Title

APPLICATION OF TENSEGRITY STRUCTURES IN MEDICAL ROBOTICS FOR INTRACRANIAL SURGERY

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APPLICATION OF TENSEGRITY STRUCTURES IN MEDICAL ROBOTICS FOR INTRACRANIAL SURGERY

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A capstone project submitted for Graduation with University Honors

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University Honors
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ABSTRACT

In neurosurgery, medical machines need to have a high degree of precision and accuracy in order to effectively perform their tasks without risking harm to patients. For one particular surgery involving drilling into the cranium, a mounting and guidance system is used to ensure that tools are operating within the desired area and approach angle. However, these guiding systems need to be customized for individual patients and can be inefficient to produce. A potential solution to this involves utilizing the properties of tensegrity structures, which consist of various bars in constant compression and wires in constant tension, and incorporating it as a part of a guidance system. By utilizing the equilibrium shape changing properties of tensegrity structures, a two stage triangular tensegrity structure was devised as a skull mounted guidance system capable of supporting and directing surgical tools. This structure was virtually and mathematically modeled, physically prototyped, and tested. The virtual modeling visually confirmed the wide range of tilt and rotation angles made possible by the structure given alignment constraints when using simplified ball joints and bars. The mathematical modeling computed various string input lengths that could be used to generate a structure configuration with the desired tool tilt and rotation angles relative to the base of the structure. The physical prototype confirmed the motion capabilities of the structure but displayed that certain states were infeasible through the standard tension string setup alone. Through this proof of concept design verification process it was determined that this structure would have to be modified to be suitable for intracranial surgery applications and other areas, with various feasible modifications recommended for the structure.

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INTRODUCTION

In high stake fields such as neurosurgery, having the right tools can make the difference in performing a successful operation. When dealing with highly sensitive areas such as the brain, tools need to be incredibly precise and well controlled to avoid damaging unintended areas, all while leaving as little unnecessary impact as possible. While tools exist that are able to accomplish this in many areas, the technology used in intracranial neurosurgery can still be further optimized and improved with tools that move with and relative to the patient rather than current methods that operate from predetermined locations with an immobilized patient (Kwoh et al. 154). While attempts have been made with the goal in mind to create different robotic systems that could make adjustments needed for each individual case, there still exists room for improvement that allows for the introduction of new designs and concepts.

With this research project, an effort is made to utilize the various aspects of tensegrity structures in order to provide a new system of intracranial surgery tool guidance and stabilization. Tensegrity structures, which involve various ‘bars’ in compression and ‘strings’ in tension, have unique geometric functionality that allows for adjustments in various dimensions while retaining its overall form. Such structures allow for systems of feedback and control , allowing people to set overall specifics with relatively simple changes (Skelton et al. 4255). With a tensegrity structure, the aim is to increase the overall workspace and insertion angle range to allow for a wider area that various tools can cover depending on starting target points. This should allow for a more minimally invasive surgery, which should lessen negative effects of various operations in general, including common goals such as tumor removal, evacuating blood clots, and controlling hemorrhages.

Tensegrity structures have been widely studied and utilized in fields ranging from architecture (including various bridges) and art to even space exploration applications (with NASA's Super Ball Bot). While the motion and structures are well documented, there seems to be less focus on applications for medical devices and tool guidance usage (Sultan and Skelton 4640). Despite this, multiple sources suggest that there exists potential for this application in minimally invasive surgery (van de Wijdeven and de Jager 2522).

One particular device that was created with the same goals in mind was designed using various linear actuators that could be adjusted depending on patient specific requirements (Sheng and Desai 2511). This design worked when secured to a skull mounted pedestal and allowed for different angles of approach by tilting the area that held the various tools relative to the pedestal plane. However, this could only achieve a limited range of angles that the tool could approach from, ranging from a maximum of 5.9 degrees to 7.7 degrees (Sheng and Desai 2515). By applying a tensegrity structure, the intention is to increase the angle workspace available and allow for the tools to reach a wider potential area, thus allowing for potentially better intracranial surgery results.

