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# Next Generation Rope-Like Continuum Robots for In-Space Inspection

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**Abstract**: - Continuum robots have been an active area of research in robotics for minimally invasive surgery, search, and rescue, object manipulation, etc. NASA also has developed “Tendril”, the first long and thin continuum robot of its kind, intended for in-space inspection applications. There are disadvantages of the state of the art mechanical design producing undesirable effects during operation. These disadvantages are overcome by developing hybrid robots involving snake and continuum elements. Then the specifics of a new, next-generation, rope-like robot with a modified mechanical design using tendons comprising of a series of compression and extension springs that are interconnected using threaded links is provided. This improves the performance by having key features like controllable bending along its entire length, local compression, and potentially smaller actuation package.

**Keywords—*continuum robot, actuators, tendons, concentric tube design.***

## I. Introduction

Continuum robots are also known as snake-arm robots although these terminologies are restrictive in their definitions and cannot be applied to all continuum robots. A continuum robot is a robot with a continuously curving manipulator, similar to the arm of an octopus. An elephant’s trunk robot is a good example of a continuum robot. This has generally been associated with whole arm manipulation – where the entire arm is used to grasp and manipulate objects, in the same way, that an elephant would pick up a ball.

This is an emerging field and as such, there is no agreement on the best term for this class of robot. Continuum robots are often used in association with another device, where the other device is to introduce the snake-arm into the confined space. For example, the introduction of axes includes mounting a snake-arm on a remote-controlled vehicle or an industrial robot or a linear actuator. In such cases, the shape of the arm of the robot is coordinated with the linear movement of the introduction axis enabling the arm to follow a path into confined spaces.

Various types of continuum robots have been designed over the past few years. The three major design alternatives commonly used are tendon based approaches, concentric-tube designs, and locally actuated backbone design. Serially connected constant curvature sections are the underlying principle in almost all continuum robots. NASA developed “Tendril”, the first long and thin continuum robot of its kind, intended for space inspection. Tendril was developed with both snake and continuum structure. But there were some undesirable disadvantages due to the mechanical design. This disadvantage was overcome by developing a modified mechanical design in which tendons were used. This “Next-generation Tendril” improves key features like controllable bending over the entire length, local compression and extension, and smaller actuation package. This “Tendril” experiment has opened a new way of designing continuum robots.

## II. Design Principle

A continuum robot can be defined as a robot with a continuously curving core structure, or backbone, whose shape can be actuated in some way. Another property is that the backbone is compliant by yielding smoothly to externally applied loads. These properties explore the physical capabilities of the continuum robots which allow them to adapt the backbone shape to maneuver the robot within more complex environments and to access a wide range of objects than the feasible ones with rigid-link robots.

The design space available to achieve the above properties is very large. For example, the backbone core does not even have to be continuous. The body of a snake has a continuous structure, but are vertebrates, with an internal segmented backbone comprised of (many very small) rigid-links. Robots similar to snakes with segmented rigid-link interior backbones with a continuous external form have already been developed.

These are sometimes termed “continuum-style” robots. However, such designs are rare, and most designers have sought to create fully continuous backbone structures. The most significant exceptions are the “snake-arms” of OC Robotics, the only continuum style robot currently commercially available. These robot arms, as the name suggests, are composed of serially connected modular rigid-link sections. While not fully continuum, with enough modules, it resembles a continuous backbone. They have been deployed in nuclear reactors and inside airframes, among other applications.

The design of robot structures in the absence of rigid elements is an unfamiliar process for most robotics designers. However, several basic design principles can be identified by a detailed study of biological “tongues, trunks, and tentacles”. In particular, the group of animals with structures termed as “muscular hydrostats”, which includes octopus arms, elephant trunks, squid tentacles, and mammalian tongues, has provided a thoughtful insight for continuum robot designers. Animals do not have to be the only source of inspiration, the creepers, climbers; tendrils of plants are a source of inspiration also.

