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MODULAR ELASTIC LATTICE PLATFORM FOR RAPID PROTOTYPING OF TENSEGRITY ROBOTS

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ABSTRACT

This paper presents a new platform for prototyping tensegrity robots that uses an elastic lattice structure for the robots' tension network to compliment traditional cables and springs. This approach significantly reduces the time required for design, manufacturing, and assembly, while increasing experimental repeatability and symmetry of the tensioned robot. The platform allows more scientific experiments to be performed in less time and with higher quality.

This lattice platform, with associated laser-cutting design techniques developed in this work, has been applied to three types of tensegrity structures: 6-bar spheres, 12-bar spheres, and multiple-vertebra tensegrity spines. For the 12-bar tensegrity case in particular, this new lattice platform has allowed multiple different shapes to be explored as designs for future robots. Basic testing confirmed a reduction in robot assembly time from multiple hours down to a mean of one-two minutes for the 6-bar prototype, five-ten minutes for the various 12-bar prototypes, and approximately seven minutes for the spine.

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FIGURE 1: The TT-4$_{\text{mini}}$ prototype, the first tensegrity robot that uses the elastic lattice platform. This robot moves by adjusting the lengths of its cables with respect to its elastic lattice.

INTRODUCTION AND PRIOR RESEARCH

Challenging environments for robot locomotion, such as those in space applications, have motivated recent research into tensegrity (tension-integrity) robots [1, 2, 3, 4, 5]. These robots consist of rigid elements held together in a network of cables in tension. As designed for use in space, tensegrity robtos can be made as spheres that roll on a variety of terrains [6, 7, 8, 9, 10, 11], snake-like robots which crawl along the ground [12, 13, 14], or as part of walking four-legged robots [15, 16, 17]. All of these robots are designed to exploit the various beneficial properties of tensegrity structures: low mass, variable stiffness [1], redundancy to failure [18], among other benefits.

Although tensegrity robots have the potential for robust locomotion, practical prototyping of each of the above robots has presented challenges. Manually attaching the springs and cables of each robot introduces human error, and takes a long time for assembly. These difficulties provide the motivation for this work.

Tensegrity Structures as Robots

Tensegrity structures were first introduced in the mid-1960s in architecture and art [19, 20, 21]. The structures' passive combination of cables-in-tension and bars-in-compression became a significant design feature in several architectural and sculptural structures [22, 23].

In contrast, tensegrity robots change their shape by adjusting the lengths of their cables. Many different types of tensegrity robots have been created, including robot designs that use pneumatic actuators [6], shape-memory alloy actuators [24], linear motors to pull on cables [25], direct actuation via servomotors [26], as well as motors attached to spools [27]. Regardless of the actuation method used, a tensegrity structure must have all tensile elements in tension to maintain a stable structure.

Tensegrity Robots at the BEST Lab and NASA Ames Research Center

The University of California's Berkeley Emergent Space Tensegrities (BEST) Laboratory has been collaborating with the National Aeronautics and Space Administration's (NASA) Ames Research Center on using tensegrity structures as the basis for the next generation of space exploration robots [15, 7, 5]. These structures have used as spherical robots, designed to land and roll along different terrain, and robot spines designed to help a four-legged robot walk.

In particular, a spherical tensegrity robot has the potential to be used as both a lander and a rover since it has the ability to passively distribute forces across the entire structure. The tension network provides shock protection from the impact of landing without requiring complex parachute systems while also serving as a mobility platform for exploring unpredictable environments.

Five different actuated spherical tensegrity robots have been developed within this collaboration: the SUPERball at NASA Ames [15], the TT-1 and TT-2 robots at UC Berkeley [7, 8], the TT-3 robot at UC Berkeley [5] (Fig. 2), and the new TT-4_{mini} first presented here (Fig. 1). Each of the four "TT" robots from UC Berkeley have incremental improvements on design, actuation, and control. The new TT-4_{mini} contributes a major step in manufacturing and assembly for these robots.