DESIGN METHODOLOGY

After thoroughly looking through the various tensegrity structures created, a type of tensegrity prism had interesting properties that seemed most applicable to the design goals of the project. Tensegrity prisms are composed of two plates in the shape of a regular polygon with a bar and string tied at each corner, with each string bar pair joining at one plate's corner and being one corner rotation separated on the other plate, in an almost zig zag pattern between the two plates. As the regular polygon number increased, the tensegrity structure's movement was more limited, with a triangular tensegrity prism having the least constrained movement. Examining the movement of the tensegrity prism yielded three different modes of movement of the top plate with respect to the bottom plate: a tilting, a twisting, and a translation movement. The tilting comprised most of the movement, where the bars lacked symmetry in movement from a vertical initial configuration, allowing the top plate plane to be normal to a variety of tilt vectors. However, looking at the normal vector from the center of the top plate showed that during tilt the normal vector would never be inline with the center of the bottom plate. For twisting, the bars move radially symmetrically either clockwise or counterclockwise, resulting in a rotation of the top plate alongside a coupled change in structure height. With this the normal vector would stay vertical and would always be inline with the center of the bottom plate, but would achieve no tilting angle. Lastly, the translation occurred when the bars moved in the exact same direction, resulting in the top plate shifting in a horizontal direction coupled with a decrease in structure height. Here, the normal vector stayed vertical, but was offset from the center of the bottom plate as the top plate moved parallel to the bottom plate. Each type of movement individually could not accomplish the desired tilting and normal vector focusing, yet could achieve partially what was desired. Ignoring the twisting mechanism, a structure that comprises both the tilting movement and the translational movement was considered as a potential solution.

To accomplish this, a two stage structure was designed, with the upper stage being used purely as a tilting mechanism and the lower stage being used as a compensator stage by translating the upper stage top plate's normal vector to be in line with the lower stage bottom plate's center. Since the bottom plate of the upper stage would be essentially stacked on top of the top plate of the lower stage, it is possible to combine the two plates into one middle plate, making the structure composed of three plates with three bars and strings between each pair of plates for a total of 6 bars and strings. By adjusting the two tensegrity prisms independently, it would be possible to create tilt while still maintaining alignment between the top and bottom plates. However, to actuate the structure, the string lengths need to be controlled, which can be achieved by using a winch on one end of each string to adjust the string tension. To simplify the structure, the winches were placed on the top and bottom plates, using the string endpoints on the middle plate as fixed points. By using small holes in the plates for strings to pass through, it is possible to to position the winches at an offset from endpoints so that they don't interfere with the bar movement. With six winches, it is possible to control the string lengths to determine the structure's configuration, resulting in a structure that could be controlled for both tilting and focusing. The combination of tilting and translation triangular tensegrity prisms theoretically could make a structure capable of tilting and guiding surgical tools, but the structure required virtual, mathematical, and physical modeling to confirm the feasibility of the design.

VIRTUAL MODELING

With the conceptual design established, it became necessary to verify that the structure could achieve significant tool tilt from the vertical axis across the full rotational angle range. In order to determine the structure’s capability, a simplified model was constructed using the computer aided design (CAD) software SolidWorks. In this model, the upper and lower stages had simplified bars, consisting of spheres on either end of an extruded bar, while the plates had hemispherical holes of the same radius, approximating ball joints through concentric mates that were also applied to the connections between the bars and the top and bottom plates. The middle plate joining the upper and lower stage was constrained to be parallel to the bottom plate, while the top plate was initially free to move as the bars would allow it. Finally, an axis perpendicular to the center of the top plate was defined, and was constrained to be in line with the very center of the bottom plate, which represented the path any mounted tool would take. With these constraints in place, the model would move relative to the fixed bottom plate while the top plate would continuously be in line with the bottom. Bars used square cross sections to test various angles relative to the bottom and middle plates, but provided no other significant purpose other than testing. The middle plate used a reduced frame in order to assess angles that would result in normal vectors that pass between bars endpoints, which could further become a limiting feature of the structure.

