Extrinsically-Actuated Tendon-Driven Continuum Robots

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ABSTRACT

COMP0205 Mechatronics and Making Project Report outlining a extrinsically-actuated tendon-driven continuum robot simplified into a mechanical system that can be modeled mathematically. The report outlines the design process, mathematical and computer aided design models, and the final assembles prototype.

Keywords: Extrinsic Actuation, Mechanical System, Continuum Robots

1 INTRODUCTION

Continuum robots are a growing field with applications from their most common use of accessing otherwise unreachable places (such as inside narrow and curved spaces) to underwater, surgery and physiotherapy, and space applications as noted by Walker's analysis on continuum robot applications [5]. Modeling after biological structures, continuum robots imitate the key qualities of muscular hydrostats in vertebrates and invertebrates like tongues, trunks, and tentacles. Those qualities include resistance to change in volume during movement while supporting bend and stretch in the structure, thus any change in one dimension implies change in the other dimensions [2]. By manipulating the interactions between multiple dimensions, wide ranges of motion along numerous axes can be achieved by the proposed mechanism. In contrast with rigid redundant systems, continuum robots highlight the advantages of soft robotics in terms of increased flexibility and dexterity.

Common designs of continuum robots are categorized by their method and location of actuation, namely extrinsic and intrinsic actuation [3]. Extrinsically-actuated mechanisms are only driven from the base of the robot, allowing remote control and streamlined designs of the robot body itself [1]. Some examples include tendon-actuated and telescoping pre-curved tubes usually seen in concentric tube robots [7]. Those devices are commonly used in robotic surgery, specifically neurosurgeries, as decreasing the bulk of the device can allow it to travel through smaller incisions, minimizing the amount of physical trauma and recovery time experienced by the patient [6]. Intrinsically-actuated mechanisms are composed of actuators throughout the central vertebrae, where each actuator is driven by pneumatics, hydraulics, magnets, or smart materials' properties [4]. According to recent studies, shape memory alloys (SMAs) and electroactive polymers are materials whose properties provide additional features for the device: reducing the size of drive units and integrating actuators, sensors, and structure within one material [1].

This report outlines the kinematics and mechanics of a tendon-driven, externally-actuated continuum robot as a basic mechanic system. The mechanism consists of five interconnected "vertebrae" modules joined by four continuous non-elastic strings (tendons) and four pieces of elastic springs between modules. The continuum robot design allows for six degrees-of-freedom and the modular design gives the user full control of the amount of grip or length associated with the system. Since the design is externally-actuated, the overall number of degrees-of-freedom remains independent of the number of vertebrae, as the motion of the vertebrae are dependent on one another. The modular design, however, does allow for control of the angle precision that is increasing with the number of vertebrae. This report outlines a mathematical model relating robot specifications and measurements to vertebra motion and concludes with a mechanical analysis of the design of the continuum robot system.

2 MATHEMATICAL MODELING

Table 1 outlines the symbols used in Figure 1 and the rest of the report while Figure 1 shows a frame of the labelled mathematical model.

Symbol	Quantity
α	Exterior angle of each vertebra
θ	Angle forming the L_1 and L_2 arcs
r	Radius of the circle of the arcs
d	Diameter of each vertebra
n	Number of nodes
L_1	Length of the inner tendon (variable)
L_2	Length of the outer tendon (constant)

Table 1. Nomenclature.

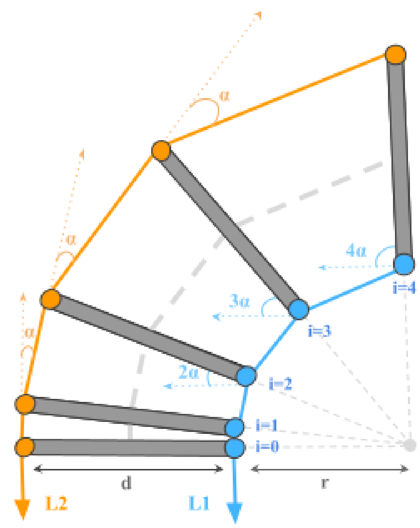

Figure 1. Labeled Diagram of the Continuum.