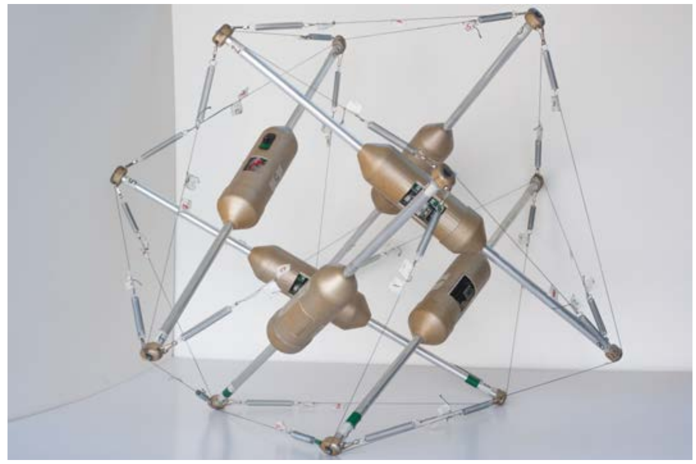


FIGURE 2: Tensegrity robot TT-3 prototype. Note how all tensile members consist of cables and springs, each of which was individually tied together.

The UCB-NASA collaboration is extending the research of spherical tensegrity robots to 12-bar tensegrity structures, which represents the next largest symmetric form. We are simulating and creating rapid prototypes of two geometric forms of 12-bar structures in order to learn more about their mobility, impact, and payload characteristics. We anticipate that the 12-bar structure will increase the capabilities of tensegrity robots for planetary surface exploration. This paper presents the first designs of these 12-bar robots.

Finally, tensegrity spine robots have been developed to assist the walking of four-legged (quadruped) robots over uneven terrain. The Underactuated Lightweight Tensegrity Robotic Assistive Spine (ULTRA Spine) is a tensegrity robot with five independent vertebrae that can bend and twist, emulating a backbone's motions [15]. Though simulations and controllers have been developed for the ULTRA Spine, the development of hardware prototypes has been hampered by the challenges of manually assembling the robot, and the difficulty in creating symmetric tension on both sides of the spine. This research addresses both of those challenges, among others.

CHALLENGES IN TENSEGRITY PROTOTYPING

Tensegrity structures are notoriously difficult to assemble because the members are not in balanced compression and tension until the structure is fully assembled. In the intermediary steps of assembly, forces are unevenly distributed and the structure is difficult to constrain. It is easy to make mistakes in assembly, such as connecting the wrong tension and compression members to one another. To illustrate the complexity of assembly, a low-fidelity prototype of a 6-bar tensegrity structure made with wooden dowels and springs can take as long as an hour for a team of five people to assemble.

Additionally, it is challenging to maintain symmetric tensions in the elastic members in order to create a symmetric tensegrity structure. For example, using a cable in series with an extension spring for the elastic member, as is done on TT-3, requires that the cables be of equal length to achieve equal tensions. This means that the system needs to be carefully manufactured or calibrated; if not, the system is susceptible to undesired deformation and will not perform shape-shifting maneuvers as expected. Other methods for the elastic members, such as using bungee cords or other elastic materials, have the same difficulties.

DEVELOPMENT OF THE MODULAR ELASTIC LATTICE

The idea for an elastic lattice came from examining an assembled 6-bar tensegrity structure and conceptualizing how the tension members (cables in series with springs) could be deconstructed from a 3D structure to the 2D plane. The external geometry of a 6-bar robot is that of an icosahedron with the tension members forming a portion of the vertices. The triangular faces of the solid could thus be mapped onto a flat sheet of material. A new elastic medium, silicone rubber, was selected to replace the traditional cables and springs. The new configuration was first tested using a plastic sheet, which was cut to trace the tension members of an assembled 6-bar tensegrity robot. The production of this low fidelity prototype made it evident that eight triangular units, such as the one in Figure 3, were needed to form the 6-bar tensegrity structure.