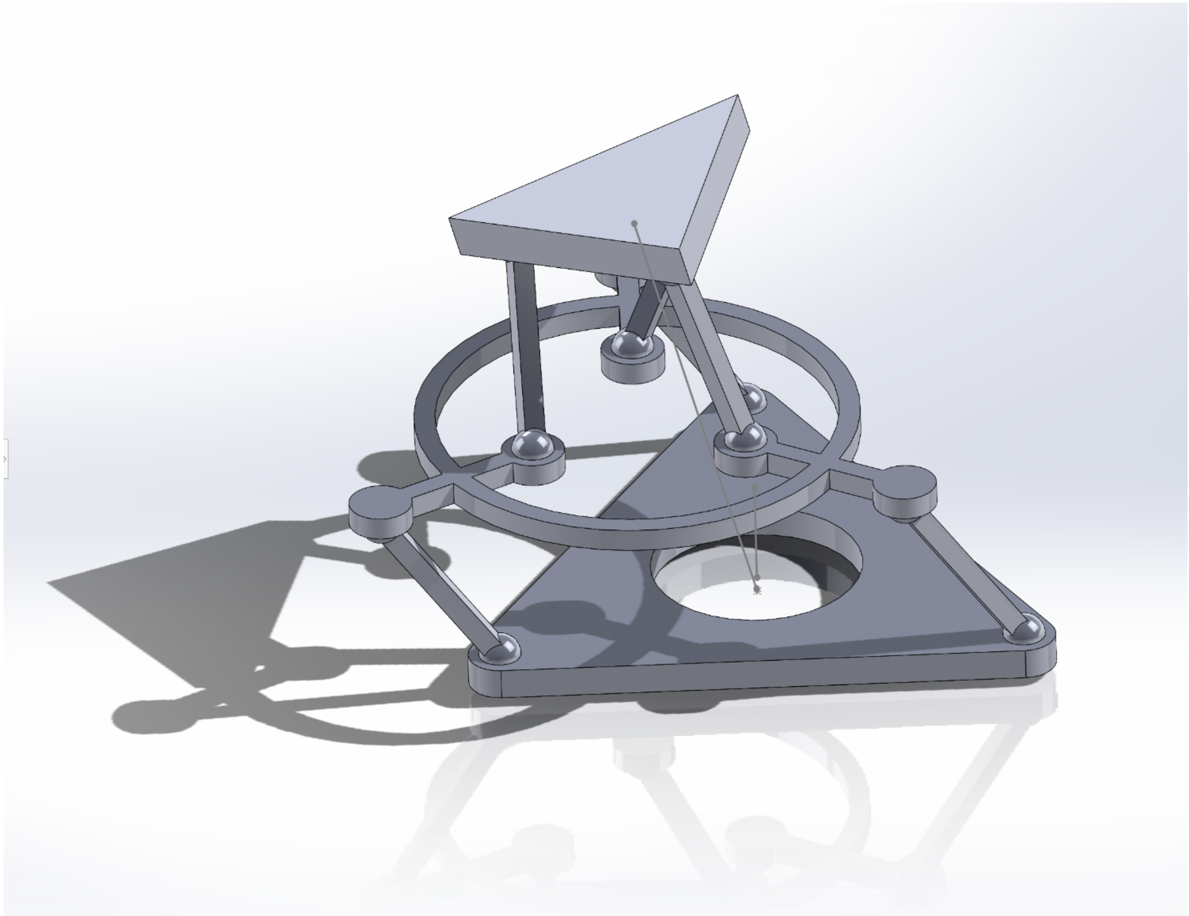

Figure #1: Virtual test model used for movement verification

As expected, the model was able to demonstrate that the structure could generate significant tilt in all directions away from the vertical axis, with the upper and lower stages working simultaneously. Line segments were used as visual indicators of the normal vectors assigned to the top and bottom plates, visually confirming alignment. However, the model was impractical at determining the exact configuration for various input tilt and rotation angles as well as the string lengths, which led to the necessity for a more mathematically based approach.

