Modular, Elastic Lattice Platform for Rapid Prototyping of Spherical Tensegrity Robots*

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***Abstract*—This paper presents a new platform for prototyping spherical tensegrity robots that significantly reduces the time required for manufacturing and assembly. This simplifies tensegrity system design and allows for more scientific experiments to be performed in less time. This work describes the design architecture of the TT-4$_{mini}$, an example of a robot that uses this prototyping platform. The TT-4$_{mini}$, developed at UC Berkeley in collaboration with NASA Ames, is a lightweight, low cost, modular, and rapidly prototyped spherical tensegrity robot. In order to demonstrate the platform's use for scientific experiments, we show the use of the TT-4$_{mini}$ to achieve uphill climbing, which has not been performed by any other spherical tensegrity robot. This paper discusses preliminary observations on the system's performance in uphill climbing from simulations and testing, including evidence of climbing up to 13 degree inclines. Furthermore, this paper illustrates the use of the platform for a related application, the rapid prototyping of 12-bar tensegrity structures.**

I. Introduction

Tensegrity structures consist of rods suspended in a network of cables, where the rods and cables experience only compression and tension, respectively, under equilibrium conditions. Because there are no bending moments, tensegrity systems have inherently fewer failure modes. They are also naturally compliant, exhibiting the ability to distribute external forces globally. This compliant characteristic makes tensegrities a great candidate for co-robotic applications, which require low risk for human injury during operation.

The UC Berkeley Emergent Space Tensegrities (BEST) Laboratory has been collaborating with NASA's Ames Research Center on using tensegrity structures as the basis for the next generation of space exploration robots. A tensegrity robot can be used as both a lander and a rover since it has the ability to passively distribute forces globally. This ability can provide shock protection from unexpected forces and makes them a robust robotic platform for mobility in an unpredictable environment.

II. Prior Research

Tensegrity structures were first introduced in the mid-1960's by the three scientists, Richard Buckminster Fuller [1], David George Emmerich [2], and Kenneth D. Snelson [3]. The structures' passive combination of cables-in-tension and bars-in-compression became a significant design feature in several architectural and sculptural structures [4, 5].

The idea of applying the same principles to an active combination of cables-in-tension and bars-in compression has inspired several scientists and engineers to build soft tensegrity robots. "Due to their high strength-to-weight ratio, robustness and deformability, tensegrity structures are an appealing platform for emerging field of soft robotics, with applications ranging from search-and-rescue to field-deployable structures [6]."

The Reservoir Compliant Tensegrity Robot (ReCTer) and the Spherical Underactuated Planetary Exploration Robot ball (SUPERball) are two examples of these soft robots, both of which were prototyped at NASA's Ames Research Center [7, 8].

The BEST Lab at the University of California, Berkeley has collaborated with NASA's Ames Research Center to design, develop, and prototype several versions of a tensegrity robot. The TT-1 tensegrity robot demonstrated a possible active structural design. In this prototype, the bars were made from balsa wood and the controller unit was placed in the center of the structure. This robot, with the help of 24 linear actuators connecting the ends of each of its rods to the other adjacent ends (nodes), was the first in the BEST lab to be capable of locomotion.

The TT-1 version contributed significantly to later generations of tensegrity robots. The next-generation robot, the TT-2, had substantially improved functionality and materials. The balsa wood bars were replaced with fiberglass struts, and upgraded parts and enhanced algorithms gave the robot better locomotion [9].

The third-generation tensegrity robot, TT-3, underwent fundamental changes in mechanical design (see Fig. 1). While the TT-2's 6-bar structure was kept, the fiberglass struts from the previous version were replaced with aluminum rods. The central controlling unit, hanging from the center of the structure, was divided into 6 separate control units, and each control unit was placed on its own respective rod.

Additionally, linear actuators were replaced with cable-spring-motor systems, which increased the TT-3's locomotion speed from 1 cm/s to 5 cm/s.

