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Scalability and Design of Six Rod Tensegrity Soft Robotic Structure

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Abstract

Robots based on tensegrity structures (interconnected rods and cables) offer many advantages such as low weight, small volume when packed, and have high impact resistance. Unfortunately tensegrity robots can be difficult to make and scale due a fundamental design trade-off: they need to have enough tension in the structure to maintain its integrity, while not having so much tension that it is difficult to actuate, change shape and move. This paper addresses this issue with three approaches: 1) Traction based pulley actuation that is less sensitive to the tensioning of the structure, 2) A mix of elastic and inelastic cables allowing for a better balance between tensioning and actuation and 3) Using flexible rods allowing for actuation with inelastic cables. We test configurations and show that these approaches can indeed increase the scalability and usefulness of tensegrity robots.

1 Introduction

Historically, tensegrity structures have been static structures focused in areas such as aesthetics and art, or children's toys due to features such as interesting composition, lightweight construction, and robustness [1]. However, recently there has been a shift for robotic tensegrities that can take advantage of the inherent advantages of tensegrities (flexibility, robustness, size-weight ratio) in order to utilize them for various purposes such as planetary exploration missions, exo-suits and soft UAVs [2–6]. However, one key challenges involved with tensegrity robots is scalability. While tensegrity structures scale well in terms of weight, large tensegrity robots can have difficulty with having a proper level of tension and robust actuation. This paper focuses the three ways to address these issues:

- A mix of different elastic coefficients within the same tensegrity.
- Bendable rods.
- New traction pulley configuration offering improved traction.

For testing various combinations of all these three changes are combined together in rapidly prototyped models of the structure of various sizes ranging from 12 inch (30.5 cm) rods to 36 inch (91.5 cm) rods. The criteria for success is based on the robustness of the structure. Using a preconfigured locomotion pattern, each structure is run for several minutes and its performance is assessed on its ability to roll without interruption, and whether or not it needs additional aid such as constant recalibration.

2 Background

Tensegrity structures are structures composed of elements of pure compression and pure tension. Typically for the compression element, rigid rods are used and for the tension element an elastic cable or spring is used. These structures are versatile and are able to be created using anywhere from three or more rods to create structures of different shapes and sizes. The research relevant to this paper comes from the idea to use tensegrities as dynamic robotic structures and to actuate them to enable them to perform various tasks. Some of these tasks include tensegrity exoskeletons that humans could wear to aid in rehabilitation, tensegrity spines which could create flexible spine robotics, and ball shaped tensegrity robots (i.e. Super Ball Bot). The reason tensegrities are being selected for this variety of tasks is due to the numerous advantages that they inherit from their materials and composition. Such advantages include low launch volume, high compressibility, robustness, high configurability, high flexibility, ease of deployment and a carrying capacity that increases by a cubic factor to its weight. Over the previous years, a team at NASA has worked on optimizing tensegrity structures by means of rapid prototyping and experimentation. Improvements have been made in design such as the decision to use pulley actuators instead of linear, as well the discovery of various locomotion patterns.

3 Methodology

This project aims to increase the scalability of tensegrity robotics. This is done through three means:

- Modified structural tension components
- Modified structural compression components
- Modified servo configuration

Our method of the evaluation of success for each tensegrity configuration is based mainly on successful locomotion and how actuatable the structure is. Each of these variables is rated based on the goal being met and how robustly the robot performs. For locomotion, the goal is for the robot to move using a preconfigured pattern. For robustness, the goal is to increase reliability and to minimize the need for adjustements between operation. For actuatability, what is taken into account is how much the structure could change shape during actuation and how much force the actuation can produce before slippage. In addition, the same small servos are used on all structures to show that efficient scaling can be performed without the need for heavier, more powerful components. All of our experimentation is performed on a six-rod tensegrity ball structure (three sets of parallel rods). The face of these structures are composed of a set of open faced triangles and closed faced triangles. Motors are always placed on the acute angle on an open face triangles with one motor per rod and all motors having in parallel and opposite pairs.