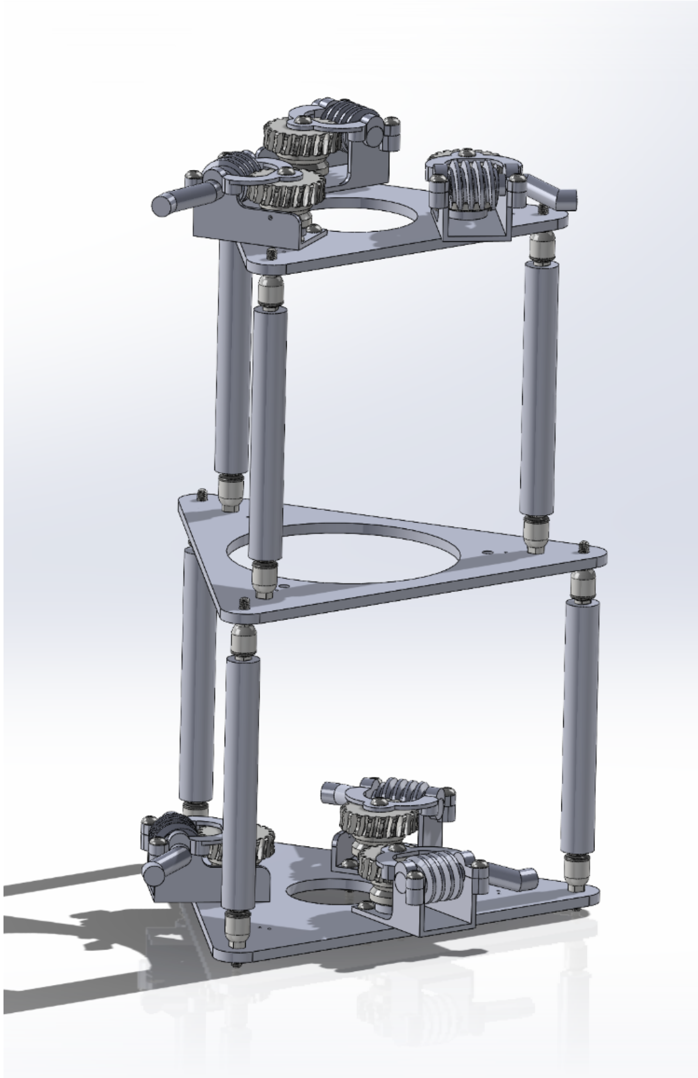

Figure 2: Full virtual assembly model

Finally, a virtual model using commercial off the shelf inline ball joints was created, in addition to worm gear cranks and worm wheel spools to form string winch subassemblies. The bottom, middle, and upper plates were designed for laser cutting, while the bars were machinable with a lathe. For the winch subassembly, it was easiest to 3D print the four components needed, as the complex geometry made regular machining impractical.

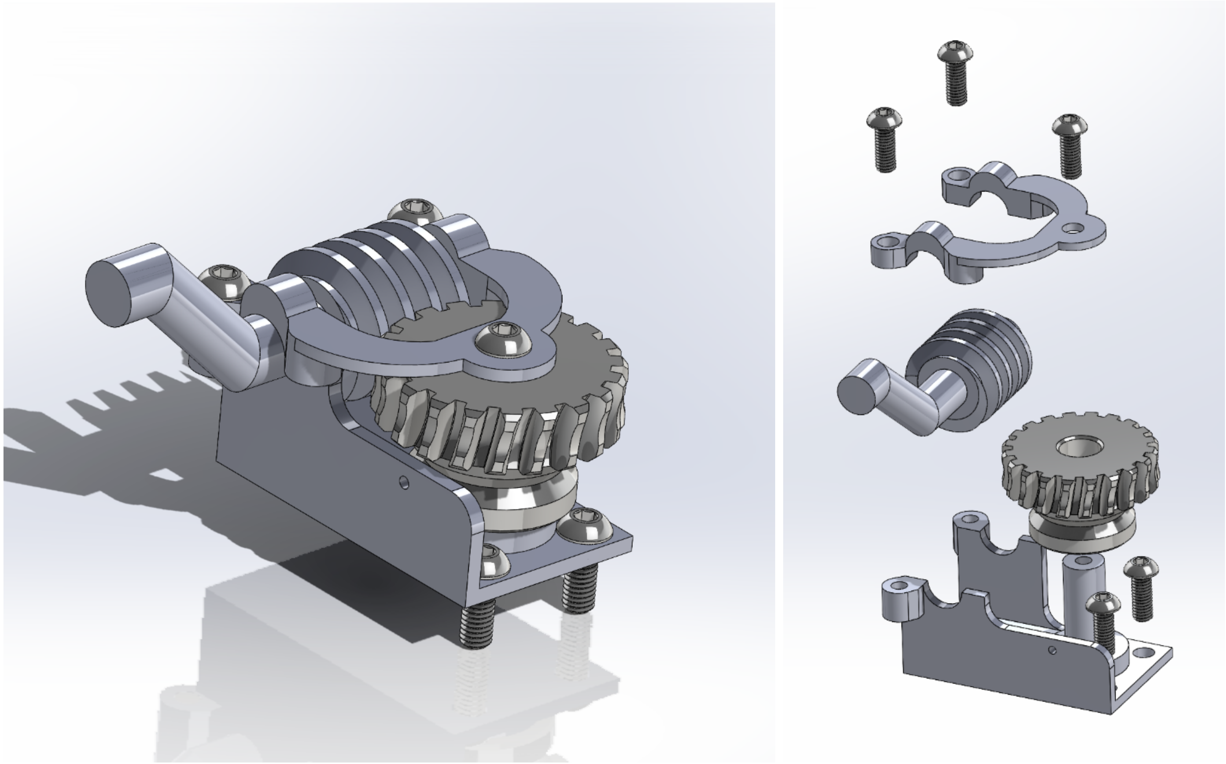

Figure 3: Worm gear winch subassembly with exploded view

Using a crank attached directly to the worm gear allows for simple control of the worm wheel. The primary purpose of the worm gear and worm wheel is to prevent the winch from being back-driven, since a string in high tension trying to rotate the worm wheel will push horizontally against the worm gear without being able to rotate it, locking the worm wheel in place.