The first elastic prototypes of the lattice for a 6-bar spherical tensegrity were created using 0.02 in. thick, 20A durometer silicone rubber and cut with a single-beam Universal Systems laser cutter. The lightness of the silicone rubber caused challenges during the laser cutting process. Because it was so light, the venting system of the laser cutter caused the rubber to lift up and flap as it was being cut, risking the correct profile of the cut. This risk was averted by putting masking tape on both sides of the rubber sheet, thus making the sheet heavier so it did not lift up and flap. This ensured that the proper design could be created without impeding the cutting ability of the laser.

After we made a number of prototypes with this silicone lattice, it became clear that the 0.02 in. thick, 20A durometer silicone rubber did not have the correct material properties for the 6-bar tensegrity; the hardness and thickness of the silicone rubber did not provide enough tension to the system, even with different width profiles.

The prototypes in the next iteration were made with 0.0625 in. thick, 60A durometer silicone rubber. By experimenting with various widths of the rubber elastic lattice, the desired tension in the system was achieved using this material. These prototypes were produced using a double-beam Universal Systems laser cutter. The heavier silicone rubber did not face the same manufacturing issues as the 20A durometer silicone rubber but presented new difficulties in the laser cutting process. Initially the laser cutter only etched the silicone rubber instead of cutting it. The optimal laser cutting setting was achieved on the cutter by using only the top laser beam instead of both laser beams.

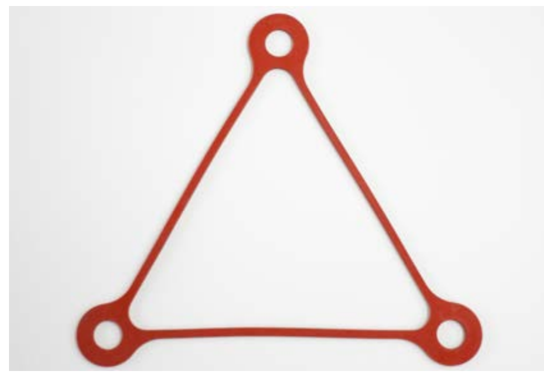


FIGURE 3: Modular elastic lattice prototype made with 60A durometer rubber.

The elastic prototypes made with 60A durometer silicone rubber (Figure 3) were much stiffer than the previous versions and could withstand higher tension. Thus, these prototypes better demonstrated the unique characteristics of tensegrity structures.

ADDRESSING THE CHALLENGES OF TENSEGRITY PROTOTYPING WITH THE ELASTIC LATTICE

The benefits of the modular elastic lattice address many of the challenges of tensegrity prototyping. As the laser cut profile of the lattice can be very quickly customized, these benefits are applicable to any tensegrity structure.

First, the lattice enables rapid manufacture and assembly. Laser cutting is simple and fast, so the lattice is quickly produced. Assembly of the structure with the lattice is on the order of minutes, as exemplified by the cases of the 6-bar, 12-bar, and spine tensegrity structures. Previous methods required an hour or more. Additionally, the modularity of the lattice allows experimentation with the number of lattice pieces to optimize assembly time for a given tensegrity system.

Second, the lattice gives significant control over the system's tensions. The precision and consistency of the laser cutter results in identical elastic members, making achieving symmetric tensions in a system much simpler. Additionally, the spring constant of the elastic member can be changed by adjusting the profile of the laser-cut elastic member, and thereby the system's tensions can be designed.

We conducted simple tension tests with the 60A durometer rubber to estimate how changing the width of the elastic members alters the corresponding spring constant. The laser cutter was used to produce equal length strips of the lattice material of six different widths. The experimental setup consisted of securing one side of the strip and pulling on the opposite side with five different forces and recording the respective displacement. Nine repetitions of this process were conducted on each of the widths; the resulting data is seen in Table 1. This data is used when designing new lattices to estimate the width that will result in the desired spring constant and therefore the desired tension.

TABLE 1: SPRING CONSTANT TO WIDTH COMPARISON.