Fig.1. Snake arm robot

Muscular hydrostats are structures that are comprised almost entirely of their own actuators (muscle), with some extra fluid and connective tissue. They have the flexibility to bend and twist and often extend to any point along their structure. The muscles are arranged in organized arrays (longitudinal, transverse, and oblique) so that it enables the motive force and structural support for bending, extension, and torsion to be provided by the muscles. There is some initial work aimed to mimic the muscular hydrostat design concept in continuum robots, using various artificial muscle technologies. Practical continuum robots require not only significant bending but also high force generation, and the state of the art in artificial muscle technology was not capable of satisfying these needs at scales suitable for continuum robots. In the future, if there is sufficient advancement in artificial muscle technologies, the possibilities for design and operation of continuum robots could be revolutionized.

In the absence of advanced technologies that can mimic the key inspirations from nature, designers had to follow several alternative paths. The basic requirements were to produce active bending, some extension, and local torsion, of continuous backbone structure which possesses some predesigned internal energy properties. As a result, three alternative fundamental design strategies have emerged. Each strategy and the continuum robots constructed using it are summarized in the following chapters.

## III. Tendon Based Design

One of the most direct approaches for bending a continuous structure is the use of actuated tendons. Given a backbone which, in the absence of external loads, consistently attains a given shape, tendons can be used to deviate it from that shape via bending. Tendons are steered along the backbone and terminated in groups at some points down it. Forces that are applied to the tendons at the base points produce torques at the termination points, resulting in bending. Motors are used as actuators. The design is quite simple and straightforward to realize as hardware. The “Tensor Arm”, is one of the good examples of a tendon based design. Tendons, routed through spacer elements, were used to bend the core backbone element in several “sections.” The termination points of these tendons along the backbone define the sections.

### A. Advantages and disadvantages

Some of the common features of Tendon-based continuum designs are as follows: (1) the backbone shape resolves into a series of sections whose endpoints are defined by the tendon termination points along the backbone; (2) the forces achievable with the device are relatively high; (3) some method must be found to prevent slack and backlash in the tendons; and (4) the design requires a bulky actuator (motor) unit at the base of the robot. Most implementations either actively actuate all tendons or use a single actuator to actuate antagonistic tendon pairs, with a spring mechanism to take up the slack. The location of the actuator unit outside the backbone leads to the tendon design being categorized as an “extrinsically actuated” continuum robot design.

### B. Application

Tendon-actuated continuum robots have been designed for space operations and, in particular, medical procedures. A spring-based tendon-driven backbone continuum robot was developed for sinus surgery and another developed for ACL surgery. A “robot octopus” with six cable-actuated limbs was demonstrated underwater.

### C. Tentacle

The "tentacle" robot developed by Clemson University is a tendon-based continuum robot, with a flexible and incompressible backbone. It is constructed such that each section will bend such that the curvature and torsion within that section is approximately constant. It has a slender backbone profile but lacks local extension or contraction. A modified version was developed with varying section lengths to achieve a greater variety of shapes, but it lacked local extension or contraction.

### D. Raven

A compliant probe having a camera was integrated into RAVEN, a type of surgical robot. RAVEN served as a flexible tool, again for minimally invasive surgery, comprising of compression springs for the distal section, and a spring enclosing a flexible tube for the proximal section. These springs were mainly used to achieve bending with the help of cables running through them on the inner side, and thus utilizing their capacity to compress and extend for turning. The tool adapter slides along a linear insertion axis providing a translation of the probe. Tool adapter slides along a linear insertion axis providing translation of the probe.

