Senior Design Final Report

Senior Design Group 4

The Tumbleweed

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1 Internet Search

Internet research was the first step when we were still searching for a design idea. We focused on researching topics related to the preliminary descriptions of tensegrity systems, current engineers working on related projects, such as professors and NASA employees, their ongoing research and robots already built with their respective material selection, forms of actuation, and information on what types of motion algorithms.

Tensegrity is a term formalized by Buckminster Fuller that refers to tensional gravity and is a structural principle based on the use of isolated components in compression inside a net of continuous tension. The compressed members do not touch each other and are called struts, the prestressed members delineate the system spatially and are usually referred to as cables. Most of the common tensegrity applications so far are related to art sculptures, civil engineering structures such as bridges, and supports and biology models of DNA and musculoskeletal systems [1].

For the purposes of our project we are concerned with tensegrity and robotic applications in order to create an actuated tensegrity spheres of six struts capable of moving and avoiding obstacles. We found that the NASA Super Ball Bot is an actuated tensegrity robot that has been under research since 2013 with an initial Titan mission plan [2]. Moreover, research on the current Berkeley Emergent Space Tensegrity (B.E.S.T) Laboratory revealed alternative designs that use an outside mesh of stretched rubber-like material in addition to the cables that connect the struts. Some of their research shows progress in steep angle climbing motions and a most recent Laika quadruplet robot with a tensegrity trunk. [3]. Lastly, the Creative Machines Lab at Columbia University also worked on tensegrity robots. Professor Hod Lipson was analyzing the possibility of achieving motion in multiple degrees of freedom by using one actuator,
due to the mechanically redundant design. [4] Further investigation of all those projects, led us to research about what design and material compositions were the most important for building the robot, what types of motors were used, and efficient motion algorithm with capabilities that would allow for the robot to move efficiently.

2 Journal Search

Our journal search began by using various Columbia University Library web pages such as Engineering Village, ScienceDirect and the Google Scholar portal. Using these resources, we continued researching the NASA Space Ball and similar actuated tensegrity systems. In addition, we further researched the topics on our Internet search, looking for more specific case studies and experiments. There is not much information on the material selection for these types of structures, but some internet articles argued about the use of metals such as titanium and aluminum - high hardness to weight ratio - for the struts as well as tension cable materials such as Kevlar, Nylon or Polyvinylidene - high elasticity and strength properties. An article from the International Journal of Solid Structures analyzes the optimal mass to stiffness ratio for this type of structure and proposes actions to regulate the amount of stiffness on prestressed cables depending on the stiffness matrix, number of members, and classification of the tensegrity structure. [5]

In terms of actuation, either rotary or linear actuators can be implemented to introduce mobility, although there is a stronger preference for linear actuators as many robots so far use pulling mechanisms on the cables, shifting the center of gravity of the robot and causing it to move. The location of the actuators and the pulling algorithms are different for each robot. We found a helpful journal that discussed how to actuate and control the rolling of tenseg-
rity robots, specifically a six strut system similar to our design. They found that using multiagent learning methods, their robot performed better and in a more robust manner. In addition, they specifically discuss actuation through a spool and cable mechanism, in which the spool reels the cable, reducing its length, therefore inducing motion, as well as a twisting mechanism, in which an aggregate of cables is twisted in order to achieve the same goal as the spool and cable implementation [6].

Another parameter that we considered important relating to tensegrity robot applications is the motion planning algorithm that is used to control the direction of motion for the robot. An article published through the University of California in San Diego goes over calculations and simplifications to standardize a path planning program that satisfies tensegrity conditions. The conclusions reached were that for a modular tensegrity structure the rules can be parameterized in terms of few geometric and force parameters, which simplifies the execution of tensegrity motion [7]. A different mobility option being used for these types of robots are wheels. Wheels are used for tensegrity robots that climb ducts. This method would allow our robot to travel efficiently and quickly. However, wheels add weight to the struts and could possibly break during a drop test. This journal also discussed the use of flexinol wire to actuate their wheels. Flexinol does not allow for as much less actuation but far less weight than other types of actuators. A wheel method would be an useful idea to implement [8].