Width (mm)	Spring Constant (N/m)	±Error (N/m)
6.35	986	24.52
7.94	1472	35.56
9.53	2104	55.96
11.11	2364	56.50
12.70	2812	67.75
14.29	2973	68.22

In order to demonstrate the advantages of the elastic lattice prototyping method, the following sections will describe the use of the lattice on the 6-bar, 12-bar, and spine tensegrity structures.

USE OF THE ELASTIC LATTICE TO ASSEMBLE A 6-bar TENSEGRITY STRUCTURE

The elastic lattice enabled rapid prototyping of 6-bar tensegrity structures. We experimented heavily with the modularity of the elastic lattice for this structure. We found that combining the eight triangles into a single piece made assembly quicker and simpler. The single-piece lattice is shown in Figure 4. This lattice structure is then used in the demonstration assembly shown in Figure 5.

Figure 5 illustrates the step-by-step sequence required to assemble a 6-bar tensegrity structure using this newly developed prototyping method. Since the main two elements of a tensegrity structure are tension and compression, we decided to use thin-walled aluminum rods as the compression elements in our static tensegrity prototype. The 3D printed endcaps were used as the connection between the modular elastic lattice and the aluminum rods. A fully assembled 6-bar tensegrity structure requires one of the one-piece lattices (eight connected rubber elastic triangle lattices), twelve of the 3D printed endcaps, and six of the aluminum rods.

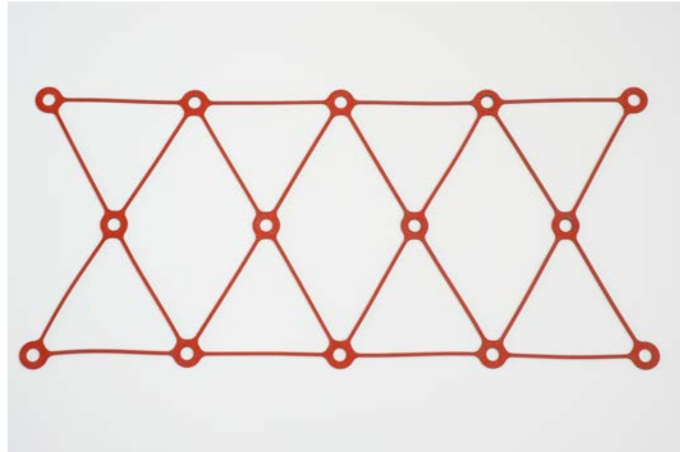


FIGURE 4: Single-piece elastic lattice for 6-bar tensegrity structure.

The result is a tensegrity structure that can be built in a few minutes by a single person, whereas previous 6-bar structures required 1-2 hours and two or more people. We conducted a test in which we gave ten subjects clear instructions and asked them to assemble a 6-bar tensegrity structure with the elastic lattices. It took the subjects an average of 77 seconds with a standard deviation of 24 seconds.

USE OF THE ELASTIC LATTICE PLATFORM FOR AN ACTUATED 6-bar TENSEGRITY ROBOT

Although a static model is used to demonstrate the basic concept of a tensegrity structure, the addition of actuators are required to gain scientific insight into the tensegrity robot's capabilities. To do so, a 6-bar tensegrity robot with six actuators was constructed, which is referred to as the TT-4_{mini}, the 4th generation spherical tensegrity robot of miniature size (Figure 1). The TT-4_{mini} makes use of small components and the modular elastic lattice to allow for rapid hardware iterations and performance testing.

With the new tensegrity prototyping platform, we were able to quickly manufacture and assemble a passive 6-bar tensegrity structure as the basis of an actuated tensegrity robot. Previously, it required days to assemble a new version of a tensegrity robot. With the new technique, we were able to assemble a new functional six-bar tensegrity robot under a hour. This platform drastically increased the rate of prototype development, which allowed us to experiment on new concepts quickly.

