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TREE: A Variable Topology, Branching Continuum Robot

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Abstract— **We describe the design and physical realization of a novel branching continuum robot, aimed at inspection and cleaning operations in hard-to-reach environments at depths greater than human arm lengths. The design, based on a hybrid concentric-tube/tendon actuated continuum trunk core, features two pairs of fully retractable continuum branches. The retractable nature of the branches allows the robot to actively change its topology, allowing it to penetrate narrow openings and expand to adaptively engage complex environmental geometries. We detail and discuss the realization of a physical prototype of the design, and its testing in a simulated glove box environment.**

I. Introduction and Background

Continuum robotics as a field is still in its infancy. The snake robots of the early 1980's [1] represent some of the earlier examples of continuum robots. Beginning with such early designs, continuum robots have found use in a variety of fields, such as medicine [2], inspection [3], agriculture [4], navigation within hazardous environments [5], and biomimetics [6] [7], [8] Their targeted applications differ from those of "conventional" rigid link robots, mainly because their smooth continuous bodies can provide a maneuverability which rigid link robots often cannot. They possess a fundamentally different structure and rely on large- to (theoretically)-infinite degrees-of-freedom to achieve a high level of compliance.

Traditional rigid-link robots differ from continuum robots in various important aspects, chiefly arising from their physical design. In contrast to rigid-link robots, continuum robots have a "smoother" and a more compliant backbone enabling them to configure into a wide variety of curved shapes. Continuum manipulators are most useful in applications where the dexterity of the manipulator is of a higher priority than its accuracy. Given their inherently flexible nature, continuum manipulators are well suited for navigating through congested spaces, grasping irregular objects, or negotiating a priori unknown structures [9].

Most continuum robots developed so far have been at a relatively small scale, typically significantly less than one meter in length. Some larger scale continuum robots have been demonstrated. In [10], [11] for example, thin continuum "Tendril" robots of length over one meter are detailed, aimed at the exploration of complex areas that are not easily accessible. Another relatively long design (over one meter) is the "snake-arm robots" of OC Robotics (OCR), which are used in inspection operations [12]. However, the OCR robot arms have segmented backbones, are not used as manipulators, and lack truly continuum structures.

The only example of a truly large-scale continuum robot to date is the EMMA™ [5] manipulator which was a 52.5 ft (16 m) hyper-redundant manipulator aimed at waste tank remediation. EMMA™ used a tower system which lowered the entire 5-stage arm into the area of access and had a motor drive to enable it to rotate along the tower axis. However, this system was tightly focused on its specific task, and the design is not easily generalized to other applications.

Continuum robots to date have predominantly been single backbone systems, without branches. Systems featuring multiple continuum robot backbones have been considered [13-19] for surgical applications, notably single port access surgery. Once again, these systems have been highly focused on their specific application task, operated to enable low profile access and using their relatively small-scale multiple backbones for that single specific procedure, rather than more adaptively creating and exploiting variable topology.

There is significant motivation to bring the adaptability of multi-backbone continuum robot structures to bear at the multi-meter scale, as this could enhance robot penetration of traditional application areas for robotics including hazardous materials inspection/handling, and enable new applications in areas such as in agriculture, food service, warehousing, and construction.

In this paper, we introduce a large-scale continuum TREE (Tree Robot for Extended Environments) robot, featuring two pairs of fully retractable continuum branches, at the multi-meter scale. The robot trunk is the first, to the best of our knowledge, concentric tube robot realized at the scale of backbone length greater than a meter (1.8m fully extended). The overall goal is to realize a larger-scale robot with dexterity exceeding that of existing continuum robots, with a longer reach and a payload capacity higher than that of thin continuum counterparts at the multi-meter scale.

In the following section, we introduce the underlying design for the tree robot, and describe the realization in hardware of a prototype of the design. In section III, we discuss experiments conducted to evaluate the physical capabilities of the hardware. Section IV describes demonstrations performing inspection and cleaning tasks in a mock-up hazardous materials handling "glove box" environment. Conclusions are presented in Section V.

II. Design and Hardware Realization

A. Design Concept

The design for the robot features a core extensible continuum "trunk" and two pairs of fully retractable continuum "branches". We first discuss the trunk design and then that of the branches.