Figure 1 models a five-vertebra continuum system with an approximately right-angle bend. The model assumes the outer tendon is held at constant length while the inner tendon is shortened by a certain amount (ΔL_1). Thus, the length of L_1 is the independent variable of the mathematical model. By finding the relationship between the angles each vertebra forms with each other and the ground, and the change in L_1, we can create a relatively accurate model of each vertebra's behavior to demonstrate the motion of the entire system.

For the purposes of the model, we will assume the vertebra remains equidistant with each tendon being of equal length. However, this assumption and keeping the number of vertebrae constant presents a limitation to the mathematical model such that not all angles will require all vertebrae to shift or rotate equally. In the physical implementation, each vertebra is less inclined to change position and direction than the one that follows, meaning the fifth vertebra in this model will be the first to rotate followed by the fourth and the third and so on. Thus, a small curvature (the definition of small changing with respect to the stiffness of the springs surrounding the tendons) may be achieved without the first few vertebra having to rotate or change position. This model assumes the same change in all vertebrae with respect to the previous and can thus be considered as modeling the vertebrae (except the first) that have to change direction with respect to the horizontal axis (i.e. the first vertebra). However, the model still presents a relatively accurate representation of the change in the vertebrae participating in the curvature.

To start developing the model, we need to compute our constant values. For the purpose of this model, we will assume a five-vertebra system; thus, $n = 5$. Using the n value, we can find L_2 which is the total height of the continuum robot in its neutral state (when neither tendon is contracted). The mechanical design considers each tendon (surrounded by springs of accompanying length) to be 40 millimeters and the height of each vertebra is set at 3 millimeters. Thus, the total length of the system in its neutral state can be calculated as:

$$L_2 = n \cdot 3mm + (n-1) \cdot 40mm = 175mm$$

The last remaining constant is d, the diameter of each vertebra, which was set to be 4 millimeters in the design.

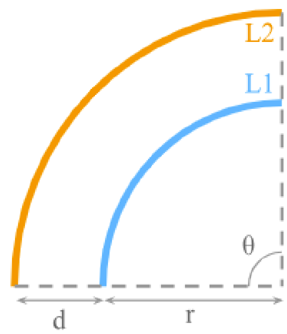

Figure 2. Tendons represented as arcs.

Using the constants and the independent variable, we can derive equations for the dependent variables that can then be used to determine the final mathematical model. The dependent variables that need to be considered are r, α and θ. To help with the derivation of these values, we can consider the inner and outer tendons (L_1 and L_2) to form two concentric arcs as depicted in Figure 2. Using similarity we know that:

$$\theta = \frac{L_1}{r} = \frac{L_2}{r+d}$$

Expanding out the right-hand-side and middle of the θ expression to isolate r in terms of L_1 and L_2 (known variables) yields:

$$L_1 \cdot (r+d) = L_2 \cdot r$$

$$r = \frac{L_1 \cdot d}{L_2 - L_1}$$

Plugging the expression for r found above into theta expression gives the following expression for θ, defining its relationship with L_1:

$$\theta = \frac{L_2 - L_1}{d}$$

Knowing θ, we can derive an expression for α (the exterior angle of each vertebra) which can then be used to model each end of the vertebrae. The sum of the exterior angles of an arc is equal to the central angle forming the arc, which in this model is θ. Thus, each exterior angle, α, will equal θ divided by the number of angles – which in this case equals n. Thus we can derive the following expression for α using new expression derived for θ:

$$\alpha = \frac{\theta}{n} = \frac{L_2 - L_1}{n \cdot d}$$

As shown in Figure 1, each vertebra is rotated by α, thus making the angle each makes with the horizontal axis (assuming the first vertebra, $i = 0$, is on the horizontal axis) increase by α, making it equal i. Since all vertebra are assumed to be equidistant, the difference between each will be $\frac{L_1}{n-1}$ and $\frac{L_2}{n-1}$ for the inner and outer ends of the vertebrae, respectively. Since the angle each vertebra makes with the horizontal axis ($\alpha \cdot i$) is known, we can define the Cartesian coordinates for each inner junction point recursively for $i > 0$ as follows:

$$(x_0, y_0) = (0, 0)$$

$$(x_i, y_i) = (x_{i-1} + \frac{L_1}{n-1} \cdot -\cos\alpha \cdot i, y_{i-1} + \frac{L_2}{n-1} \cdot \sin\alpha \cdot i)$$

After the Cartesian coordinates for the inner junction points are computed, the outer can be calculated as being separated by d in the same direction as the shift in the vertical axis and the exact opposite in the horizontal since the outer points are directed away from the center of the curvature, resulting in the following recursive expression for $i > 0$:

$$(x_0, y_0) = (0,0)$$

$$(x_i, y_i) = (x_{i-1} + d \cdot \cos\alpha \cdot i, y_{i-1} + d \cdot \sin\alpha \cdot i)$$

The previous two equations conclude the mathematical model which can then be plotted using MATLAB (or other) software to yield the following outcomes for a given L_1 value, in this case $L_1 = 130mm$ as shown in Figures 3 and 4.

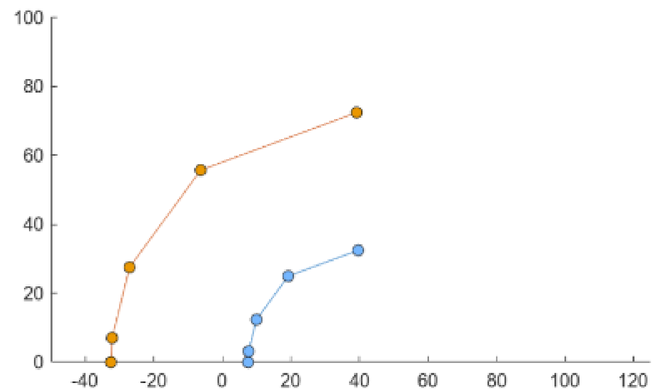

Figure 3. Model of Junctions.

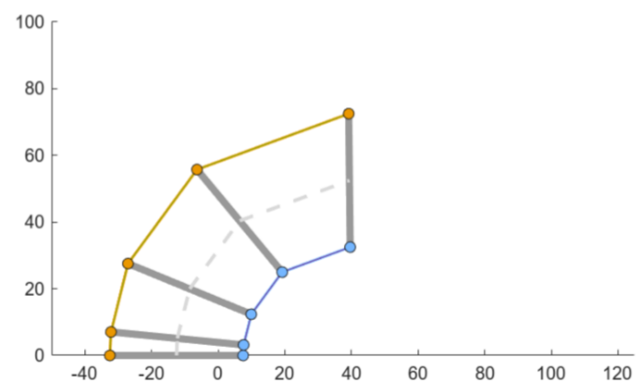

Figure 4. Model of Junctions with the Vertebrae and Tendons.

Ultimately, this model predicts the motion of the vertebra relatively accurately for a small range of angles that require the particular number of vertebrae determined, as explained earlier. This model, while two-dimensional, can be used to predict the behavior of the six degrees-of-freedoms associated with the continuum robot by applying the model for the two pairs of tendons in the design.

3 MECHANICAL ANALYSIS

The mechanism in Figure 5 contains six degrees-of-freedom as it is manipulated by four tendons. Since the vertebra cannot be controlled independently, the number of degrees-of-freedom remains independent of the number of vertebrae. Initially, by moving along the standard x, y, and z-axes in 3D space, the model is introduced to three degrees-of-freedom via translational motion. By keeping two or three tendons in a neutral position and manipulating the remaining free tendons, the structure bends to the side of the shortened tendons by different degrees as demonstrated in the mathematical model. This action creates rotation along the vertical x-y and y-z planes, thus the robot gains two more degrees-of-freedom.