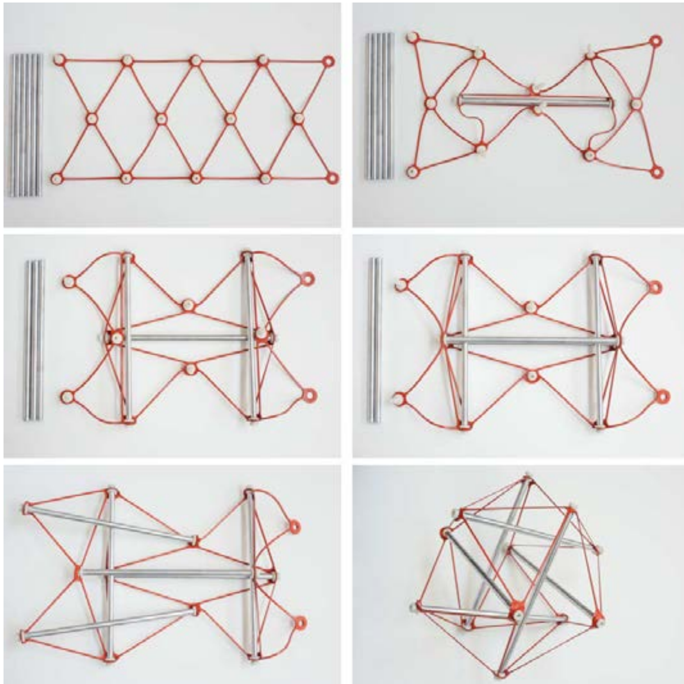
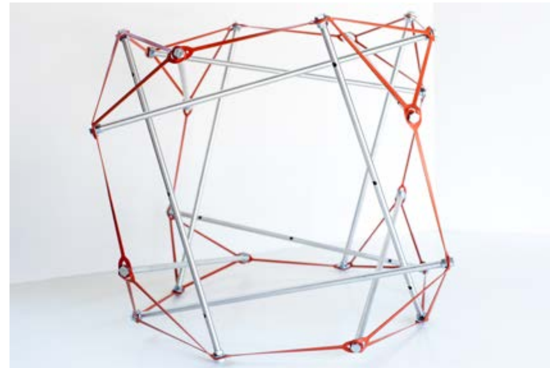


FIGURE 5: Step-by-step assembly sequence of a 6-bar tensegrity static model.



(a) Cube

(b) Octahedron

FIGURE 6: Prototypes of two 12-bar tensegrity structures constructed using the elastic lattice. They are robust and quick to assemble, and they allow significant control over the systems' properties.

USE OF THE ELASTIC LATTICE FOR RAPID PROTOTYPING OF 12-BAR TENSEGRITY STRUCTURES

In addition to 6-bar tensegrity robots, the BEST Lab is investigating 12-bar tensegrity structures as a new platform for tensegrity robots for planetary surface exploration. There are several variations of symmetric 12-bar tensegrity structures. Our lab is conducting a design study of two 12-bar tensegrity structures to select one that will best serve the design objectives of the robot. These structures are the cube and the octahedron, so named for the shapes from which the pattern of rods of the structures evolve.

We created structural prototypes with the goal to gain preliminary design insights into their deformation and impact characteristics when tested by hand. Prototyping these structures presented significant challenges. Each of the 12-bar structures has 36 cables and a complex geometric form. They are also higher tension systems than the 6-bar structure. These factors can make them difficult to assemble and, important to the design study, difficult to achieve symmetric tensions in the elastic members.

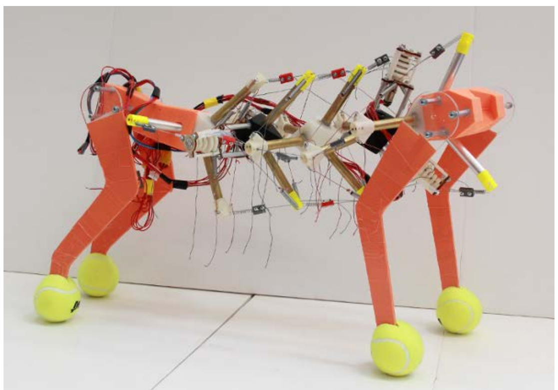
Initial attempts at creating structural prototypes without the elastic lattice were slow and necessitated the building of jigs. It took several days to make simple prototypes from wooden dowels and elastic bands. Regular tension and structural robustness was very difficult to achieve in these early prototypes. Consequently, hand tests of deformation and impact characteristics yielded low scientific returns.