III. 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

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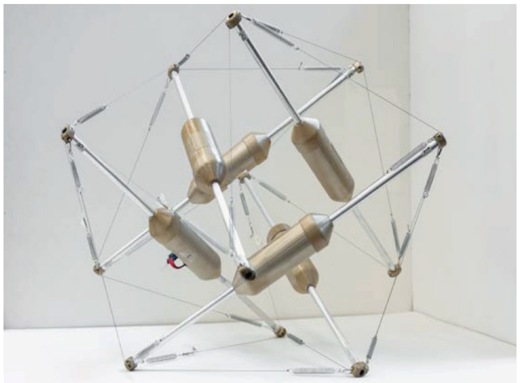

Fig. 1. Tensegrity robot TT-3 prototype

intermediary steps of assembly, forces are unevenly distributed and the structure is difficult to constrain. It is also easy to make mistakes in assembly, such as connecting the wrong tension and compression members. 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 to assemble.

Since the research team at UC Berkeley has been simulating, designing, and prototyping various tensegrity systems, it is critical to develop an efficient prototyping platform for rapid creation of new tensegrity robots to experiment with novel concepts.

IV. 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. Then a new elastic medium, sheets of silicone rubber, could be used to construct the tension members.

It was observed that the tension members of the six-bar robot form an icosahedron. Thus it was expected that a regular pattern of triangles would map the structure in the 2D plane. This was 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 Fig. 2, were needed to form the six-bar tensegrity structure.

The first elastic prototypes of the lattice for a six-bar spherical tensegrity used 0.02 in. thick, 20A durometer silicone rubber using a single-beam Universal Systems laser cutter. The lightness of the silicone rubber caused challenges in the laser cutting process as it was so light that the venting system of the laser cutter caused it 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 a number of prototypes using this silicone lattice, it became clear that the 0.02 in. thick, 20A durometer silicone rubber did not have the right material properties for our 6-bar tensegrity application. The hardness and thickness of the

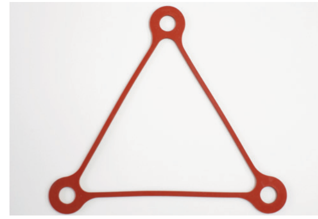

Fig. 2. Modular elastic lattice prototype made with 60A durometer rubber.

silicone rubber was not providing 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 was just etching 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.

The elastic prototypes made with 60A durometer silicone rubber (Fig. 2) were much stiffer than the previous versions, and they could withstand higher tension. Thus these prototypes better demonstrated the unique characteristics of tensegrity structures.

V. Use of the Elastic Lattice to Assemble a 6-bar Tensegrity Structure

The modular, elastic lattice enables rapid prototyping and testing of tensegrity structures. Production of the elastic lattice is efficient, as laser cutting is straightforward and fast, and the timeline of assembly of any tensegrity structure is vastly accelerated by the use of an elastic lattice, so that assembly is on the order of a couple minutes rather than an hour. Many other tensegrity structures have tension members arranged with triangles as the basic unit, so this methodology can be used to prototype tensegrity structures other than the 6-bar structure.

Modularity is a benefit for early-stage construction and for more complex structures. For the six-bar tensegrity, it was found that combining the eight triangles into a single piece

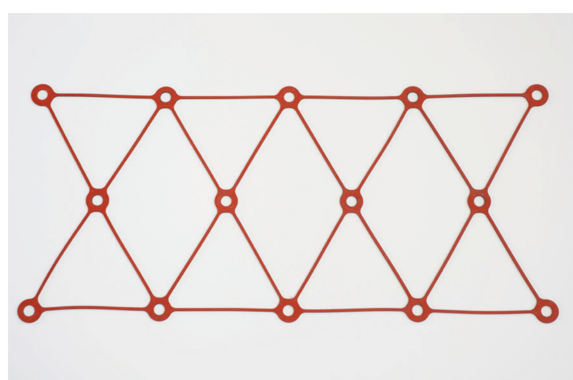

Fig. 3. Single-piece elastic lattice for 6-bar tensegrity structure.