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A.1 Trunk Design

Since EMMA™ [5], there have been few continuum robots realized at the multi-meter scale, and these have been thin tendril-like robots [10], [11] with low load capacity. Since the trunk herein is required to support multiple branches and their payloads, an alternative design approach was required. Our overall goal for the trunk was to design and prototype an extensible continuum-style robot with a minimal number of tendons, capable of operating and supporting branches at lengths of well over a meter, while providing the same amount of dexterity found in typical continuum robots at sub-meter lengths.

In consideration of the success of concentric tube continuum robots used in medical applications at a significantly smaller scale, we decided to use a concentric tube design for our trunk robot. As in the case of medical continuum robots, the extension and the retraction of the tubes relative to each other is realized by linear actuators at the base. In order to minimize the number of motors needed for tendons, we elected to use two tendons, spaced at 180° apart around the robot circumference, to achieve bending for each section, while providing another motor at the base to directly actuate relative rotational motion between the tubes of successive sections. This results in each section bending in a single plane with the rotational base motors rotating that plane about the backbone tangent at its proximal end, in order to access the full 3D workspace. The overall design concept for the trunk is shown in Figure 1.

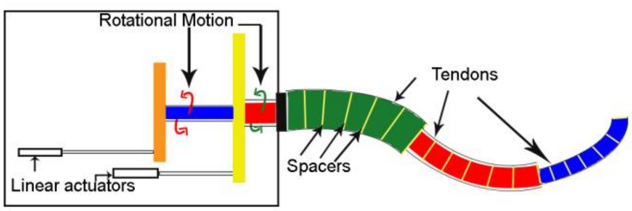

Figure 1. Design concept of concentric tube continuum trunk robot

A.2 Branch Design

The design concept selected for the branches features two pairs of branches, two "elbows" and two "feelers". Both pairs are required to be fully retractable, with the elbows emanating from the most proximal section of the trunk, and the feelers emanating from the most distal section. See Figure 2.

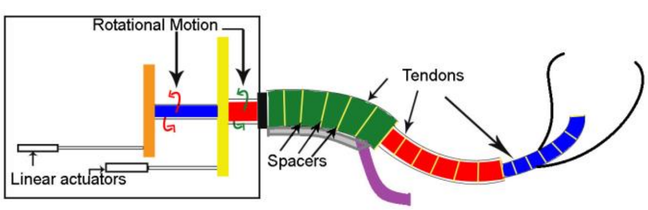

Figure 2. Design concept of trunk robot with branches

The inspiration for the "elbows" comes from the way low hanging tree branches often grow towards the ground and use it for support as they continue to grow. An example of this behavior is found in the branches of the Angel Oak Tree on Johns Island, South Carolina, U.S.A. (Figure 3) [22]. Due to the horizontal orientation of the trunk and the flexibility of the materials with which it is built, its tendency is to sag. The elbows were designed to stiffen and support the trunk as it extends. With compression springs as backbones, the branches remain dexterous and are actuated by three tendons, spaced at 120° apart. As the springs compress, the elbows stiffen, and the spacers lock together to form rigid structures which support the weight of the trunk.

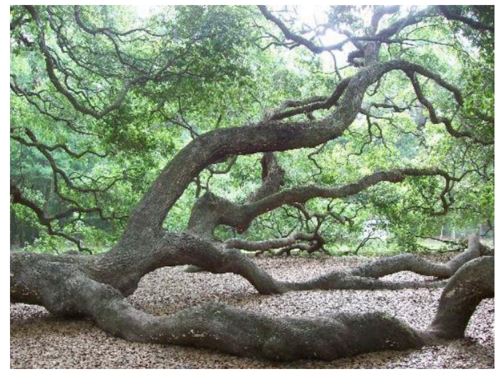

Figure 3. Inspiration for "elbows" found in nature – Angel Oak Tree (Photo courtesy of TripAdvisor [22])

The "feelers" are adapted versions of the Tendril [11]. These branches use the same diameter carbon fiber tubes as the middle section of the Tendril and are actuated by four tendons. Three tendons are spaced 120° apart, and one is threaded between two of those tendons and terminated approximately 1' (0.3 m) from the tip. This allows the branch to produce more complex configurations. These vine-like continuum branches provide extensive inspection capabilities when equipped with a camera, such as viewing the end effector from different angles. They can also perform cleaning tasks on a very small and delicate scale.