MATHEMATICAL MODELING

In order to mathematically model the dual triangular tensegrity structure, the structure was split up by the upper and lower stages, with the upper stage being entirely dependent on the desired tilt and rotation angles, while the lower stage was dependent on the top stage configuration. With both configurations determined, it is possible to determine the string lengths that would generate this structure, resulting in the inputs needed to achieve the desired tilt and rotation angles. Using MATLAB, this process was used to determine the structure configuration and output a visual model as well as the string lengths needed to obtain the model.

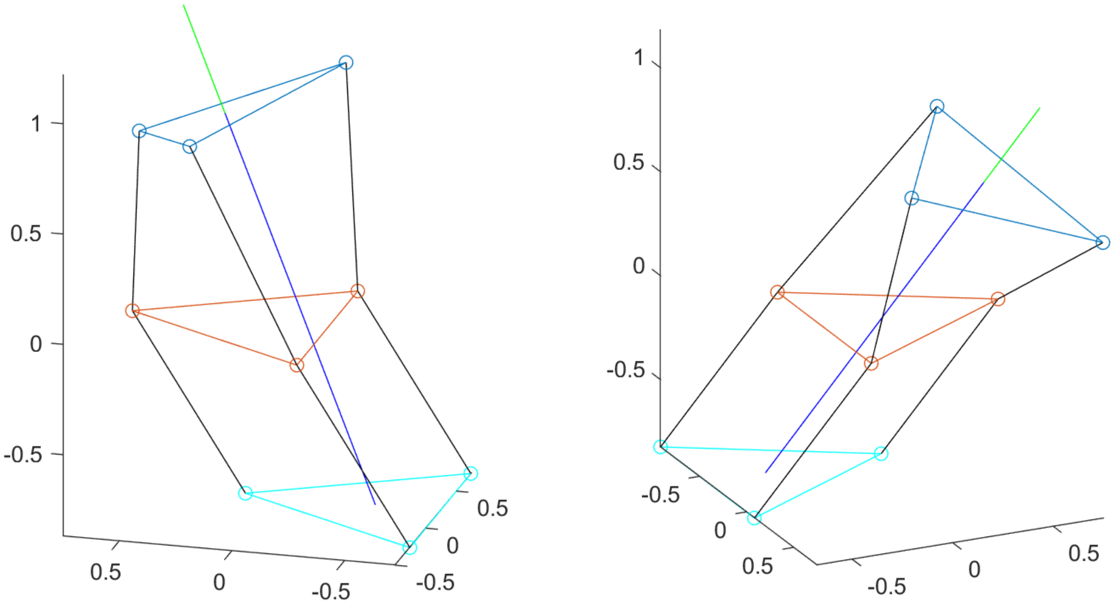

Figure 4: Example MATLAB outputs for different input tilt and rotation angles

Upper Stage Mathematics

The upper stage is composed of two plates with three bars and three strings in between. Since the bar endpoints correspond to the corners of each plate, it is possible to define the entire system with 6 points in space. Using a local coordinate system with an origin at the center of the bottom of the two plates, a z axis perpendicular to that plate, and an x axis parallel to one of the triangle sides, it is possible to organize the coordinate system so that the top and bottom plates can be defined as a plane between sets of 3 points, with the bottom plate contained within the x-y plane.

Since the bottom and top equilateral triangle side lengths are known, using simple geometry it is possible to specify the three coordinates of the bottom triangle end points, which are located at $(0, \frac{w\sqrt{3}}{3}, 0)$, $(\frac{w}{2}, \frac{-w\sqrt{3}}{6}, 0)$, and $(\frac{-w}{2}, \frac{-w\sqrt{3}}{6}, 0)$, where w is the triangle width (will be notated as B_1 through B_3). Since the bottom points are known, the only unknowns are the three top point locations, which results in nine unknown components (x, y, and z values). To solve this, nine equations are needed, which can be divided into groups of three. The first group of three equations are based on the length of each bar, as the distance between complementary bottom and top points are of fixed length L. As such, a 3D point distance calculation can be made, where each bar can be converted to a vector using the difference between complementary directional components. As such, the first equation ends up in this form:

$$\sqrt{(T_{1x} - B_{1x})^2 + (T_{1y} - B_{1y})^2 + (T_{1z} - B_{1z})^2} - L = 0 \qquad \text{(Equation \#1)}$$

This makes the first group of three equations, progressively moving through T_1 and B_1 through T_3 and B_3. For the second set of equations, instead of making use of the bar length, the top plate triangle width is used. Here, another 3D point distance is made, but using the triangle top points instead. As such, the equations ends up like this:

$$\sqrt{(T_{1x} - T_{2x})^2 + (T_{1y} - T_{2y})^2 + (T_{1z} - T_{2z})^2} - W = 0 \qquad \text{(Equation \#2)}$$