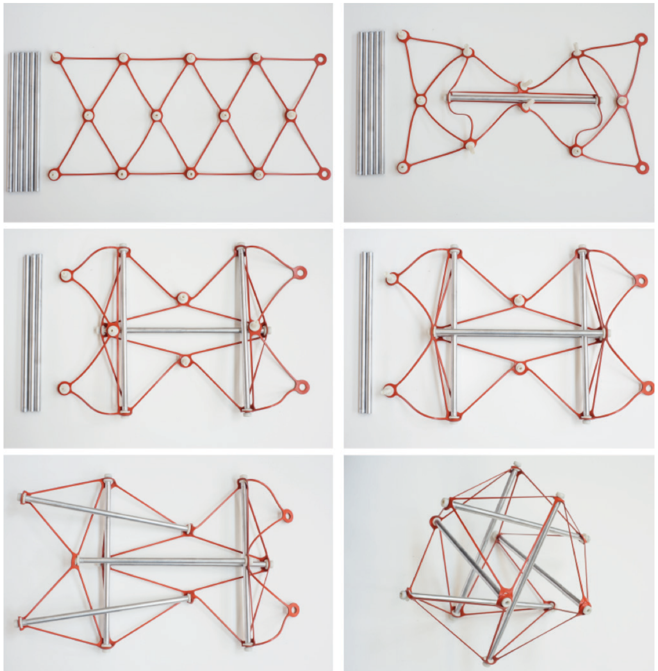

Fig. 4. Step-by-step assembly sequence of a 6-bar tensegrity static model.

made assembly quicker and simpler. The single-piece lattice is shown in Fig. 3. This single-piece lattice is used to demonstrate assembly.

Fig. 4 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. We used 3D printed endcaps 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 (or eight of the rubber elastic triangle lattices), twelve of the 3D printed endcaps, and six of the aluminum rods. The result is a tensegrity structure that can be built in a few minutes by a single person.

VI. Modular, Elastic Lattice Platform for an Actuated 6-bar Tensegrity Robot

While a static model is used to demonstrate the basic concept of a tensegrity structure, an actuated tensegrity robot is required to gain scientific insight into its capabilities. To do so, a 6-bar tensegrity robot with six actuators was constructed, which we refer to as TT-4_{mini}, the 4^{th} generation spherical tensegrity robot of miniature size (Fig. 5). The TT-4_{mini} makes use of small components and the modular, elastic lattice to allow for rapid hardware iterations and performance testing. The design of the robot is described in order to illustrate the use of the prototyping platform.

A. Modular Actuation Unit

Actuators are required for rolling locomotion through shape-shifting in a tensegrity structure. Shape-shifting is used here to change the projected center of mass of the robot by adjusting tension within the elastic lattice network, which effectively causes the robot to perform a punctuated rolling

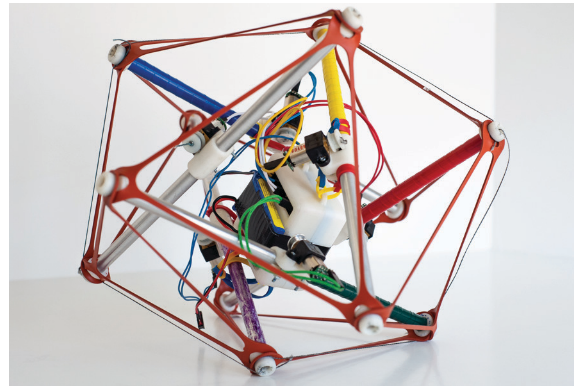

Fig. 5. TT-4_{mini} prototype.

motion [10]. Twenty-four actuators are needed to achieve full actuation of the system, but six actuators still allow for complete forward locomotion and are used for simplicity. The 6-volt, 298:1 DC micro-gear motor from Pololu [11] was selected as the actuator. Each motor is positioned on the center of a rod, and adjust the shape of the system by spooling in cables to change the distance between endcaps.