4 Heterogeneous Tension Elements

Traditional tensegrity structures have the same tension elements throughout the structure. A tensegrity with high tension is more rigid, but harder to actuate and change shape. A tensegrity with low tension is easy to actuate, but easily collapses

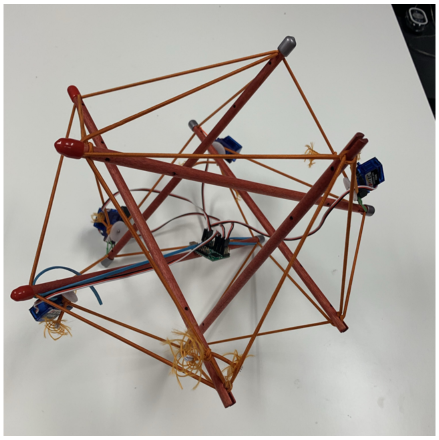

Figure 1: Closed triangle geometry.

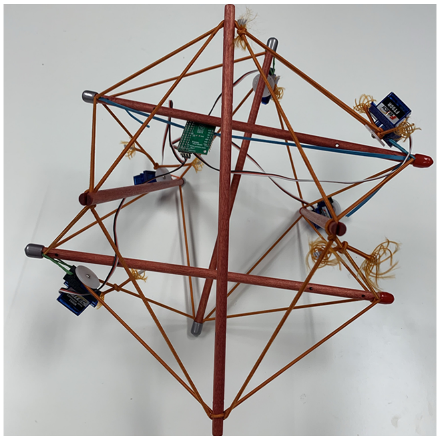

Figure 2: Open triangle geometry.

and has difficulty carrying a payload. Ideally we would like a tensegrity that is both rigid and easy to actuate. To achieve this goal, we carefully modify tensegrity structure to have high-tension elements in part of the structure, and lower-tension elements in other parts of the structure. Placement of these elements is done in such a way that motors tend to pull against lower tension elements allowing more actuation, while other cables are tensioned higher to provide rigidity. Specifically this is achieved by placing more elastic cables on any node ends without a servo actuator, and less elastic cables on the actuated ends (see Figure 3). This allows the structure to maintain a high enough level of tension that it is rigid and robust while not compromising on weight by having to use heavier motors to increase torque or change motor gearing which would compromise on speed.

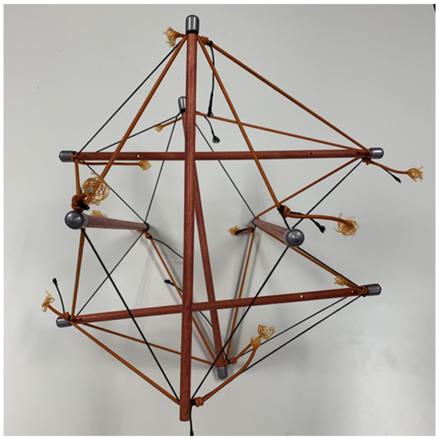

Figure 3: Dynamic tension network structure. Black cables have higher spring rate and less elasticity than orange cables. The motors are placed on the node with the black cable on it.

5 Bendable Rods

Traditonal tensegrity structures are built from rigid materials such as steel, aluminum, and wood. In contrast, we can also use bendable materials such as carbon fiber rods. This change of materials also changes the source of elasticity. While traditional tensegrity structures either have elastic cables or elastic springs inline with the cables, when bendable rods are used, the cables need not be elastic. Another change is that the way the tensegrity structure changes shape is much different, especially the relationship between the ends of the rods and the cables. In a traditional tensegrity structure, the ends of the rods are well outside of the convex hull formed by the cables, and there is little chance of the cables being snagged by the end of a rod. However when rods are bendable, the ends can easily be caught in the cables, especially if tension is too high. In order to mitigate this issue, endcaps are carefully constructed so that one side of the endcap is flush to the rod, allowing the cables to slip off when there is an overlap as shown in Figure 5.