After cycling through the three combinations of the points (T_1 and T_2, T_2 and T_3, T_3 and T_1), that gives a total of six of the nine equations. For the last equation, it is necessary to utilize both the geometry of the top plate (angles between vectors connecting the top points) and the input angle. For the input angle, it is necessary to convert it to a unit vector, which is done by using trigonometry combinations on the tilt and azimuth angles shown here:

N = [cos(azimuth)•sin(tilt) sin(azimuth)•cos(tilt) cos(tilt)] (Definition #1)

With the normal vector defined, it is possible to relate the fact that it is always perpendicular to the top plate, which is defined by the cross product of the vectors of two sides. As such, one can split the cross product into three parts, one for each directional component.

$$((T_{1y} - T_{2y}) \cdot (T_{1z} - T_{3z}) - (T_{1z} - T_{2z}) \cdot (T_{1y} - T_{3y}))/(W^2 sin(60°)) - N_x = 0$$

(Equation #3)

By doing each cross product calculation (with corresponding adjustment to convert to unit vector), it is possible to do this for all three Normal Vector components (N_x, N_y, and N_z). Using a computational solver like MATLAB, it is possible to solve for the nine position points for the three top point coordinates, fully defining the top structure shape.

Lower Stage Mathematics

For the bottom structure, the entire section acts as a compensator to align the tilt vector from the origin of the bottom structure to the top plate normal vector. This is done by the bottom structure acting as a parallel plate mechanism, where each bar is parallel to each other bar at all times, keeping the the upper plate where the top structure is joined parallel to the bottom plate. This is accomplished by having any XY shifts coupled with a Z shift, which allows for better control for moving the top structure. With a base shape that is able to have a circumscribed circle touching all points where the bars are, there is the possibility for twist, which would end up rotating the top structure and not be desirable. However, with a shape like a rhombus that is nearly square, by having all bar end points not equidistant from a point twist can be prevented. With good string control the twist could be prevented while still having an equilateral triangle shape. In order to determine the bar positioning needed, it is necessary to use the top structure position information to compensate. Since the top structure normal vector can be rewritten as a 3D line equation expressed as $(x_0, y_0, z_0) + t*(N_x, N_y, N_z)$, it is necessary to first calculate the center of the top structure top plate to determine x_0, y_0, and z_0. This is done by simply averaging the top coordinate components (just adding T_{1x} through T_{1x} and dividing by 3 for example). With the equation of the line, it is necessary to first account for the height of the bottom stage, which is directly added to z_0. With this prepared, through vector addition it is possible to have the bottom structure tilted bar vector of length L added to the normal vector of unknown scaling to equal a vector that goes from the center of the bottom plate of the bottom structure to the top plate of the top structure. This can be split into three equations, one for each directional component, with three unknowns (bar tilt angle φ, bar azimuth angle θ, and normal vector scaling s) shown here:

$$x_0 + s*N_x + L \sin(\varphi)\cos(\theta) = 0 \qquad \text{(Equation #4.1)}$$

$$y_0 + s*N_y + L \sin(\varphi)\sin(\theta) = 0 \qquad \text{(Equation #4.2)}$$

$$z_0 + s*N_z + L (\cos(\varphi) -1) = 0 \qquad \text{(Equation #4.3)}$$

Using an equation solver such as MATLAB, it is possible to solve for the tilt angle and azimuth angle of each bar (though the scaling factor s can be discarded). Once the angles have been found, the bottom structure becomes fully defined and the top structure top plate normal vector becomes in line with the origin of the bottom plate.

String Length Mathematics

The string lengths, which are connecting adjacent string top and bottom end points, are easy to calculate, as with the bar endpoints, one can use the 3D distance formula between relevant points, similar to equations #1 and #2. These values are what are set to determine how the bars are positioned to achieve the top plate tilting needed for aligning whatever tool may be attached to it.

Real Life Model Deviations

Due to the realistic constraints on this build, it is necessary to make adjustments. For instance, having the ball joint for each bar end in line with the plate means having a sunken area for the inline ball joint to be screwed into, since there is a non zero distance between the start of the screw area and the center of the ball. Additionally, it is not feasible to have the string end exactly where the ball joint is, meaning that there needs to be some offset distance. Lastly, there is likely a non zero thickness of the middle plate joining the two structures, adding in further separation in the z direction.

