confirm the complexity of manufacture and deployment.

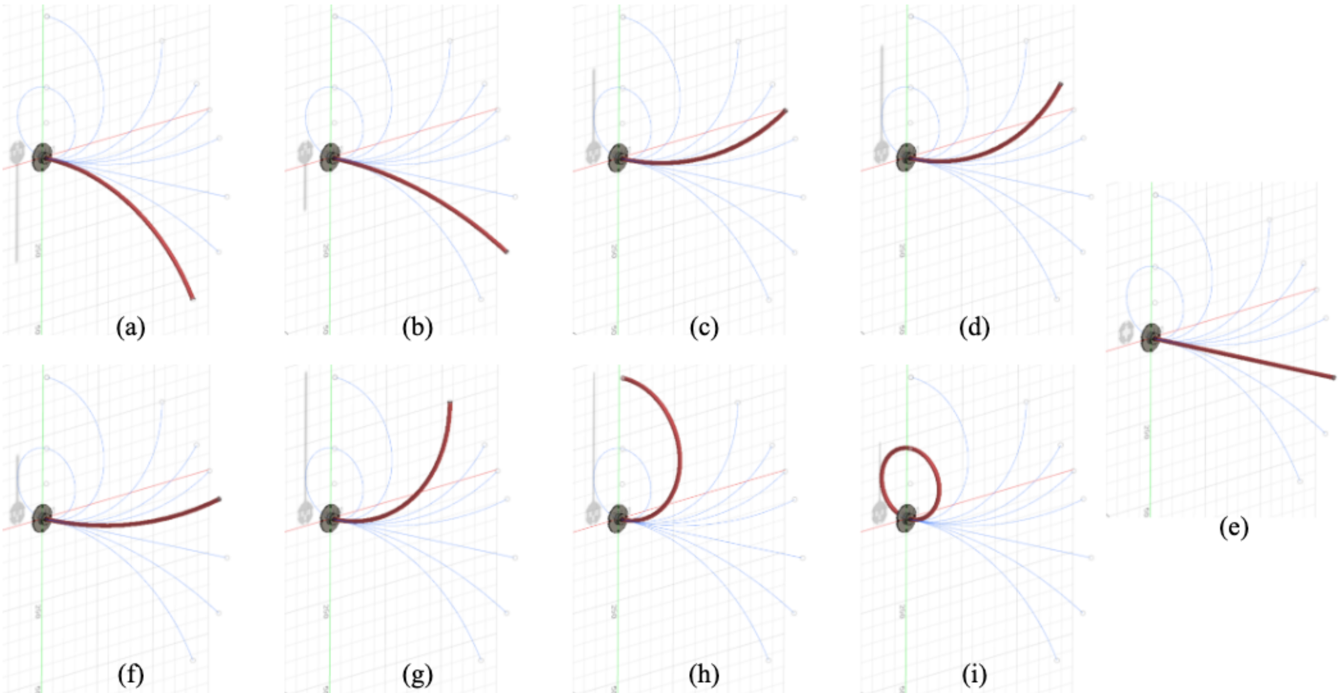

Fig. 7: Different bending angles actuated with. The diagram is generated by simulation based on constant curvature model and 3D configuration measurement.

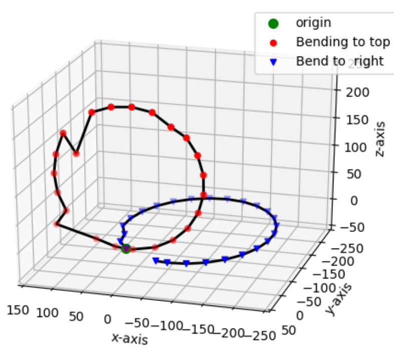

Fig. 8: The robot (red) bend up without support vs the robot (blue) bend to its right with supports from the table.

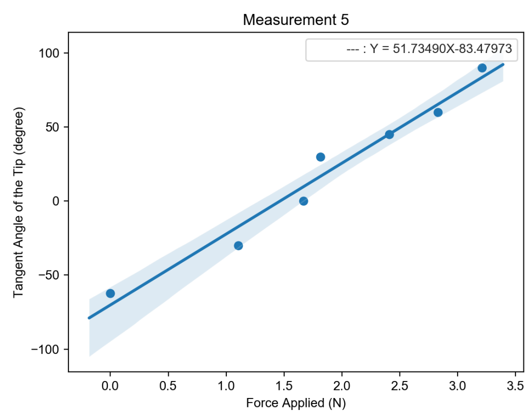

Fig. 9: Tangent angles of the tip vs Forces applied to the top tendon.

V. Conclusion

Overall, the long and thin continuum robot is functional without any stabilizing mechanism. It can navigate through low complexity environments. However, at the current stage, the robot is hardly applicable to the real-life scenario. Therefore, a stabilizing mechanism is necessary. After comparing two stabilizing mechanism, we believe the tripod approach is better and has the potential for further investigation.

To improve on the current prototype, stronger design structures and materials should be used. The current design is built for light self-weight, which occurs that it breaks easily. Furthermore, a better connection mechanism should be considered. The current solution, which is super-glue, is not secure enough. The disks shift and twist under high tension.

Several concerns were raised. Once the robot is long and the lever arm is large, the force applied will be less and less effective. If the disks start to shift and twist under length, it will break more often when a long body is designed. Additionally, a simulation that modeling snapping and resistant caused by internal equipment, such as wires and cables for camera, sensor, and lights, is also challenging to create. Therefore, for navigation purposes, a designer might want to consider and compare another actuation method instead of tendon-driven actuation.

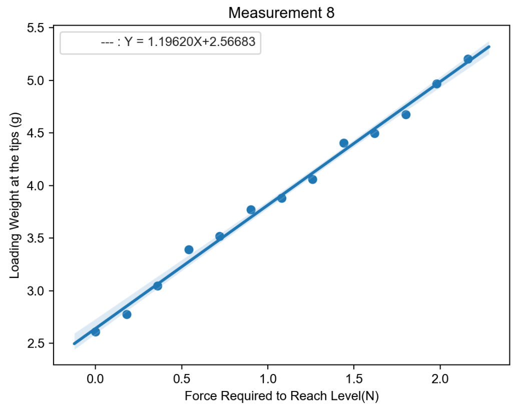

Fig. 10: Loading Weight at the tips vs Forces applied to reach the top level.

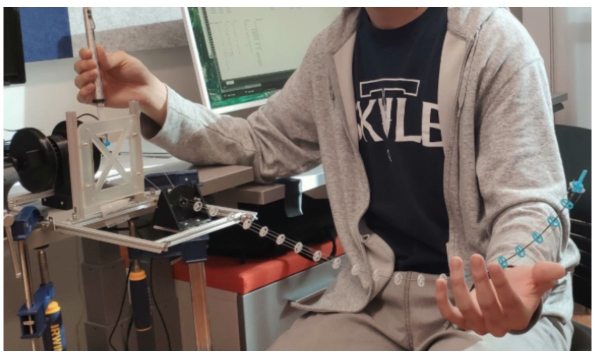

Fig. 11: Loading Weight at the tips vs Force applied to reach the top level.

VI. Acknowledgment

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