The rubber lattice prototyping method allowed us to build these two tensegrity structures much more quickly and with significantly more control over the systems' tensions. Following a similar methodology as was used for the 6-bar tensegrity structure, we created a lattice for each of the 12-bar structures by observing geometric patterns and designing modular pieces. We estimated the appropriate profile of the pieces to achieve desired tensions in our system using the data from Table 1. We then connected the pieces to create lattice shells. Next, we attached bars to the interior of each lattice shell to erect the tensegrity structures. The final structural prototypes are shown in Fig. 6. Once the lattices are designed, assembling each structure takes between 5 and 10 minutes.

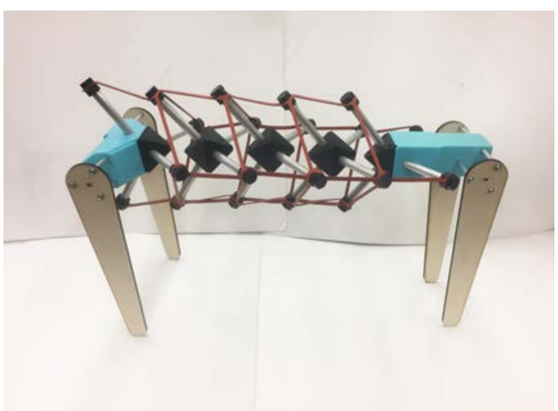
We have used these elastic lattices effectively in our design study, and, because of the ease of assembly, robustness, and control over system properties that they allow; these prototypes will serve as the basis for actuated 12-bar robots.

USE OF THE ELASTIC LATTICE FOR RAPID PROTOTYPING OF A SPINE TENSEGRITY STRUCTURE

The 6-bar and twelve-bar research led to the exploration of a tensegrity spinal system. The ULTRA Spine topology is defined by vertebrae that are attached to each other using horizontal and saddle connectors. By shortening the horizontal connectors, the vertebrae to move closer together. Changing the length of the saddle connectors causes the vertebrae to rotate with respect to each other, creating a torsional motion in the spine. By implementing a tensegrity spine on a quadruped robot, we want to minimize weight and the complexity of the control systems without sacrificing locomotion.



(a) Cable Prototype



(b) Lattice Prototype

FIGURE 7: Prototypes of two spine tensegrity structures constructed using the different prototyping methods described.

The first prototype of the spine was manufactured and assembled using cables and springs. The cables in the tension network are made of braided Dyneema, purchased off-the-shelf. The saddle cables are attached to stiff 4.45 cm long springs with a 1226 N/m spring constant in order to provide the structural support for the horizontal cables. The horizontal cables utilize a 2.22 cm long spring with a 187.3 N/m spring constant, allowing more change in length during cable actuation without needing large motors. The springs and cables are fastened to the thin-walled aluminum rods using unique 3D printed endcaps with screws and washers.

The assembly process for the cable tension network is not only time consuming, but also very prone to error. The spine's geometric complexity makes the design very hard to visualize and assemble without experienced assistance. Even with detailed instructions, the process takes over three hours with at least two people measuring, cutting, and placing each of the thirty two cables. Different assembly jigs must be used at specific times during the assembly. Suspending each core from the ceiling allows initial cable connections to be established between each cable without needing to hold on to the individual cores. After the cables are loosely attached to each vertebrae, the saddle cables are hand tuned to maintain rotational stability, and the horizontal cables are tightened until the robot is able to stand. However, due to the relationship between each tensioned component, this process can be very tedious and inaccurate. When one saddle or horizontal cable is not the correct length, the vertebra are unevenly spaced, yielding an uneven distribution of weight across the robot. These inconsistencies result in low scientific returns when cables are actuated during tests.