Fig.2. The Tentacle

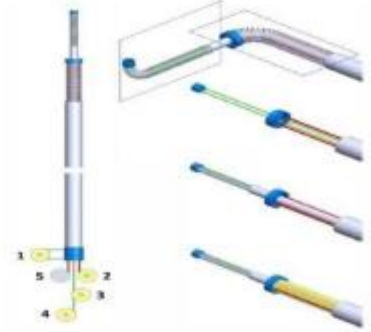

Fig.3. Flexible image probe for “RAVEN”

## IV. CONCENTRIC TUBE DESIGN

The second form of extrinsically actuated continuum robot is based on a backbone formed by concentric compliant tubes. The tubes are free to move (translate and rotate) with respect to each other with the translations and rotations actuated at the base of the robot. The effect is similar to those in some telescopes: the structure can be extended and contracted by translational motion of the tubes longitudinally and the structure can achieve a local rotation by rotation of the tubes.

As a result, the concentric tube design achieves both extension and torsion. However, it does not inherently provide for backbone bending. The easiest approach to this problem is to use pre-curved compliant tubes. When this is combined with the directly controllable extension and torsion, it provides some useful variation in the shapes of the backbone. Servo motors can be used as actuators. Another approach is the usage of tendons for bending the tubes. However, this significantly increases the complexity of the design.

### *A. Advantages and disadvantages*

Advantages of the concentric tube design include the inherently clean and thin design with no tendons to bend the tubes and the fact that the actuator values directly correspond to backbone shape variables unlike the Tendon based design. Disadvantages include the need for an external actuator package and the lack of inherent support for actively controlled bending resulting in limited degrees of freedom.

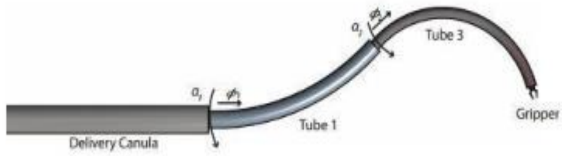


Fig.4. Concentric tube robot.

### *B. Application*

Concentric tube continuum robots have found a nice application in the medical field, where their small profile and high compliance are well suited for minimally invasive procedures. In this case, they are smaller-scaled and lower-force devices than their partners built via the other two designs and are sometimes termed “active cannulas”. For example, in sampling-based motion planning techniques are used to design a concentric tube robot specifically for the task of navigation through the human lung. In an MRI-compatible, piezoelectrically actuated concentric tube robot is designed for neurosurgery and percutaneous interventions.

### *C. H.A.R.P*

The Highly articulated Robotic Probe (HARP) introduced by Carnegie Mellon University and the multi-turn catheter by MIT are snake robots, working on variations of the principle implemented in the Shape Lock patent of USGI Medical. Their ability to achieve multiple bends about their entire length is promising. Both, however, have highly complicated mechanical designs and require a large actuator package. The former is bulky and the latter one needs a proper contact surface to enable its motion. All this is unfavorable for a robot operating in space.

## V. LOCALLY ACTUATED BACKBONE DESIGN

The third design type varies from the previous two. as the actuators directly included in the backbone. This type of design consisting of locally actuated continuum robots typically forms the backbone from its actuators. In this manner, this design is closest to the biological continuum structures which motivate the continuum robots. This also gives rise to the categorization of the design as “intrinsically actuated”.

Normally locally actuated designs form the backbone from pneumatic “McKibben” muscles, though different versions using shape memory alloys have also been built. The strategy is to form the backbone from independently actuated sections. Each section is built from typically three independently actuated muscles connected together across their length. The muscles can be “extenders” (increased length as a function of increased pressure) or “contractors” (decreased length as a function of higher pressure).

The selection actuators for intrinsically actuated continuum robots could be from any existing type of artificial muscle.

This includes the artificial muscles based on engineered polymers, such as elastomers. An extensive study of the potential of these types of actuators is presented. However, at this time, only the pneumatic, hydraulic, and motor actuator technologies feature the combination of bending and force generation capabilities for continuum robots at the human scale or larger.