To address all these problems, there are some solutions. For the offset distances between the center of the ball joints and the screw start as well as the thicknesses of the plates, there is a trivial adjustment needed which is just factoring the total offset into the z_0 value, minus the offset on the very top plate (which will have an offset inline with the normal vector, which can be accounted for in the scaling factor s which was discarded). Due to the string offset, there just needs to be a small distance separation that moves the endpoints slightly closer to each other, effectively reducing the string length but not reducing the effectiveness of the controls.

The last concern would be the tilting limits of the ball joints, which would restrict the total angles able to be created. This would require specialty made parts for large tilt angles, while standard parts would be suitable for small tilt angles.

PHYSICAL PROTOTYPE

Using the virtual CAD prototype created, it was possible to make a physical assembly of the dual triangular tensegrity prism structure. Using a combination of 3D printed parts, laser cut plates, lathed bars, and commercial off the shelf inline ball joints and screws, it was possible create the complete assembly by creating the six winch subassemblies and attaching them to the assembly of bars and plates, and finally adding the strings.

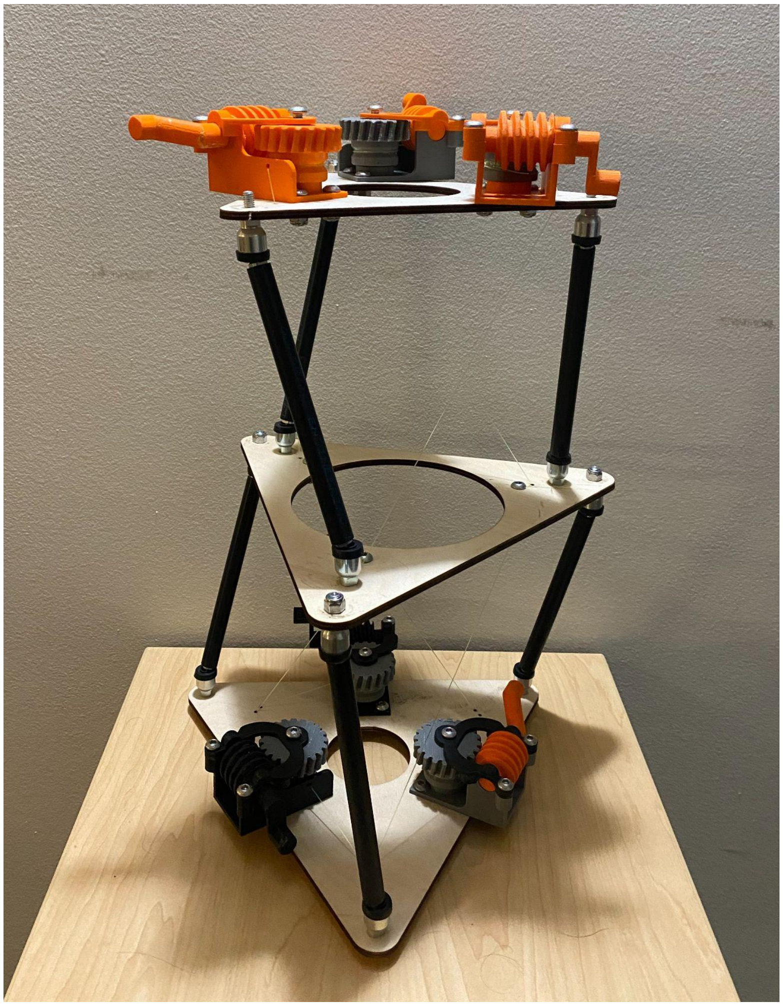

Figure 5: Complete physical prototype assembly

The strings were initially placed with the midpoint in the center, wrapping each side around one end of an additional screw in the middle plate, and then passing through the hole again, making the string pass through the guidance hole a total of three times for each of the three middle plate fixtures. This ensured that the string was not only fixed with minor added structural redundancy, but that the effective fixed endpoints for the string could be shifted slightly to be at the hole openings and not be dependent on the wrapping of the string around the fixing screw. The guidance holes on the top and bottom plates served similar purposes, with pairs of guidance holes necessary on the bottom plate for repositioning the worm gear crank subassemblies to be vertically above the plate, reducing the need for additional stands. The bar mounting holes in the corner of each plate were tapped, except for the middle plate, which were clearance holes, as it would be impossible to rotate the bar subassemblies on both ends when attaching multiple bars to each pairing of plates.