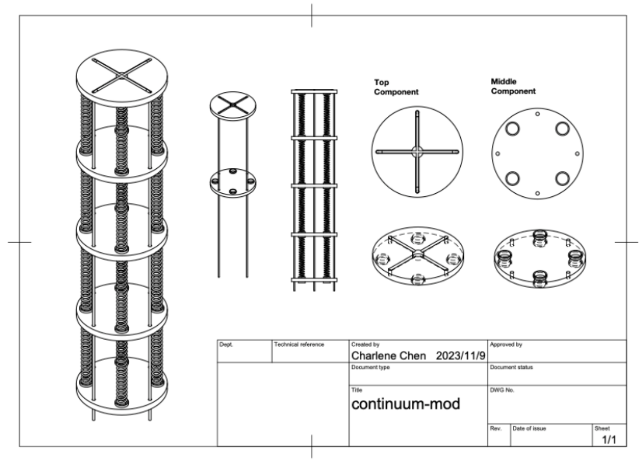

Figure 5. Six DoF Continuum Robot Assembly Drawing.

The remaining rotational motion, and thus the last degree-of-freedom, is achieved when the robot is manipulated in a non-neutral state, such as pulling a third tendon while two were already pulled. This series of string manipulation allows the continuum robot to rotate on the y-axis, parallel to the x-z plane, completing the sixth degree-of-freedom for this system. All in all, the system contains three translational and three rotational ranges of motion, resulting in a total of six degrees-of-freedom.

Figure 6. 3D Rendering of Tendon-Driven Continuum Model.

4 SYSTEM ASSEMBLY

Figures 7, 8 and 9 depict the assembled continuum robot from different angles. Due to supply limitations, different springs (length and stiffness) have been assembled between each vertebra, however the four separating each vertebra pair are the same kind of spring to ensure balance. Another difference from the design is that the robot was built with six vertebrae instead of the five initially planned, allowing for greater length and flexibility than initially designed.

Figure 7. Neutral position of assembled prototype.

Figure 8. Bent position of assembled prototype.

5 DISCUSSION AND CONCLUSION

As can be seen in the assembly images (Figures 7, 8 and 9) and the three dimensional design figures (Figures 5 and 6), the initial design of the system was fairly simple to manufacture and assemble, barring a few minor alterations noted in the system assembly section. Overall, the working prototype can be considered successful as it behaves as expected as well as abiding by the general principle of the design. Looking over the general design process, the final system can be seen to be aligned with most extrinsically-actuated continuum robotic systems currently in-use as well as being a simple modular prototype that can be modified and controlled relatively easily. The assembled prototype shows a good level of flexibility and can fully move in all six degrees of freedom associated with the system.

This model, while being very simple and easy to manufacture and model, does have room for improvement. To begin with, the springs could be chosen to all have equal length and stiffness or have decreasing stiffness when moving away from the base to stabilize the system. The assembled prototype showcases both as the two sets of springs closest to the base are the most stiff while the remaining three sets are less stiff and similar. Thus, it can be seen that the stiffer springs at the base allow for more stable motion while the less stiff springs ensure that the compression starts from the top, creating a curling-like motion. Another change that could be considered about the springs could be using springs with higher rotational stiffness to ensure the springs actually compress instead of bending since that would be easier to control if the system was moved to a motor-actuated version. Lastly, a separate mechanism to hold and/or control the tension of the strings could be a good addition as it can be difficult to control all four strings with one or even both hands without having a base for the assembly.

Overall, the system and prototype demonstrate an effective system to create elastic motion with significant mobility in six degrees of freedom that can be modularised to fit any particular use including creating more or decreasing flexibility and precision.

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Figure 9. Top view of assembled prototype.

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