Design and experiments of a bio-inspired tensegrity spine robot for active space debris capturing

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Abstract — Aiming at active space debris capturing, this paper proposes a novel tensegrity spine robot, inspired by the structure and mechanism of vertebrates’ spine. It consists of a series of conical rigid elements, which are linked with springs and stabilized in a tension network. The continuous bending of the robot is achieved by the actuation of three sets of cables. A prototype is built and a closed-loop control method is proposed for proof-of-concept experiments, including bending motion control, capturing a non-cooperative target, and tests of load performance. The experimental results show that the proposed tensegrity spine robot has potential application prospects in space debris capturing.

1. Introduction
Active space debris removal is one of the major challenges in space missions. The difficulty lies in reliably and effectively capturing non-uncooperative targets with irregular shapes. Various capturing methods have been proposed, including net capturing, harpoon mechanism, and robotic arms, etc\textsuperscript{[1]}. The advantage of using robotic arms is a higher degree of controllability over the captured targets. However, traditional rigid robotic arms are heavy, and the rigidity can easily lead to rigid collisions and cause more secondary damages. To tackle these problems, many researchers proposed flexible soft robots, inspired by octopus tentacles, snakes, and elephant trunks\textsuperscript{[2]}. Recently, a proof of concept was presented\textsuperscript{[3]}, showing the feasibility to use tentacle robots for capturing non-cooperative space debris. Soft robots are also lightweight and robust, but their controllability may not be as good as rigid robots. Tensegrity robots, which are composed of compression elements and tension elements, offer a good alternative to either soft and rigid robots. Tensegrity robots, like soft robots, are lightweight and compliant\textsuperscript{[4]}. Due to the underlying tensegrity principle offering a high strength-to-weight ratio, tensegrity robots can exhibit good load performances. In addition, the tensegrity mechanism only involves rigid bodies and tensile strings, thus achieving good controllability. Tensegrity robots have found wide applications, such as locomotion robots\textsuperscript{[5]} and a fish robot\textsuperscript{[6]}. In this paper, we present the design and experiments of a bio-inspired tensegrity spine robot, which provides a new approach for the compliant active capturing of space debris.
2. Bio-inspired Robot Design

2.1 Inspirations from Animal Spines
Biological characteristics provide many useful inspirations, which help to design robots with good performances, such as compliance, robustness, and motion diversity[7]. One such example is the spines of vertebrate animals. As revealed by anatomy, the spine can be roughly divided into three types of units: vertebrae, connective tissues (ligaments), and muscles[8-10]. From Figure 1(a), we can see that the vertebrae are in no direct contact but connected by intervertebral discs in between. Together they constitute the backbone of the spine. Then, the movements of the spine are driven by muscles, especially those that cross multiple vertebrae, as shown in Figure 1(b).

These features of the animal spines can be conceptualized as the tensegrity principle. The vertebrae correspond to the compression elements, while the connective tissues correspond to the tension elements. Together they constitute a compression-tension network that ensures the integrity and stability of the spine structure.

2.2 Design of A Tensegrity Spine Robot
We employ the conceptualized tensegrity principle to design a tensegrity spine robot that mimics the mechanism of vertebrates’ spines. Specifically, conical rigid elements are used to mimic vertebrae, and springs are used as the tension element to mimic the connective tissues. Between every two conical elements, we use six springs to form a tensegrity joint, so that the conical elements are suspended in the tension network, and there is no contact between them. Each conical element can achieve relative rotation around tensegrity joints. Then, cables are used to mimic the muscles. A cable connects the base to an anchor point, running through multiple conical elements. Actuations can be performed by pulling the cables.

The overall structure of the spine robot is a serial mechanism composed of several conical elements, which are linked with prestressed springs. Although the conical elements are rigid, this mechanism can
achieve structural compliance due to the elastic properties of springs.

The conical element can be described in two parts, an annular platform and a set of three props, as shown in Figure 2(a). In the circumferential direction of the annular platform, three protruding parts are evenly distributed at 120°, and each protruding part has several cable holes. Spring slots are distributed on the converging position of the three props and the annular platform to hold the springs.