B. Prototype Development

In this section, we describe the development of a prototype of the above design. We first developed a prototype of the trunk, followed by development and integration of the branches. These developments are described below.

B.1 Trunk Development

We faced several challenges in considering materials selection, as discussed in [20], which details our initial efforts. In order to achieve sufficient curvature, the design requires a higher level of flexibility in the materials while also maintaining the backbone stability, i.e. sufficient stiffness to prevent kinking. We initially considered PEX (crosslinked polyethylene) for all sections since the bending achievable was more than sufficient for our requirements and the material was able to regain its shape upon release and relaxation of the tendons. However, at larger diameters (>2", or 0.05m), achieving the necessary curvature became increasingly difficult, and ultimately resulted in kinking because of the required application of a significantly high force. As discussed in [2], materials with a high elastic strain limit are usually associated with a lower Young's modulus. For our desired application, we required a material with high elastic stress limits (a product of elastic strain limit and Young's modulus).

After taking these factors into consideration, we ultimately selected PVC duct hoses for the middle and proximal section tubes. These tubes provided sufficient stiffness and were reasonably pliable in their direction of inherent curvature. We selected section tubes having lengths of 2' (0.6m), 4' (1.2m) and 6' (1.8m) (green, red, and blue, respectively in Figure 1). The middle section PVC tube selected had a bend radius of 6" (0.15m) and wall thickness of 0.055" (0.002m). It also had a smooth interior surface texture, which was desirable for actuation of the distal section inside it. The possibilities of the distal section getting caught at any point on the inner surface were reduced. For the proximal section, we selected a PVC tube with a bend radius of 8" (0.2m) and material thickness of 0.047" (0.0012m). PEX (cross-linked polyethylene) remained a suitable material for the distal section, and with the diameter at ½" (0.02m), the bend achieved proved sufficient. The resulting initial prototype is shown in Figure 4.

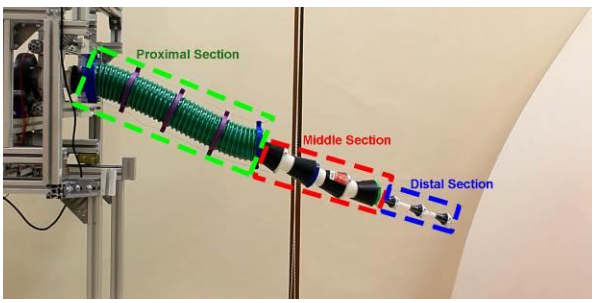

Figure 4. Prototype of the trunk design concept

The inner diameters of the tubes in the prototype in Figure 4 were selected to be ¾" (0.02m), 2" (0.05m) and 4" (0.1m), for the distal, middle and proximal sections respectively. We incorporated spacers for tendon routing. For concentric operation of the tubes, the outer dimensions of the spacers (inclusive of ball bearings located in them to reduce friction, see next paragraph) needed to match the inner diameter of their respective outer tubes/sections for smooth linear and rotational actuation. We constructed the spacers using an additive manufacturing, i.e. 3D printing, process. Each section had two tendons routed through the spacers, at 180° apart radially, and terminated at the end.

To achieve smooth linear as well as rotational actuation for the middle and distal sections, it was desirable to minimize the amount of friction between the tubes. We integrated ball bearings in the spacers since the spacers were already conveniently in existence along the length of the tubes. The bearings provided sufficient support at every point of contact, while also reducing friction between the materials. The resulting hardware is shown in Figure 5. To integrate the ball bearings, we used a 3D printer to create the spacers. The spacers were printed in halves, and glued to enclose most of the bearings. This solution significantly reduced friction for linear and rotational actuation.

For the middle section, because there was threading on the outside of the PVC hose, the spacers were printed with tapping on the inside so that they could be screwed on to the hose. Because of the presence of spacers on the outside of the tubes, the surface created a challenge for linear actuation of the tubes, as the spacers could "catch" on the end of the outer tube, and cause the inner tube to stick. To prevent this, we added conical plastic guides on the spacers, so that during actuation, the guides aligned the inner tube with the opening of the outer tube. The 'guides' were attached to the sections in the direction of actuation as shown in Figure 5.