Much of the research done was to examine different tensegrity structures and how to actuate the structures. Building a system that can withstand the high tension and compression that is present in these systems is crucial to the realization of a tensegrity robot. Moreover, a precise motion planning algorithm and control system is required to guarantee functionality and success. Our project aims to find a balance in cost-effectiveness for these parameters, such that we
can develop a working prototype of a tensegrity six strut sphere. Pros and cons exist for each type of actuation such as weight and efficiency in actuation.

3 Patent Search

We started our patent search with Buckminster Fuller’s tensegrity art structures. Fuller is a leader in these compression tension systems. His patent, US3866366A, is similar to the design we intend to use for the body of our tensegrity robot. We intent to employ a six strut tensegrity system using Fuller’s idea of rods in compression and a plurality of tension elements. This search led us to find other patents for similar structures, categorized as three-dimensional framework structures.

Patent US3169611A described similar tensegrity structures and their application for decreased weight to load ratios. A discussion of a novel type of joint to attach to the ends of the rods in compression in order to allow attachment or adjustment of a tension network was reviewed. This type of joint could be beneficial in actuating the structure, and enabling movement of our robot. Patent ES2367381B1 which builds on the previously mentioned patent, defines the term for a generic tensegrity robot that can change its form when actuated by controlled motors. Most recently, patent WO2018161089A1 described an elastic lattice for tensegrity robots and structures. We found this patent interesting because the elastic properties keep constant tension on the struts. The application date is recorded as 2018-09-07 and it has not been granted yet.

Nevertheless, a specific patent for a similar design to the one we plan on pursuing was issued by NASA. Patent ARC-E-DAA-TN15339 describes the system NASA is working on to actuate their space tensegrity robot for use on the moon of Titan. They implement "end caps" that contain all of the mechanical and electrical components needed to actuate their robot including pressure and ac-
CELEROMETER data. They are using this method to enable a modular approach to building their robots. It also makes the wiring of their robots to be easily accessible and allow for efficient wiring. Inside the end caps are the cables and a spring, a power system, shaft collar, an actuator and rod end. This system also allows for the power supply to be located close to the actuating mechanisms, DC motors in this case. Discussion of their cable material is also discussed. They used Vectran cable which is a useful material to use in space exploration due to the ability to withstand UV light and a lower creep [9].

Lastly, a motion control system using wireless communication was reviewed. A state feedback algorithm is implemented to overcome deficiencies that exist in spherical robot motion. Patent CN103135549A will be a useful resource for when we try and implement motion in our robot.

3.1 Patent Summary Table

<table>
<thead>
<tr>
<th>Patent Number</th>
<th>Patent Description</th>
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<tbody>
<tr>
<td>US3866366A</td>
<td>Structural design for tensegrity system [10]</td>
</tr>
<tr>
<td>ES2367381B1</td>
<td>Tensegrity Robot [12]</td>
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<tr>
<td>WO2018161089A1</td>
<td>Elastic lattices for design of tensegrity structures and robots [13]</td>
</tr>
<tr>
<td>ARC-E-DAA-TN15339</td>
<td>Design of Tensegrity Robot Hardware for SUPERball [14]</td>
</tr>
<tr>
<td>CN103135549A</td>
<td>Motion control system and motion control method for spherical robot with visual feedback [15]</td>
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Table 1: Summary of Patents

Some of the next steps on which we hope to focus include tackling the technically challenging process of determining how best to analyze location and execute motion. Given that we are attempting to roll the tensegrity robot towards a goal through actuation, it will be critical to determine which actuator to pull on to produce the desired shift in center of gravity. This can only be done
with math, coding, and some sort of sensor that determines current orientation
in space. Ideally, pressure sensors will give an idea of one of a few possible
orientations which will be hard coded into an algorithm to actuate an actuator
and, in doing so, produce the desired motion.

One of our highest possible levels of success involves using the elastic nature
of tensegrity and the actuators to produce a jumping effect. This will be code
intensive and may not come to fruition but we feel this functionality would
greatly add to the mobility of the tensegrity robot and could be a huge asset to
its users. In the coming weeks, we plan on making material choices (balancing
weight and strength as mentioned above) and then purchasing the required
materials to begin a basic skeletal assembly without actuation or sensors. Once
we have the framework up, we can begin the process of actuation. In fact, this
can be worked on in parallel while we determine material needs through testing.
4 References

3. https://best.berkeley.edu/best-research/
8. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5954060/