In a tensegrity joint, the lower conical element can be regarded as a stationary base, and the upper conical element can be regarded as a follower, as shown in Figure 2(b). The internal springs provide a repulsive tension network to support the follower suspended above the base. The external springs can provide an attractive tension network to hold the structure. This set of balance forces makes the follower and the base maintain a relatively stable connection. Tensegrity joints are connected in series to form the structure of the spine robot.

Motors are used to actuate cables, changing their lengths, which move the spine to bend θ angles in the bending plane ϕ. In order to reduce the number of driving motors and increase the motion stability of the robot, we designed the capstan as the traction device of the cable. A capstan connects the cables on the same side of the robot, and the grooves on the capstan make the tensegrity joints rotate at the same angle, as shown in Figure 2(c).

![Figure 2 CAD model of the tensegrity robot. (a): conical element. (b) tensegrity joint and its bending driven by three cables. (c) schematic diagram of capstan connecting cables. (d) tensegrity spine robot.](image)

The overall 3D model of the proposed bio-inspired tensegrity spine robot is shown in Figure 2(d), which includes three elements: tensegrity spine, three sets of actuation cables, and a robot base. Three DC motors are installed on the robot base and connected with capstans. The DC motor drive three groups of cables that distribute at 120° around the tensegrity robot. The movement of the motor can realize the continuous deformation of the tensegrity spine in a certain direction.

3. Prototype Hardware

3.1 A Prototype of The Tensegrity Spine Robot

In order to verify the performances of the proposed tensegrity spine robot, a prototype shown in Figure 3 was built according to the last subsection. The rigid parts of the robot, such as the conical elements and
capstans, are 3D printed with photosensitive resin. The springs are made of 304 stainless steel, and the cables are stainless steel wires. The length and diameter of the spine were 730mm and 72mm, respectively.

Figure 3 Robot prototype and some parts

3.2 Hardware of A Control System
Three stepping motors are used as driving devices of the robot. The inertial measurement module is an angle sensor, which is installed at the end of the tensegrity spine as a signal feedback device. Arduino MEGA as Microcontroller Unit (MCU) of the control system. The upper computer (PC) sends the signal of the target position to the MCU through the Universal Asynchronous Receiver/Transmitter(UART). MCU detects the signal of the angle sensor and sends Pulse Width Modulation(PWM) to the motor driver to control the rotation of the motor. The hardware connection of the control system is shown in Figure 4.

Figure 4 Control system schematic

4. Experiments and Results
When the spine is bent by the cables, it is also subject to axial forces. Thus, the spine will be compressed, and the lengths of the three cables change with the bending angle and compression. So, the traditional kinematics modeling is not accurate. However, we can derive the relation between the length of the cables and the bending angle, as follows:

\[
\begin{align*}
\theta &= f(K_{i,1}L_1, K_{i,2}L_2, K_{i,3}L_3) \\
\phi &= (i - 1) \frac{\pi}{3} \\
\end{align*}
\]

(1)

Where, \( \theta \) is the bending angle of the spine, \( L_N (N = 1, 2, 3) \) is the length of cable \( N \), \( \phi \) is the bending direction of the spine, \( K_i \) are the corresponding coefficient matrix:
According to this relationship, we use closed-loop control to realize the precise motion of the tensegrity spine. Specifically, we use a PID control algorithm, and the expression is given by:

\[
\begin{align*}
K_1 & = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \\
K_2 & = \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \\
K_3 & = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \\
K_4 & = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\
K_5 & = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\
K_6 & = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}
\end{align*}
\] (2)

The system control block diagram is shown in Figure 5. In the control system, according to Equation (1) and (2), the upper computer sends the command of the robot's target bending angle \( \tilde{\theta} \) and bending direction angle \( \phi \) to the controller. The controller obtains the robot's bending angle \( \theta \) in real-time through the inertial measurement module, compares the difference between the target bending angle and the current bending angle, inputs the angle parameters into the PID control Equation (3), and converts the obtained data into the corresponding PWM pulse wave frequency to control the corresponding stepper motor speed.