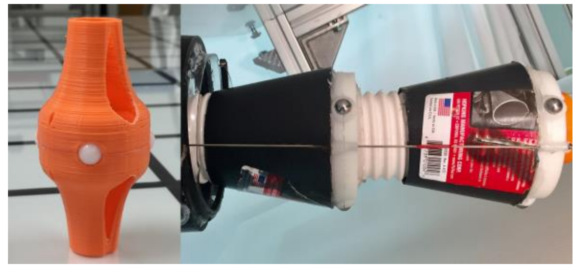

Figure 5. Conical guides for the tubes

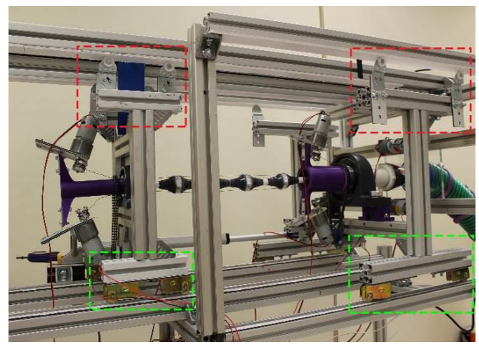

Figure 6. Mechanism for linear actuation. Upper rollers (in red), lower rail and rollers (in green)

The actuation of the robot was engineered as follows. For linear extension and contraction of the tubes, we used a simple rail-guide mechanism connected to a linear actuator. The base of each section was mounted on a 'slider' running on rails. As shown in Figure 6, the base of each section was attached to a pillow block bearing which was mounted on the slider highlighted by green border. Rollers were mounted on top of the slider (highlighted by the red border) for additional support and to prevent the assembly from toppling over. We used linear actuators capable of moving up to 150 lbs (68 kg) to push/pull the sliders with speeds of approximately 1 inch/second (0.03 m/s). One drawback of this mechanism is that for the middle section to retract, the distal section needed to be retracted first, and similarly for the distal section to extend, the middle section needed to extend first. However, the arrangement proved to work well in practice, and the tubes extended and contracted smoothly.

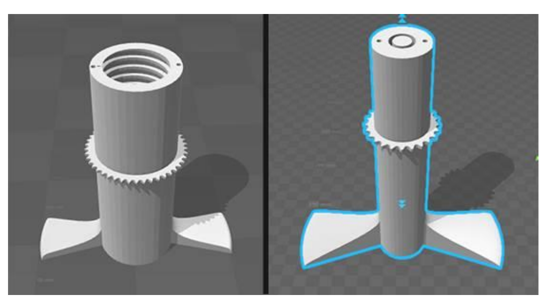

Figure 7. Mounts for middle (on left) and Distal (on right) sections

The base of each section was mounted on 3D printed pieces (collars) shown in Figure 7, which facilitated rotational motion and had the tendon-pulling motors mounted on them. These collars were attached to pillow block bearings mounted on the abovementioned sliders. As seen in Figure 7, the collar for the middle section had tapping on the inside matching the outer thread on the middle section hose. Also seen is that the collar for the distal section had a slot for the pipe to be fitted into. The design featured a sprocket for a #25 chain on each of the collars (middle and distal) and two holes on the sides of each for tendons to pass through, as shown in Figure 8.

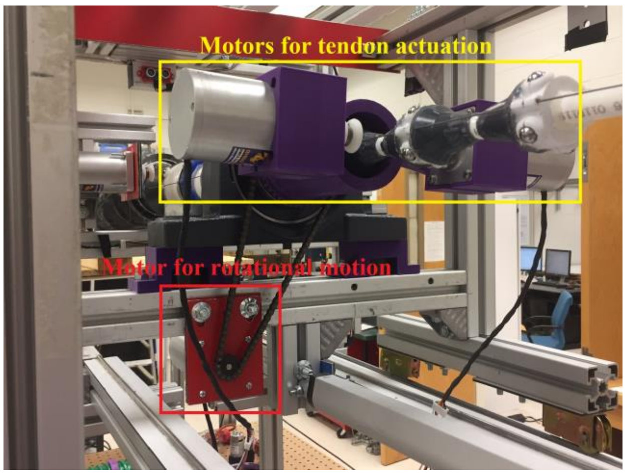

Figure 8. Motor placement (Middle section)

A motor mounted below the slider controlled the rotational motion of each section. The motor had an attachment, enabling it to rotate the section using the chain-sprocket system. Also attached on the 3D printed collar were the tendon-driving motors to effect bending of the sections.