### A. Advantages and disadvantages

Locally actuated continuum robot designs have the key advantage of naturally providing the backbone with extension, bending, and torsion. This is a feature not directly provided by either tendons or concentric tubes, as discussed in the preceding subsections. Disadvantages of locally actuated designs include relatively low force generation capabilities fairly complex tube routing/valving, and the need for external pressure regulation equipment and a compressor.

Fig.5. Oct-Arm Continuum robot

### B. Application

The locally actuated continuum robot design has been the subject of much research and numerous realizations in recent years. In particular, the high-profile “Oct-arm” (Fig.5) and “European Octopus”, projects featured continuum robots based on this design. Other adaptations of the design include the “Bionic Assistant”, which resembles the trunk of an elephant. Shape memory alloy actuation has been used to steer an active cannula for medical procedures, and in, dual shape memory alloy-based backbones are used in a system designed for single port access surgery. Also, a locally actuated system has been utilized for endoscopic stitching intended for surgical obesity treatment, and design for colonoscopy insertion is described.

## VI. THE CONTROL MODULE

In order to control the motion and actuation of the continuum robots, we need to install a control module. A control module consists of microcontrollers and microprocessors. The microcontroller and microprocessors are chosen according to the application such as PIC, AVR, 8051, etc. These microcontrollers and microprocessors are used to create PWM signals that control the motors, In addition to these microcontrollers; the PID controller is used for accuracy in actuation.

### A. PID controller

A Proportional Integral Derivative (PID) controller has a feedback mechanism in a control loop that is commonly used in industrial control systems. A PID controller continuously calculates an error value as the difference between the desired set point and a measured process variable. The controller tends to minimize the error by adjusting a control variable, for example, the position of a control valve, a damper, or a new value determined by a weighted sum:

Where all non-negative, denote the coefficients for the proportional, integral, and derivative terms, respectively (sometimes denoted P, I, and D).

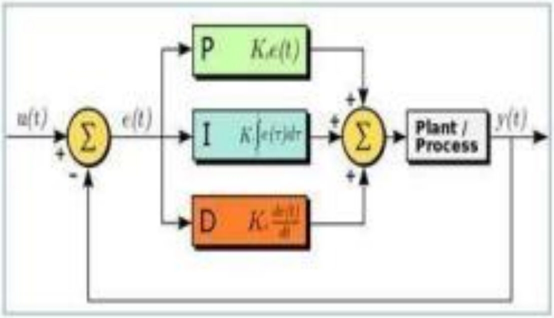


Fig.6. Block diagram of PID controller.

## VII. THE “TENDRIL” EXPERIMENT

NASA's "Tendril" is a tendon based design, comprising of a series of compression and extension springs as shown in Fig.7. are interconnected using threaded links. It has only two actively controlled bending sections. The compression springs form the two actuated sections at the distal end of the backbone and tension springs provide passive bending in the remainder of the backbone.

Fig.7. Tendril body springs.

Two antagonistic pairs of tendons are attached to each section and terminated at a pulley, whose motion is achieved by DC motors. Thus, there are four controllable DOFs. The tendons run along the entire length of the body terminating at the distal end of each section. The motors have connected

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encoders that are used to provide position feedback. For the purpose of testing and evaluating "Tendril's" capabilities, a second version was constructed from the spare parts of the original "Tendril". Linear amplifiers are used to provide the required power signals to the motors. The control system uses the interface Qmotor to directly control the motors. A simple closed-loop proportional control algorithm with an error tolerance was implemented.

### *A. Observations*

The major problem which "Tendril" exhibits is the strong coupling between the sections. When the section at the end of the robot is moved, it results in the misalignment of the proximal sections. This is mainly due to the relative stiffness of different sections. When the tendon connected to the end section is pulled to achieve bending, it causes all the earlier sections to compress/buckle(Fig.8).


Fig.8. Joint buckling due to coupling of springs.

