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Modeling and Validation of New Continuum Robot Backbone Design With Variable Stiffness Inspired from Elephant Trunk

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Abstract. Attentions to the bio-inspired robots are increasing dramatically in last two decades. Flexible structure, excellent flexibility and possibility of working in constrained environment made continuum robots attractive in robotic community. The purpose of this paper is to introduce, describe and test a novel design of continuum robot backbone design with variable stiffness which using of coil springs. A kinematic model is introduced and explained which could be applied for to a wide range of construction with two pairs of cables per section design. Furthermore, based on the geometry and material property of compliant joint, the robot is verified for justification of the robot construction. Finally, prototype motion analysis tested and repeatability experiments are carried out.

1. Introduction

Continuum robots present a several potential benefits over conventional than rigid link robots in applications that involve reaching through complex trajectories in cluttered environments or where the robot must compliantly contact the environment along its length. Because of inherited flexibility, the shape of continuum robot could be impacted by both actuation and external loading [1]. Moreover, a continuum robot has redundant degrees of freedom, able to move flexibly and has a large work-space [2]. Mostly, continuum robots are increasingly exploited in minimally invasive surgery where is required robot arm with ability to work in confined space [3].

Traditional snake-like manipulators are fully articulated serial robot arms with multiple number of joints. Each joint is actuated by one or two integrated motors [3], depending on the joint type. Unlike rigid articulated robots, continuum robots have flexible structures and hyper-redundant degrees-of-freedom (DOF) that allow for smooth elongation, shortening and bending from force and displacement control [4]. According to the hardness of the joint, it divides into two types: rigid and flexible. Rigid joint is traditionally universal joint or spherical joint, while flexible joints are utilize rubber or helical compression springs [5]. For continuum robots to reach confined and complex trajectory multiple joints are required to achieve necessary bending angle [5,6,7,8,9,10]. However, flexible backbone increases the difficulty in kinematic modelling. The section of the continuum robot generally assumed

to bend with a constant curvature[11,12]. Also, the kinematics of multi-section continuum robot was presented with the Denavit-Hartenberg parameters [7] . The kinematics of concentric tube robot has also been presented based on a constant curvature . Moreover, variable curvature kinematics has been investigated. However, controlling the robot with variable kinematics curvature is still challenging issue.
In this paper, continuum robot construction design with variable helical compression spring is adopted justified and explained. Moreover, kinematics of the continuum robot would be analysed and presented. This project presents a continuum robot with shortening and elongation properties. Section 1 presents design structure and construction features of the robot. Section 3 presents geometric modelling of the robot and conclusion will discuss and presents future development of the proposed robot.

2. Backbone design

This paper presents a bio-inspired tendon actuated multi-section flexible robot. The structure is similar to traditional snake-like robots, serially connected hard part (discs) via compression springs and actuated by 1mm metal cable. Moreover, cables actuates by dc motors.
The main feature of proposed continuum robot is a backbone structure and used materials. Thus, 3 types of compression springs had been applied with variable hardness constant. Prototype has a 3 segments, nine spacer discs and three types of compression springs. These springs have a variable spring constants: 35.3N/mm, 13.2N/mm, 8.8N/mm , outer diameter-20 mm, length- 30mm.

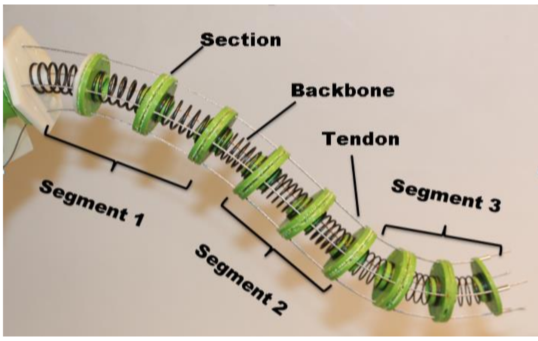

Figure 1. Experimental continuum robot prototype

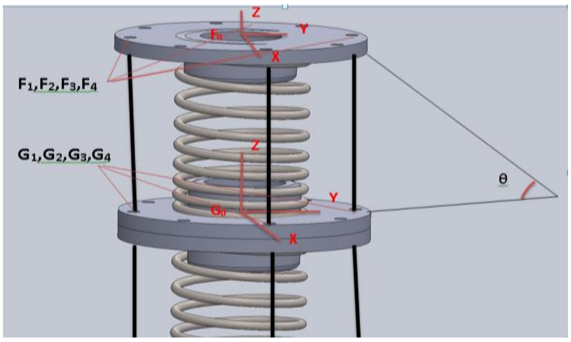

Figure 2. Nomenclature of continuum robot

The reason of using of variable spring constant is comes from a concern about static and natural formation. For this idea an optimal choice drawn came after several experiments in the laboratory. So, the main conclusion is the backbone hardness should be gradually decrease, from, bottom to the top section of the robot. Such kind of variation will increase stability and dexterity of the robot as well [figure4].

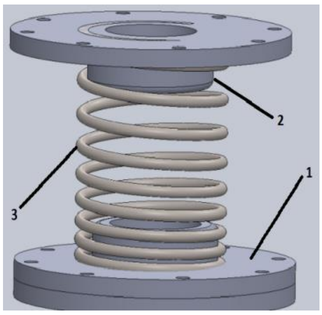

Figure 3. Single section of the robot:. 1-spacer disc, 2-constraint for spring, 3- helical compression spring

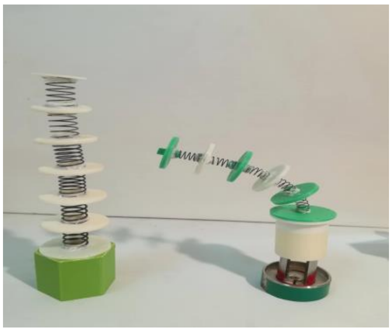

Figure 4. Comparison of continuum robot backbone hardness.