B.2 Branch Development and Integration

In order to integrate the branches into the distal section of the trunk, the goal was to find a material in which to store the branches when retracted. The challenge was choosing a material that was flexible enough to not restrict the bending of the sections but sturdy enough to permit extension and retraction of the branches. We found thin-walled, chemical-resistant tubing with an inner diameter of 7/16” (0.011 m) to be the optimal solution. We modified the design of the spacers for the distal section to allow this tube to run alongside the PEX tubing as shown in the left half of Figure 5. Since the 3D printed spacers required modification, we updated the design to include the conical shapes to improve structural integrity and aesthetics. To allow the Tendril branches to emerge from their housing, we cut a slot in the branch housing approximately 11” (0.28 m) from the tip of the distal section. Each branch is actuated by four tendons and a linear servo assembly (Figure 9) for extension and retraction. This assembly provides a maximum extension of approximately 11.25” (0.286 m) for each Tendril branch from their fully retracted positions. We constructed an entirely new distal section (Figure 10) to accommodate the necessary changes to incorporate the branches while keeping the original section intact for future experiments.

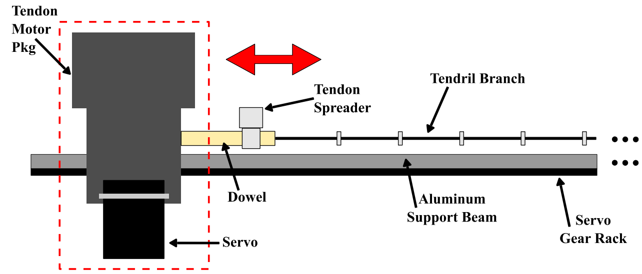

Figure 9. Tendril branch actuation assembly

Figure 10. New distal section with emerging Tendril branches

Similar accommodations were made to integrate the support branches (elbows) into the proximal section of the trunk. The same chemical-resistant tubing, with a larger inner diameter of 1.5” (0.04 m) was used to store the branches. We attached them to the bottom of the base section spacers, one offset to the left of center and the other to the right. The elbows themselves were constructed of 3D printed spacers with six teeth on top and bottom. The tops of the spacers are male fittings and the bottoms are female to allow them to interlock. For the backbones, we selected 20” (0.51 m) long compression springs with outer diameters of 0.375” (0.0095 m). They have a deflection of 10.69” (0.272 m) under a maximum load of 5.63 lbs (2.55 kg). The spacers are designed in the shape of a wedge (one side is taller than the other). This causes the top faces to be inclined, forcing the branches to take the form of a predefined curve when compressed, creating an elbow shape. Each spacer has three tendon holes, 120° apart, and tapping through the center to allow them to be screwed onto the spring, as shown in Figure 11. To simplify the compression of the spring (stiffening of the elbow), we attached one end of a carbon fiber tube to the end cap of the branch and ran the tube down the center of the spring. The branch is compressed by simply pulling this tube.

Figure 11. Construction of the support branches (“elbows”)

III. Experiments and Validation

We conducted baseline experiments with the trunk to evaluate the workspace envelope and the load capacities of each of the three sections. We report here on the vertical envelopes of the robot, which were considered to be the most significant as they are the most effected by gravitational loading. The values reported here are made with all sections extended to their maximum lengths.

A. Individual section bending envelope

The proximal section, without external load, could lift by 46.7° and depress the sections by 20.4° (Figure 12). This was considered sufficient for the proximal section to be effectively used to raise the more distal sections to an appropriate height and provide support for them.

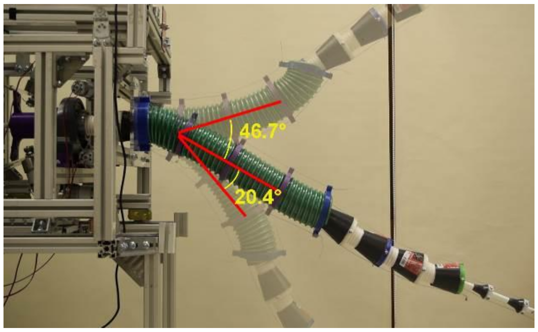

Figure 12. Working vertical envelope of the proximal section

With greater flexibility compared to the proximal section, the middle section has a greater working envelope and can cover 91.3° planar bends with the bend and 72.7° against the bend (Figure 13).