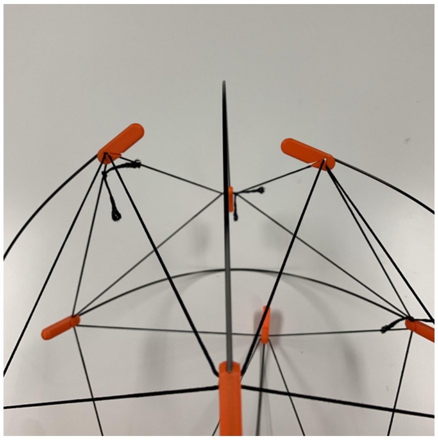

Figure 4: Overtensioned structure. Note how the rod bends higher than the orange end caps.

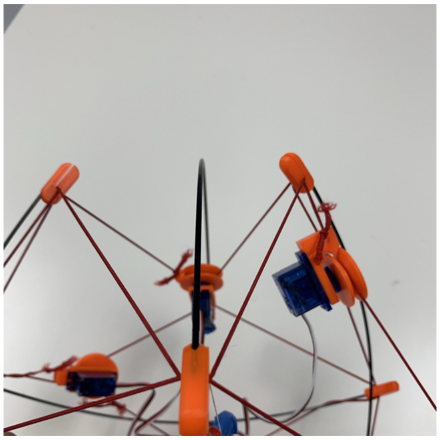

Figure 5: Properly tensioned structure. Rod is about level with the orange end caps on either side of it.

However, despite this improvement, rods still can occasionally get stuck. We further mitigated this issue by wrapping the rod around the cable opposite to the direction of the motor spin to bias it one way 6.

Due to the issues with using highly flexible rods, we also test a tensegrity structure built with less flexible fiberglass rods with heterogeneous tension levels as described above (see Figure 7). This allows for a tensegrity robot with more traditional structural and actuation properties.

6 Traction Motors

Traditional tensegrity robots use motors that are directly attached to tension elements, typically using a spool. Such mechanisms are simple and easy to control. However one downside of this system is that the motor has to burden the full force

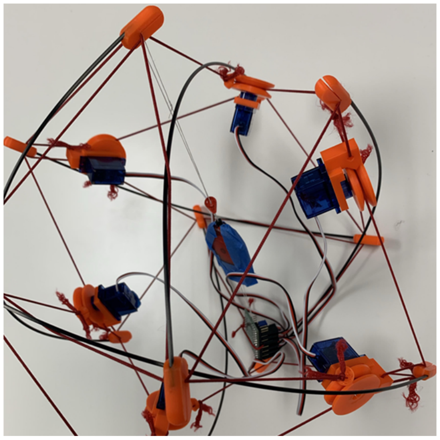

Figure 6: Rod biasing as shown by the cable being wrapped around the rod towards the bottom.

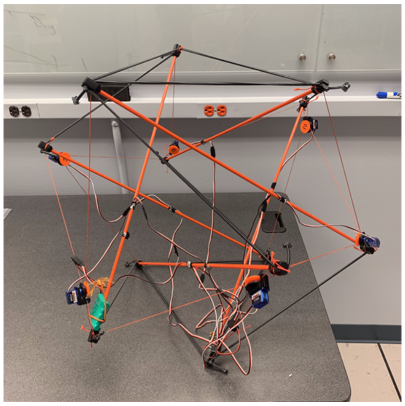

Figure 7: Fiberglass rod tensegrity structure.

of the tension element even if no shape changing is required. This creates complexity in maintaining structural integrity when the robot is turned off and also can use significant more energy as force often has to be applied just to maintain the tensegrity's current shape. An additional downside is that significant shock forces can be placed on the motors in the event of the robot hitting somethings such as in the case of a fall.