Another problem exhibited by "Tendril" is the twisting of the joint springs as shown in Fig.9. This effect is accentuated due to gravity or any load connected to the robot. The current arrangement of one motor and corresponding pulley controlling two tendons causes slack in one of the tendons. This results in the need to remove the slack by drawing in the appropriate tendon for some time before beginning the operation. Each tendon could be controlled by a single motor to prevent this issue.
Gravity causes the robot to sag a little even when it is in a vertical configuration. This effect would be more prominent if it is intended to be used in a horizontal configuration for terrestrial applications.

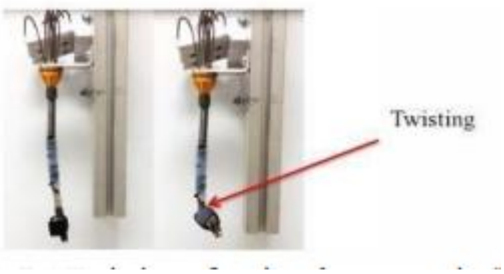


Fig.9. Twisting of spring due to gravity/load.

### *B. Conclusion*

"Tendril" is ideally supposed to follow the actively bending sections. But since the main body is only composed of passive tension springs, it is largely affected by gravity and exhibits flopping or sagging behavior.

Thus, in conclusion, "Tendril" is hard to control due to the inherent uncontrollable compressibility of the backbone, torsion of joints and inability to locally extend or contract. Also, most of its length is unactuated. Kinematic model based control has been attempted to improve its performance to some extent, but the undesirable effects are too strong to be used in useful applications.
All the above shortcomings emphasize the need for a significantly improved structural design dedicated for long and thin robots.

## VIII. "NEXTGEN TENDRIL" DESIGN

The inspiration for "NextGen Tendril" was a modified version of the tentacle robot with varying section lengths. In that design, tension springs were used in between the spacers, which were in turn attached to the flexible but incompressible backbone to achieve limited changes in section length. The "NextGen Tendril" design attempts to utilize compression springs in a similar manner to convert the disadvantage of buckling into a desired feature of local contraction.

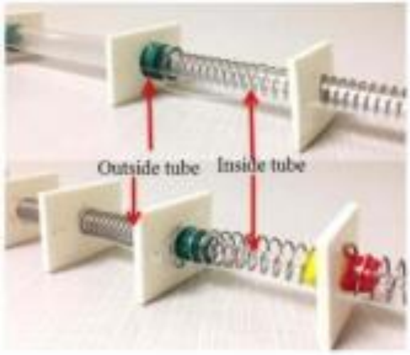


Fig.10. Concentric arrangement of backbone sections in "NextGen" Tendril prototype

The underlying concept for "NextGen Tendril" is to combine the most favorable properties of concentric tube and tendon driven spring backbone designs. The core backbone of "NextGen Tendril" is made of concentric tubes. However, in extending and contracting the tubes relative to each other, instead of a bulky mechanism using linear actuators, a spring/tendon based approach is adopted. The tubes "float" in and out of one another with springs along the backbone providing tunable resistance. Tendons are used to pull against the springs, providing both extension/contraction and bending capabilities with a compact tendon- based actuator package.

### *A. Initial prototype design*

The design features three flexible and incompressible backbone sections. PETG (Polyethylene Terephthalate Glycol-modified) was selected as the material of the three backbone sections for the initial prototype since it is readily available and is bendable and machinable. The distal end is a rod with the proximal and base sections being tubes. These are arranged in a telescopic manner like traditional concentric tube robots

### *B. Operation*

The final prototype of the "NextGen Tendril" is a three-section planar continuum robot. Tendon actuation produces bending in the direction of the tendon alignment on the backbone. Each section can be bent in two dimensions with the help of three tendons (2 DOF). The above design has the resulting backbone approximating a series of connected sets of constant curvature sections.

Fig.11. Springs and spacer arrangement using nitinol.