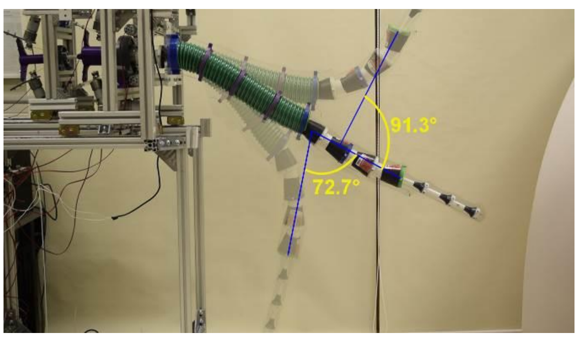

Figure 13. Working vertical envelope of the middle section

The distal section tube covered a 194.9° arc when bending (Figure 14). Further bending was found to damage the pipe structure because of surpassing its yield point or elastic limit, and was thus avoided.

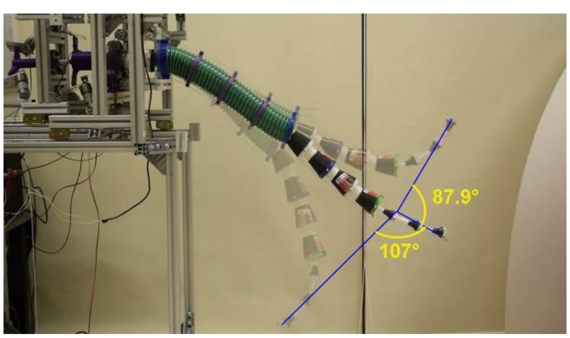

Figure 14. Working vertical envelope of the distal section

B. Static Load Tests

In order to demonstrate the static load carrying capacity of the trunk, we attached a series of loads at the ends of each section to measure the deviation in their structure. In the reported experiments, the sections were aligned in order for them to be completely horizontal. We attached a load scale at the ends of each section and recorded the angle deviation at equally spaced steps. For the proximal section, the load capacity was 11 lbs (5 kg). For the middle section, the maximum load was 8 lbs (3.6 kg), and the distal section maximum load was 2.5 lbs (1.13 kg).

The robot is controlled by an Arduino Mega microcontroller. The tendons are accurately actuated by directing the motors to specified encoder counts, and the linear actuators can be instructed to move specific distances due to the placement of ultrasonic distance sensors. The configuration of the entire robot, including the position of the tip, is modeled using a modified application of the constant curvature kinematics described in [21]. The main modification we made was ensuring that the arc length (section length) of the distal section is adjusted as the middle section is extended/retracted.

IV. Operation and Demonstrations

The tree robot design is such that it can sustain significant loads as well as reach into areas which are difficult to access. To evaluate these issues, we conducted representative demonstrations, discussed further in this section.

A. Trunk Cleaning Demonstration

The aim of this experiment was to demonstrate the use of the trunk for novel applications, and in particular its potential for maintenance operations in "glove box" type environments typically used in nuclear radiation remediation. Glove boxes are sealed containers built to perform operations on radioactive material safely within them. Remediation and maintenance of such glove boxes are potentially hazardous tasks well suited for robotics. However, their narrow entry ports and often cluttered internal environments make them challenging for entry and operation of conventional rigid link robots.

A mock-up glove box environment was constructed (Figure 15), of dimensions 32" x 44" x 32") (81cm x 112cm x 81cm). The walls were made of acrylic sheets and made to be transparent for demonstration purposes. The goal was to demonstrate the ability of the trunk to enter through the narrow 7.75" (20cm) diameter port, and reach all 8 corners of the box, to simulate a cleaning task. Such tasks are considered particularly challenging for conventional robot technologies.

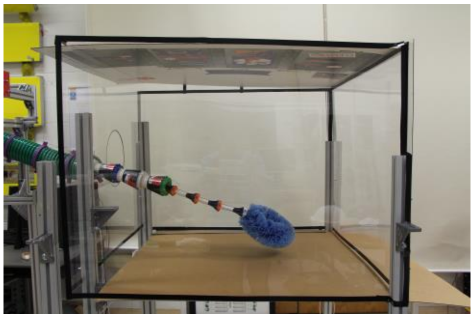

Figure 15. Mock-up glove box with robot entering through port on left

A bristled fan cleaner was fixed to the end of the trunk to simulate the cleaning attachment. The robot was inserted into the environment and maneuvered to reach the roof (Figure 16), back wall, and corners of the environment.