As an alternative, we propose using traction motors instead of spooling cables. In this paradigm cables are run through a traction pulley that can exert force on the cable, but is not rigidly attached to the cable. This mechanism allows the cable to slip in case of shock. In addition, the tension forces are no longer in line with the motor. This allows for more efficient operation and structural integrity when the motors are turned off.

Traction motors are convenient for tensegrity robotics as there is inherent tension in the cables that force the cable to bind to the traction pulley. However, note that care still needs to be taken to design the traction pulley properly so that it can exert force at various levels of tension. In our fist attempt we used a 3D printed part for the bottom half of the pulley combined with the servo head that came with the servo (see Figure 8).

The main issue with this configuration is that with scaling, as the servo traction is not enough to allow for larger tensegrity robots. To correct this, we made new designs with the purpose of increasing traction. Multiple configurations were 3D printed that made use of idler pulleys and various head sizes. The one that we settled on was a simple pulley head, except it was modified so that it was two pieces with the cable fitting in between (see Figure 9). By this method, the cable is held in between the top and bottom and "pinched" into a small gap by the tension providing additional traction. In addition traction can be increased by adding grooves on the bottom piece. To improve the configuration further, the gap between the servo mount and the pulley is closed so that the cables do not slip out.

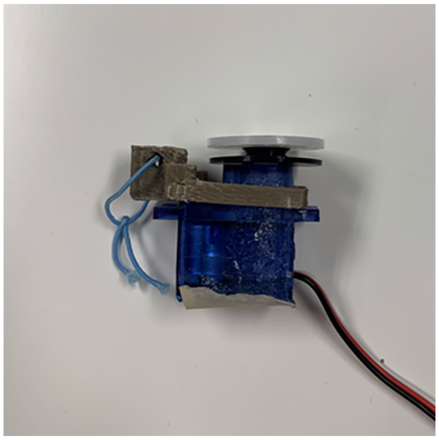

Figure 8: Old servo configuration showing 3D printed servo mount and plastic head that was provided with servo.

Multiple iterations were stress tested by pulling on the cable attaching the servo to the rod as well as the cable that was wrapped around the servo head pulley. Another adjustment made to the servo configuration was using digital servos instead of analog servos. The more traditional analog servos had the issue of not being accurate with their position leading to them overshooting often during actuation. In order to stabilize those structures, a stop was necessary on the cable in order to prevent the servo from going too far. In contrast, the digital servos are far more accurate and after fine tuning the code a back stop was no longer needed.

7 Results

Variations using either one or more of the above new configurations were tested. The test criteria was based on successful actuation and robustness of design. Successful actuation was determined by the ability of the structure to go through a six step preconfigured locomotion pattern three times successfully without getting stuck. In addition, robustness of design was determined by drop tests as well as determining whether the structure had the possibility of getting stuck, needed additional aid to reach neutral configuration. The structures were first tested in a 12” (30.5 cm) rod model and then scaled up to larger models including a 24” (61 cm) and 36” (91.5 cm) model.

The first configuration tested was with flexible carbon fiber rods and a non-elastic cable. This structure proved difficult to construct and required both a motor backstop and biased rods by wrapping them around the cable. However, the carbon fiber rods did enhance numerous properties of the structure. First, the overall weight was reduced due to the carbon fiber rods being thinner and lighter than previously used components. Additionally, due to the rods bending outwards, the carry capacity of the structure increased significantly. However, the main issue proved to be the robustness of this design. Although the flexibility of the rods added further robustness in drop tests due to an additional flexible component, it reduced

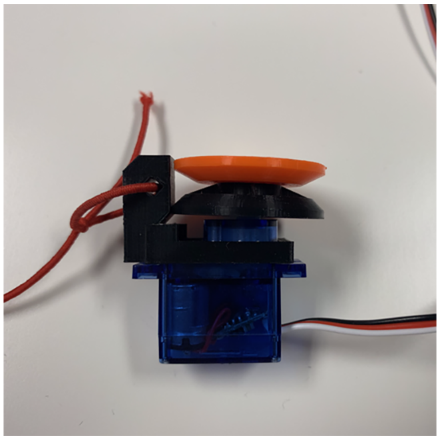

Figure 9: New servo configuration utilizing two piece servo head with updated mount to prevent cable slippage.