The actuation unit conducting this line of motion is entirely modular and comprised of four principal components: an ABS plastic motor mount that attaches to the structural aluminum rods, the motor, an aluminum spool, and a plastic motor cover. An assembly of the unit is shown in Fig. 6.

The aluminum spool is secured to the motor's shaft with a set screw. The rod is slid through the motor mount, atop which the motor and its cover are fastened using two screws and bolts. The cable is slid from the spool through the central opening in the motor mount and directed outward to one of the rod's ends. It is then tied to the endpoint of another rod. During actuation, the motor's shaft rotates the spool which permits contraction and retraction.

The modularity and simple assembly process of the actuation unit greatly facilitate accessibility for a wide range of users, while remaining cost effective.

B. Central Electronic Controller

A central electronic controller was selected to control the actuators of the TT-4_{mini}. It is protected by a plastic case and suspended in the center of the robot. This unit contains the electrical and controller components (Table I), which will be

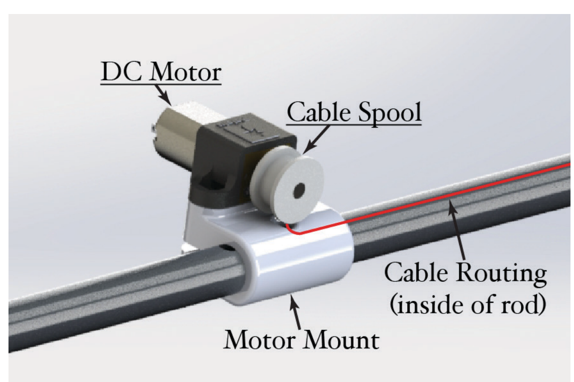

Fig. 6. Modular actuation unit attached to the aluminum rod.

discussed in the following sections. The circuit diagram is given in Fig. 7.

1) Microcontroller

The Arduino-based board Sparkfun Pro Micro [12] was the microcontroller selected for this project. It has 18 I/O pins, hardware serial connection, and internal voltage regulator, among other features. Twelve digital output pins were connected to the motor drivers to control the direction of the motor's spin.

Three routines were created to receive character values associated with the list of digital output pins. The first routine allowed the user to move the motors by using delay functions, and calibration was done by testing. The second routine allowed for the possibility to store the times needed to move each motor forward and backwards in 12 different registers of the microprocessor. These times were calibrated by the user using an Android application that we developed. The third routine was similar to the second one but without delays and calibration. The application was also modified to allow the user to control forward and backwards motion of the motors.

2) Motor Drivers

Three dual H-bridge, model L293D motor drivers were used to power and control the 6 DC motors. Each motor driver allows currents up to 1 A per channel and a peak current of 1.2 A.

3) Wireless Communication

Bluetooth technology is used as the main means of communication between the tensegrity robots and the corresponding Android mobile application that serves as a remote control.

Two Bluetooth modules, HC-05 and HC-06 Bluetooth-to-UART Serial Wireless Adaptor, were considered. Both of these met our requirements for signal coverage and were relatively low cost. The difference between them is that the former can act as both a master and slave device whereas the latter can only operate as a slave device. Since for the present application, only a slave device is required, the Bluetooth module chosen for the robot microcontroller is the HC-06. It creates a wireless serial data bridge between the connected microcontroller and smart devices that have installed the remote-control Android application.