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Figure 3 illustrates the main difference of the backbone hardness, so in construction of the robot this fact had been taking into an account. Therefore, in prototype there are 3 sections[fig1], so in section-1 mounted the hardest spring WL20-30, in section-2 WF20-30, in section-3 softest spring WR20-30, these customized springs had been ordered from company MISUMI. The reason of using springs for backbone is elongation and shrinking feature. Which gives one more additional degree of freedom. However, using of flexible backbone will accuse buckling of the flexible backbone if the force along the backbone exceeds the bucking load [7]. Therefore, the better solution in such case is to design the backbone which can mechanically minimize the twisting angle.
There are some parameters which requires a justification, for example, number of discs in one segment, length of the section, gap distance, joint length and spacer disc diameter. Gap distance or joint length is mostly depending on output bending of the robot and numbers of the sections. Therefore, the length and the bending of the section should keep the following condition: Above condition could change in terms of final output continuum bending angle. Disc diameter, in this prototype is constant 50 mm, although [4,6] claims the diameter size of the disc should gradually increase from top to the base, same as spring constant, it is because of robot singularity and dynamics. In additional such kind of approach would make simple routing of tendon, because of different size of disc allow actuating separately. Compliant joint hardness is one the crucial part of the continuum robot, so in this prototype springs variable hardness constants applied. According to the conducted experiments, same backbone hardness could increase required motor torque for joint bending

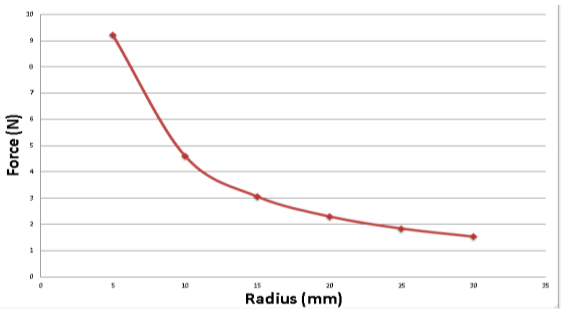

Figure 5. Force relation to the section radius

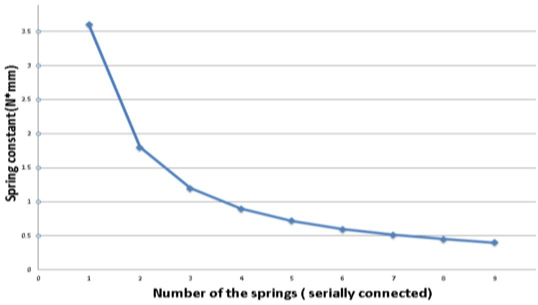

Figure 6. Relation of serially connected number of springs and hardness coefficiency

2.1 Geometric model of tendon driven Continuum Robot Manipulator

The Flexible backbone continuum Robot structure proposed in this paper consists of three modules. Each module contains three sections of individual helical compression springs connected with a 3d printed compliant joints. Each module is divided into three segments and consists of springs with different spring stiffness.

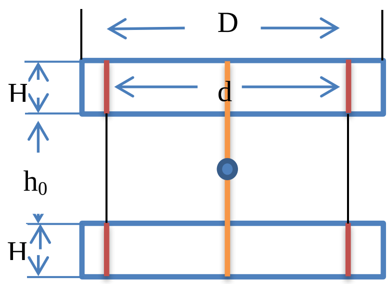

Figure 7. Section at initial state

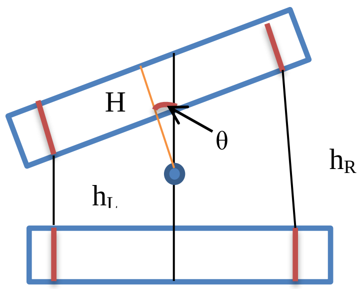

Figure 8. Section at bending state

When each join bends θ leftward, the gap distance and the wire length inside of the section eyelet remains the same. Based on simple geometry, it can be shown that the gap distance after bending is as follows[5].

$$\begin{cases} h_R = h_0 + \left[d \cdot \sin\left(\frac{\theta}{2}\right) - 2h_0 \cdot sin^2\left(\frac{\theta}{4}\right)\right] \\ h_L = h_0 - \left[d \cdot \sin\left(\frac{\theta}{2}\right) + 2h_0 \cdot sin^2\left(\frac{\theta}{4}\right)\right] \end{cases} \quad (1)$$

In summation, the total wire length after bending is shown as below

$$\begin{cases} L_R = L_0 + N\left[d \cdot \sin\left(\frac{\theta}{2}\right) - 2h_0 \cdot sin^2\left(\frac{\theta}{4}\right)\right] \\ L_L = L_0 - N\left[d \cdot \sin\left(\frac{\theta}{2}\right) + 2h_0 \cdot sin^2\left(\frac{\theta}{4}\right)\right] \end{cases} \quad (2)$$

Detailed information about kinematics of the model in [7].

3. Conclusion

In conclusion, design validation backbone with variable stiffness hardness had been tested and analyzed. According to the conducted experiments the following assumption had been confirmed: firstly, structure stiffness, robot became more rigid in control. Secondly, twisting problems were minimized backbone structure mechanically arrange the initial position and desired position of the robot. Variable stiffness backbone became efficient in control as well, for instance, to control cables were used to actuate tip of the robot, so bending was efficient with variable backbone stiffness rather than constant backbone stiffness. Because in case of actuation robot started to bend from the top part of the robot, while constant one started to bent from the middle part.

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