After completing the physical assembly, it became apparent that the limits of the inline ball joints greatly limited the performance of the upper stage. Using ball joints that had a max swivel of 35 degrees meant that each bar could only tilt a max of 17.5 degrees from vertical in any direction, which meant that the structure lacked the mobility of both the virtual model and the mathematical model. However, while the movement of the structure was not as pronounced, it was still possible to get a range of small tilt angles from the physical prototype, though significantly off the desired range. Using a redesigned structure with ball joints that have a larger swivel could fix this problem, but commercially available ball joints typically have under a 50 degree swivel. Alternatively, using a different joint such as a universal joint may be able to solve this problem, provided the joint is free to rotate with respect to the plates it is mounted onto.

The more glaring problem with the structure was that the translation movement of the lower stage was not always stable, as often the longest string would have significant slack that allowed the lower stage to rotate closer towards the center. This indicated that the lower stage will not function off of the three compression bars and tension string alone, without significant modification. From this it can also be assumed that the top stage may also have non equilibrium configurations, which were hard to visually confirm due to the tilt limiting by the ball joints. An improved model with substitutions for the ball joints would likely reveal more information about the upper stage's realm of movement, as analysis for separating equilibrium from non-equilibrium stages would be necessary, which is not feasible with the virtual model but could be done with further mathematical modeling.

RESULTS

After the creation of a virtual model, a mathematical model, and a physical prototype, it became clear that this design would need significant modifications to achieve the desired movement capabilities, as apparent by the physical prototype. The primary problem is that in certain lower stage translation configurations, a string would be slack and when tension is applied the structure would move inwards, causing a triangular tensegrity structure to want to rotate. While the bar configurations allow for the desired positions, the actuation is not sufficient with three strings for each tensegrity prism.

In order to fix this, there are a few methods that could be used. The first and simplest would be to substitute all of the tension strings for linear actuators that could also handle compression forces. Using this method, one could substitute the string lengths for actuator lengths, and the system should output the same structure configurations. This would remove the classification of this design as a tensegrity structure, but should still provide stability and guidance needed for mounted tools. The second method would be to increase the number of strings and / or bars to further define the system using additional strings and bars. For the lower stage, additional bars alone would be enough to constrain the structure to act as a parallel platform mechanism, as long as the additional bars are placed at a significant distance away from the center. This works because in order for the structure to act as a parallel plate mechanism, all bar movement must match and be of the same magnitude in the same direction. When the lower stage in a non equilibrium translation movement tries to rotate, the bars move non equally, meaning that the path that the structure takes deviates from being parallel. Looking at the degrees of freedom (DOF) of the lower stage, the movable plate has 6 DOF (3 rotational and 3 translational), and each bar has 5 relevant DOF (as rotation about its axis does not change anything). Because each ball joint reduces the DOF by 3, each bar added has a net -1 DOF change to the structure. As a result, the base triangular plate tensegrity prism has 3 degrees of freedom. With three taut strings in place, each subtracting 1 degree of freedom, the structure can be fully defined. Since the translation movement can cause a string to become slack, the additional bar can make up for the degree of freedom control and force parallel movement only. However, if the bar is placed closer to the other bars, it can become partially redundant and still allow for some deviation, especially if it happens to be placed equidistant from the center with the other bars, allowing twist.

For the upper stage, more analysis would be necessary to determine which configurations are not in equilibrium, as the movement is more involved than with the lower stage. The physical prototype was inadequate at testing a significant range of movement for the upper stage, as each tilt angle involved more tilt needed from the bars. Due to not wanting to restrict the movement of the top plate, adding in more bars is impractical, so the potential solution would be to add in additional strings. With an additional 3 strings running opposite of the current setup, it would be enough to ensure that any slack string could be compensated using an alternative string, however this method is impractical. A more efficient method that could solve any non-equilibrium configurations would be to add additional mechanical structures that could allow for the repositioning of the strings relative to the plates. Instead of having one fixed end and one adjustable end, by using manual adjustment one could create an additional path for the strings with a secondary endpoint. However, this does come with significant disadvantages, leading to the replacement of strings with linear actuators to seem more practical.

CONCLUSION

With the goal to create a tool guidance and mounting system for intracranial surgery applications, a dual stage tensegrity prism structure was designed. Using the design, a virtual model was created which confirmed that bar and plate movement capabilities were satisfactory in tilt angle creation. A mathematical model generated the configurations necessary to achieve desired variable output tilt and rotation angles, presenting the required input string lengths. The physical prototype displayed that various configurations were not in equilibrium, which is necessary for stability. Using this information, modifications were proposed to adapt the structure, which included using linear actuators for string replacement or affixing additional bars and strings. With the modifications and further testing, it is possible that the structure could still be used for medical robotics, however much development and further verification would still be needed.

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