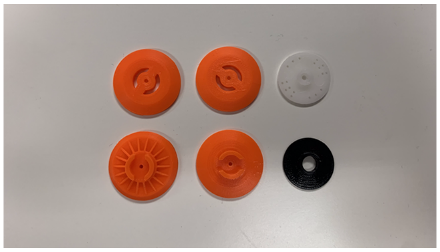

Figure 10: Evolution of servo head starting from right and ending on the left. Notice the change in how the two pieces connected as well as the larger head and addition of fins for increased traction.

robustness in terms of actuation. Often times, the structure would have issues with rods getting stuck and although the rod biasing fixed this issue, occasionally it would still miss a step. This structure was able to be successfully scaled up to a 16” (40.5 cm) model but unfortunately we were unable to scale it further. This is due to the size of the carbon fiber rods that were available to us that retained the properties we wanted.

The next interesting configuration was the fiberglass rods with the dynamic spring rate structure. This design was built in a 24” configuration. The main advantage of this structure is the fiberglass rods are more rigid than the carbon fiber and more flexible than steel or wood. This gives us the advantages of having slightly flexible rods, adding additional robustness, but allows the overall construction to be simple due to the fact that the rods still behave as if they are rigid unless put under significant tension. Additionally, this structure utilizes a tension network with heterogeneous elasticities. On each loop with a motor on it, the member with the motor is thinner, less elastic, and more rigid while the member without a motor is thicker and more elastic. This allows the structure to retain the advantages of flexibility that come with a lower tension and more elastic model while also having the advantages in actuation of the higher tension model. This structure survived the drop test and was so robust it required no back stops. The motors were able to move completely from end to end without stalling or slipping at all and were efficient. Additionally, this model was also extremely lightweight compared to previous designs. Although this did not carry over all of the benefits of the carbon fiber rods such as the increased volume capacity, the other advantages far outweigh the losses and it was determined that this structural configuration was most effective.

In addition to testing different structure configurations, we also tested traction pulley designs on a standard structure using two sizes. The first structure was a

12” model and the second structure was a 36” model. The servo was able to fully actuate both structures going from end to end without stalling or slipping. Also after all the adjustments were made to both the servo head as well as the mount, it was robust enough that it did not crack or break despite drop tests or high tension on the servo head. It was observed however that in order to function properly, the servos must be tightened adequately or else they would pinch the cable too much thus preventing it from operating smoothly. Additionally, it was important that the servo mount and head be complementary to each other to prevent large spaces in between them so that if the cables tries to come off it is unable to. Other servo configurations proved more successful than the head provided with the servo but compromised in other aspects. Most of them were far larger than the pulley that was decided upon, and the ones with idler pulleys had the common issue of the pulley breaking. Thus we determined that the most advantageous model was the simple design with the larger pulley with additional fins and that proved sufficient in the amount of traction it added.

8 Conclusion

In this project we significantly increase the scalability and ease of construction of tensegrity robots through three design changes. The most significant of these is replacing spool based motor connections with traction pulleys to actuate the tensegrity robot. This allows for a more robust design where the motors do not face significant shock on impact, and the structure maintains form when the robot is turned off. In addition, the motors do not have to pull against the full force of the tension network and instead use most of their force to change shape. The second design change is the use of a heterogeneous tension network where some of the cables have high elasticity while others do not. This configuration allows for a good balance between the structural integrity of a highly tensioned tensegrity structure and the ease of actuation of a minimally tensioned tensegrity structure. The final design change we test is the use of flexible rods. This change has mixed results as the use of flexible rods allows for a tensegrity structure that is very robust to impact and has significantly increased interior volume, but at the cost of more difficult configuration and a likelihood of cables being snagged with the rod ends.

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