TABLE I ELEMENTS OF THE CENTRAL ELECTRONIC BOARD

Element	Type/Model	Quantity
Battery	E-Flite 430 mAh 2S 7.4V 20C LiPo	1
Microcontroller	Sparkfun Pro Micro -5V/16 MHz	1
Motor driver	L293D dual H motor driver	3
Bluetooth module	HC-06 Bluetooth module	1

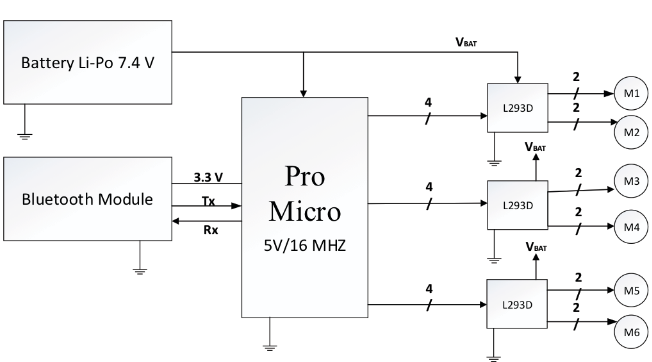

Fig. 7. Circuit diagram of the central electronic controller.

C. *User Controller*

The Android application was selected as the user controller to allow for accessibility in the user interface. The remote controller is part of a master-slave communication system, where the tensegrity robot contains the slave device and the Android device is the master.

VII. ROBOT BEHAVIOR IN LEVEL GROUND ROLLING AND UPHILL CLIMBING

A. *Simulation of Actuation Policies*

One of the unique challenges that is encountered in tensegrity robotics is the development of policies for actuation. We chose to implement a simple actuation scheme on TT-4_{mini} in which only one cable is retracted at a time. The scheme chosen for both level ground rolling and uphill climbing was the same that allowed for single-cable, forward locomotion on flat ground in previous work [13].

As there had been no previous work on uphill climbing, the actuation scheme was simulated for uphill climbing on a robot of the scale of TT-4_{mini} using the NASA Tensegrity Robotics Toolkit (NTRT) [14]. It was found that the robot could climb up an incline of 10 degrees in simulation using this actuation policy. Simulation results for uphill climbing from NTRT are shown in Fig. 8 and Fig. 9.

B. *Hardware Experiments*

Level ground rolling and uphill rolling on an incline were the two main experiments performed on the TT-4_{mini} in order to observe the behavior of the robot. To better simulate tensegrity structures for space exploration applications, it is important to understand the tensegrity robot's ability to operate on various terrain through hardware prototype testing.

1) Level Ground Rolling

TT-4_{mini} prototype's first experiment was to perform flat surface punctuated rolling, accomplished through shifting its center of mass by deforming the base triangle with a single

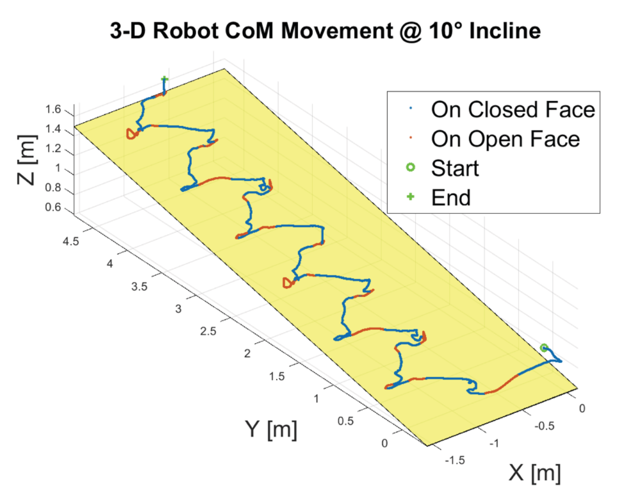

Fig. 8. Trajectory of robot center of mass position.