The lattice prototype consists of the same five vertebrae, but the tensile network is maintained by the elastomer lattice jacket that wraps around the vertebrae. The rubber replaces the horizontal and saddle cables of the original prototype, eliminating many of the assembly and manufacturing challenges. Figure 8 illustrates the sequence required to assemble the spine tensegrity structure using one full lattice and five vertebrae. The same thin-walled aluminum rods are used and a bolt and screw act as endcaps that clamp onto the lattice and fit into the rods. A fully assembled spine tensegrity structure utilizes one lattice, twenty bolt endcaps, and twenty of the aluminum rods.

With the new prototyping platform, the total assembly time for the spinal tensegrity structure was reduced from around three hours to seven minutes, even with a single person. A simple and easily visualized pattern reduces the complexity of the system and allows for the assembly process to be quickly learned with limited direction. The lattice creates a consistent and repeatable tension network that can be used when evaluating the spine's design. After applying a force to create the bending or torsional moment, the lattice allows the robot to return to its original shape through its control of the shape or profile of the robot and the tension network established by the elastomer.

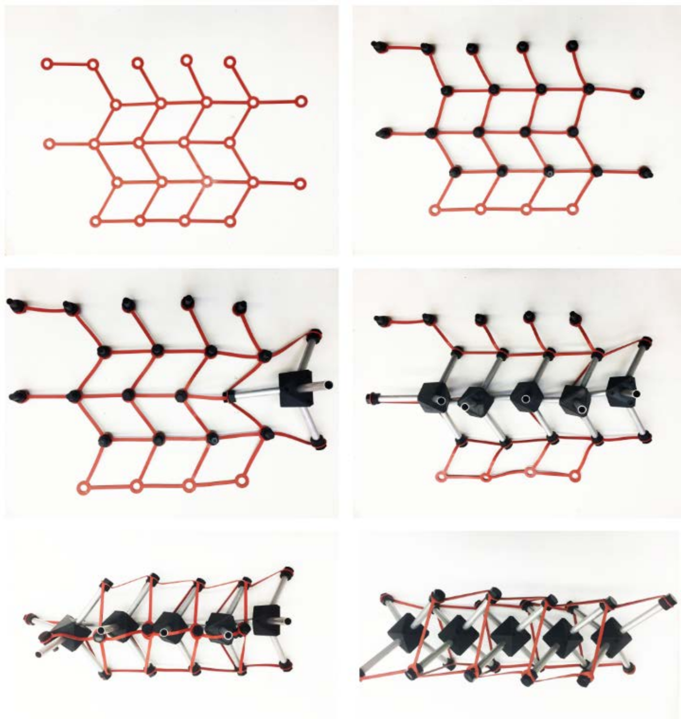


FIGURE 8: Step-by-step assembly sequence of a spine tensegrity static model.

QUANTIATIVE RESULTS: ASSEMBLY TIME

Elastic lattice designs for all three types of tensegrity robots were assembled multiple times to quantify improvements in their use. Table 2 shows the results of these trials and compares them with the general assembly times for previous robot designs, performed by members of the BEST Lab who had experience assembling traditional cable-and-spring robots. The elastic lattices significantly reduced assembly times by as much as an order of magnitude for the 6-bar and spine.

TABLE 2: ROBOT ASSEMBLY TIME COMPARISON.

Robot	Old Method	Elastic Lattice
6-Bar Sphere	1-2 hrs	77 s $\pm$ 24 s (N = 10)
12-Bar Sphere	1-2 hrs	5-10 min
Spine	3-5 hrs	6 min 14 s $\pm$ 97 s (N = 8)

CONCLUSION

The newly developed rapid prototyping method using modular elastic lattices has simplified the traditional methods of building tensegrity structures. As such, we were able to shorten the time for assembly of a static structure from one hour to within a few minutes. In addition, we were able to modify the static structure into an actuated robot by attaching actuators and a controller; the total assembly time of an actuated robot using this prototyping platform is less than a hour.

In addition, this paper illustrated the extensibility of the platform for related applications, such as the rapid prototyping of 12-bar and spine tensegrity structures. For researchers, this rapid prototyping platform can significantly reduce the complexity of constructing tensegrity structures.

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