Figure 16. Robot reaching to clean top and corner of box

The robot was able to successfully reach and maneuver the cleaning tool to all faces and all corners of the box. See video attachment to the paper for footage. This task required the distal section to bend over 180°.

B. Overall System Demonstration

We conducted additional experiments to demonstrate the capability of the overall integrated system in novel inspection and cleaning tasks.

We attached a small paint brush to the tip of the robot to use for cleaning the walls of an empty aquarium, serving as a surrogate for a glove box wall. While the aquarium was dusty, we used a dry erase marker to make highly visible marks to clean. Due to the small size of the brush and the size of the robot, it would be difficult to guide the brush to a desired location. Therefore, the goal of the experiment was to use an Enable, Inc. minnieScope –XS, 1.4 mm diameter camera deployed at the tip of one of the Tendril branches to help us guide the tip and perform close inspection of the environment (aquarium). Using this camera, we were able to guide the paint brush to the marks and clean them. The left half of Figure 17 shows the tip of the robot "holding" the paint brush, as well as the Tendril branches (one of which contains the camera). The view of the inspection camera housed by the branch is shown in the right half of Figure 17.

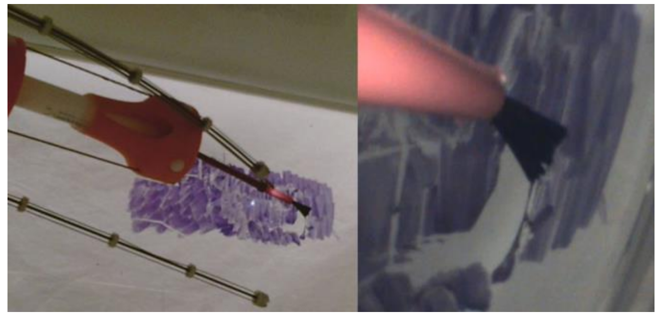

Figure 17. Using a Tendril branch for inspection while cleaning

We also tested the supporting ability of the elbows. To verify their effectiveness, we tested their stiffening capabilities under the weight of the robot itself. With both the middle and distal sections approximately halfway extended, we took measurements with and without using the support elbows. We measured the distance between the end of the base section and the shelf over which the robot was to reach to be 4 7/8" (12.38 cm). With the elbows extended and stiffened as shown in Figure 18, the distance between the robot and the shelf was 5 3/8" (13.65 cm). From this, we could conclude that the elbows improved the robot support by approximately 10.3%. The deployed elbows made the system visibly more stable than when they were not deployed.

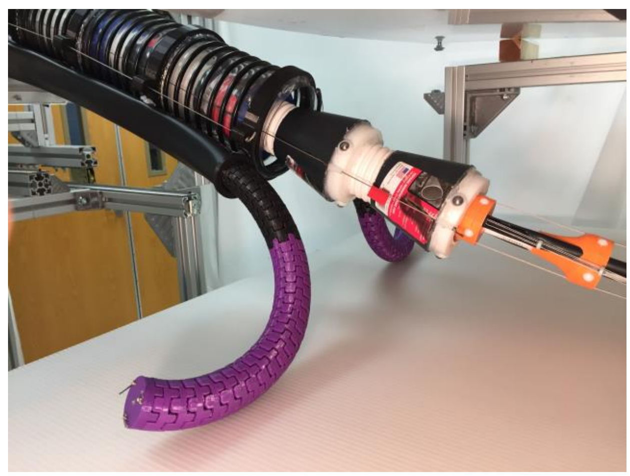

Figure 18. Fully compressed, locked support branches ("elbows")

V. CONCLUSION

We have introduced a new type of branching continuum robot, with a central continuum trunk and two pairs of fully retractable continuum branches, realized at a relatively large scale. The design enables unique functionality exploiting its novel variable topology. We detailed the design and construction of a prototype with extended length of the design. Testing with the prototype demonstrated the feasibility of the design.

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