Since the backbones are concentric and telescoping in nature, each can achieve controlled linear motion with respect to each other. In such cases, the linear motion is supported by compression springs. The tendons pull the distal backbone section inside the middle and that in tum inside the base compressing each spring to its solid length. This is counteracted by the compression springs which, on releasing the tendons help to return the backbones to their original position by reassuming their relaxed state.

### *C. Advanced Prototype*

The successful results of the initial prototype led to a revised design of a more advanced prototype where the main concerns were to achieve the thin profile and a three-dimensional version (9 DOF) of the above prototype. Nitinol was found to be the most suitable material for the backbone for achieving the above. Nitinol can be obtained in various forms including wires, tubes, and sheets with profiles ranging in millimeters and lengths in feet. Nitinol's property of super elasticity helps it to deform easily and regain its initial shape again. The oxide surface provides a lower frictional resistance, ensuring the smooth sliding of the tubes relative to each other. It is lightweight and has good tensile strength.

The "NextGen Tendril" is a new design for a long and thin version of continuum robots. It provides a significant improvement over the only existing (to the best of our knowledge) long and thin continuum robot currently present, the "Tendril". The replacement of springs with incompressible but flexible backbone elements helps eliminate uncontrollable buckling and twisting of joints. The entire body is actively controlled and hence the unactuated and passive proximal structure of "Tendril" is not an issue. Since it does not require linear actuators to achieve local extension (sliding concentric tubes), it presents a clean and simpler mechanical design compared with previous concentric tubes or shapes lock designs.

## IX. CONCLUSION

Continuum robots have the potential to yield a unique benefit with respect to their "invertebrate" structure. The Continuum backbones can twist and turn to adapt to very tight spaces, thus penetrating areas where conventional robots would be unable to enter or would get their links stuck in. The potential to achieve this ability for in-space inspection, using a long and thin counterpart led to the development of "Tendril" by NASA. However, a number of drawbacks in its mechanical design cause undesirable effects affecting its efficient operation. These effects have been identified by analyzing the "Tendril" and simple solutions are described in this paper to reduce these effects.

A review of different types of continuum and continuum style robots shows that direct implementation in a long and thin version of their current form is not suitable for space applications. Hence, there is a need for a completely new robot design to produce hardware having dedicated long and thin rope-like features, with suitability for use in space applications.

Considering the advantage of the previous developments, research into continuum robots is actively expanding. New work in areas such as motion planning and contact modeling is extending our underlying body of understanding and widening the scope of the field. Researchers are partnering with various industries to explore continuum robot solutions to such diverse applications such as terrain-adapting continuum-limbed vehicles, ship-to-ship refueling, and exploration of extraterrestrial surfaces. It is anticipated that the next ten years will see an explosion of research, both basic and applied, in the area of continuum robots.

## REFERENCES

[1] Tonapi M.M, Godage, I.S, Walker, I.D, “Next generation rope-like robot for in-space inspection,” in Proceedings of IEEE Aerospace Conference, pp. 1-13,DOI: 10.1109/AERO.2014.6836183, Big Sky, Mont, USA, 2014.

[2] I. D. Walker, "Robot strings: long, thin continuum robots," in Proceedings of the IEEE Aerospace Conference, pp. 1-12, Big Sky, Mont, USA, 2013.

[3] Camarillo DB, Carlson CR, Salisbury JK. "Configuration Tracking for Continuum Manipulators with Coupled Tendon Drive." IEEE Transactions on Robotics. vol. 25, 2009.

[4] Y -J Kim, S. Cheng, S. Kim, and K. Iagnemma, "Design of a Tubular Snakelike Manipulator with Stiffening Capability by Layer Jamming", Proceedings IEEEIRSJ International Conference on Intelligent Robot Systems (IROS), Vilamoura, Portugal, pp. 4251-4256, 2012.

[5] L. Cowan, Analysis and Experiments for Tendril-Type Robots, M.S. Thesis, Clemson University, May 2008.