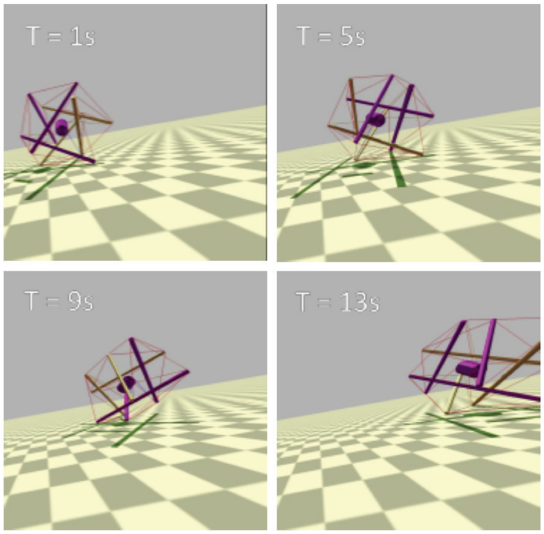

Fig. 9. 6-bar tensegrity robot rolling up a 10-degree incline with single-cable actuation.

cable contraction. This method has been successfully demonstrated with the TT-3 robot [15], and with the single-cable actuation policy, the robot reliably performed punctuated rolling in a straight line on a level ground, as shown in Fig. 10.

2) Uphill Rolling on an Inclined Surface

In order to test uphill climbing, we constructed an adjustable testing platform that allows the incline surface to be changed to the desired angle. We ran several trials in which we incrementally increased the incline angle after the TT-4_{mini} was able to perform a complete 6-step rolling sequence at the set incline. We were successful in performing uphill climbing up to 13 degrees with a single actuation policy.

Fig. 11 shows the TT-4_{mini} climbing uphill. This is first time a tensegrity robot has shown the possibility of performing uphill climbing through hardware experiments.

VIII. Use of the Modular Elastic Lattice for Rapid Prototyping of 12-Bar Tensegrity Structures

In addition to the BEST Lab's research in 6-bar tensegrity robotics, we are investigating 12-bar tensegrity structures as a new platform for tensegrity robots. Our lab's previous work in hardware development of spherical tensegrity robots has been focusing on 6-bar structures. The 12-bar structure is the next-largest symmetric structure, and we anticipate that its greater size and increased number of actuation routes will offer benefits in terms of actuation efficiency, impact characteristics, and payload-to-deadweight mass ratio.

There are several symmetric 12-bar tensegrity structures. Our lab is conducting a design study of three 12-bar tensegrity structures to select one that will best serve the design objectives of the robot. These structures are named cube, octahedron, and rhombicubotahedron. Cube and octahedron are so named for the shapes from which the rods of the structures evolve [16]. The rhombicubotahedron is so named for the shape of its exterior lattice.

The rubber lattice prototyping method has allowed us to rapidly build these three tensegrity structures. Following the same methodology as was used for the six-bar tensegrity

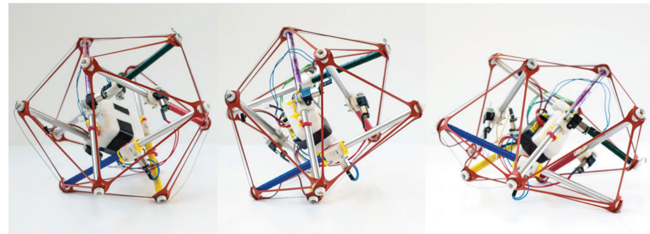

Fig. 10. TT-4_{mini} prototype rolling on a flat surface with single actuation.