4.1 Bending by PID Control

The tensegrity spine robot prototype is mounted on an aluminum-made frame, with the end of the spine pointing downward. We test the bending motion of the robot prototype in different directions. Figure 6 shows a series of video captures of the prototype’s continuous deformation toward the left direction (\( \phi = 0^\circ \)), with bending angle from \( 0^\circ \) to \( 90^\circ \). In this case, if the DC motor contracts cable 1, the tensegrity spine will bend to the left. Similarly, Figure 6 shows the tensegrity spine being bent to the right direction (\( \phi = 180^\circ \)) under the contraction of cable 2 and 3, with the bending angle from \( 0^\circ \) to \( 150^\circ \). We can also obtain similar results if we control the tensegrity spine to bend to other directions or angles. Meanwhile, we use the 3D optical motion capture device to measure and record the movement of the robot in real-time.
measured by the angle sensor, and the blue line indicates the value measured by the 3D capture device. There are errors (<5%) between the two groups of measured values, which are caused by the insufficient installation accuracy of the sensor and the insufficient assembly accuracy of the robot prototype. In this test, in order to verify the accuracy of the motion without considering the rapidity, we set the upper limit of the motor speed, so the time for the robot prototype to reach the designated position is longer (case 1: t > 25s, case 2: t > 45s). Meanwhile, we set a lower limit to avoid overshooting, which also explains why the bending speed change is not obvious. The robot prototype vibrates near the designated position because of the step angle of the stepper motor and the elasticity of the robot itself. This test shows that through the closed-loop control, the robot prototype can reach and maintain the designated position and that it can realize continuous deformation.

![Figure 7 Recorded results of tensegrity spine robot prototype in different directions and angles.](image)

### 4.2 Capturing a Non-cooperative Target

The capturing test is carried out to verify the task of entanglement capture of non-cooperative targets in space. To this end, we made a satellite model, which is a regular hexagonal prism with a height of 40cm and with a circumscribed circle diameter of 30cm. The satellite model is placed in the direction of the robot prototype to be bent and is in the state of natural suspension. Figure 8 shows the process of the robot prototype successfully capturing the target: the robot prototype bends towards the target, contacts with the target, the contact area gradually increases, and the robot prototype begins to gradually surround the target to complete the capturing.

We repeated the experiment 20 times, and the probability of capturing the target is 45%. The experiment results show that when the initial contact point is closer to the root of the tensegrity spine, the bending angle is larger and the probability of success is greater. Therefore, it is very important to locate, predict, approach, synchronize and adjust the position and pose of the tensegrity spine relative to the target.

![Figure 8 Capturing a non-cooperative target through the entanglement of the tensegrity spine.](image)

### 4.3 Load Performance

The load performance is an important factor for the capturing capability of the tensegrity spine. We test the load performance by hanging weights, as shown in Figure 9.
The test results show that the robot prototype has a high load performance. Additionally, when the load is large, the bending curvature of the root of the tensegrity spine is smaller than that of the end, because the weight has a larger bending moment on the root. Therefore, it is necessary to develop variable stiffness control of the tensegrity spine robot.

5. Conclusions
In this paper, inspired by the structure and mechanism of vertebrates’ spine, a tensegrity spine robot is proposed as a new approach for active space debris capturing. The feasibility and effectiveness of the proposed robot are verified by the proof-of-concept experiments. The conclusions are as follows:

1. The tensegrity spine combines the conical rigid element, elastic spring, and actuation cables to mimic soft spine structure. The proposed robot has the advantages of lightweight, compliance, and a high strength-to-weight ratio, which suggest good environmental adaptability and manipulation controllability.

2. We designed and built a tensegrity spine robot prototype and a control system. A closed-loop control method is used to adjust the length of the cables. Through this method, the robot prototype can achieve accurate, continuous, and large deformation bending motion.

3. We also carried out tests of the robot prototype on entanglement capture of non-cooperative targets and load performance, which shows that the robot prototype has high environmental adaptability and manipulation controllability, and has the potential to capture space debris.

Regarding further researches, optimization of spring parameters is required to achieve the axial extension and variable stiffness control of the tensegrity spine. Also, the precise mathematical model of the tensegrity spine should be established to study the control algorithm with high robustness.

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