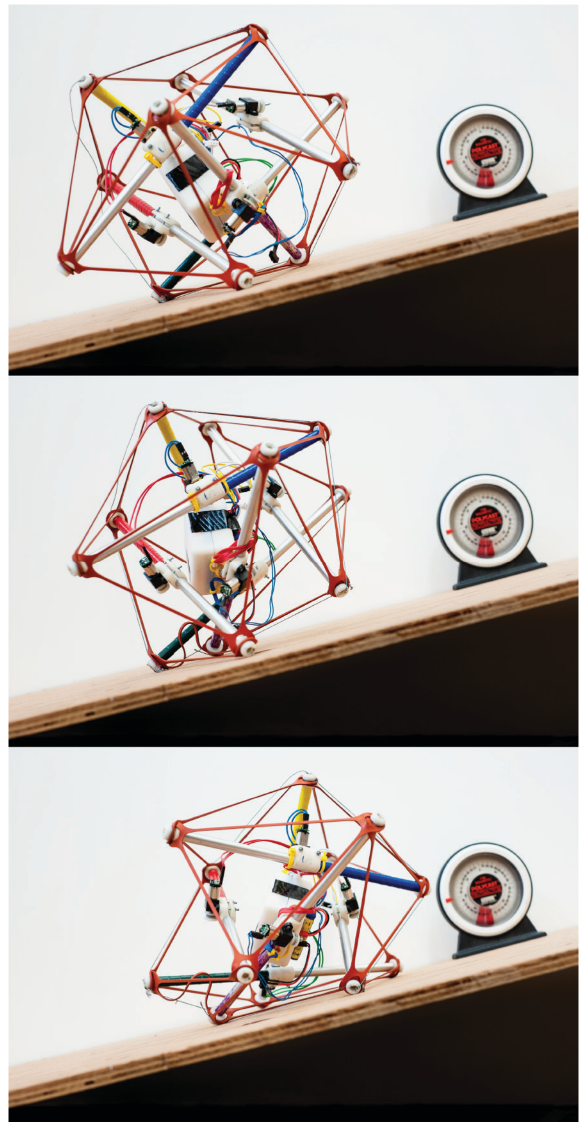

Fig. 11. TT-4_{mini} prototype climbing up a 13-degree incline surface with single actuation.

structure, we created a lattice for each of the 12-bar structures by observing geometric patterns and designing modular pieces. 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 structural prototype of the octahedron is shown in Fig. 12 as an example.

The future work is to use these rapid prototypes to empirically evaluate each structure using the metrics of actuation efficiency, impact orientation sensitivity, and

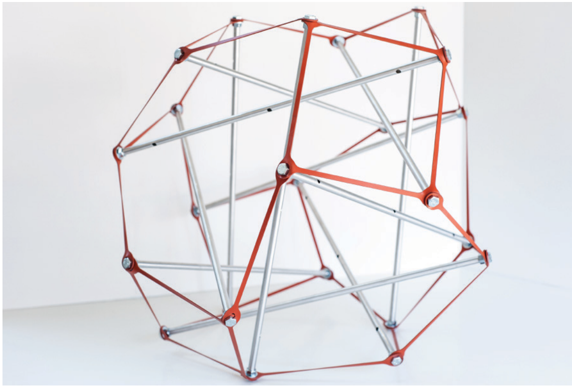

Fig. 12. Octahedron 12-bar tensegrity structure prototyped using lattice platform.

payload-to-deadweight mass ratio. We will evaluate actuation efficiency by actuating the system and measuring power required to achieve locomotion. We will evaluate impact orientation sensitivity by conducting drop tests and observing the impact deformation characteristics. Lastly, we will evaluate payload-to-deadweight mass ratio by attaching weights to the center of the structure and recording its effects on locomotion and impact behavior.

IX. 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 a few minutes. In addition, we were able to modify the static structure into an actuated robot by attaching modular actuation units and central controller; the total construction time of an actuated robot using this prototyping platform is less than one hour.

Our latest tensegrity prototype, TT-4_{mini}, was built using the modular elastic lattice prototyping system. The TT-4_{mini} was used to test actuation policies for climbing on an inclined surface, which marks the first successful demonstration of uphill inclined climbing using a tensegrity robot.

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

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References

[1] B. Fuller, "Tensile-Integrity Structures". United States Patent 3 063 521, 13 September 1962.

[2] D. G. Emmerich, "Construction de réseaux autotendants". France Patent 1 377 290, 28 September 1964.

[3] K. D. Snelson, "Continuous tension, discontinuous compression structures". United States Patent 3 169 611, 16 February 1965.

[4] M. Pars, "Tensegrity," 2016. [Online]. Available: http://www.tensegriteit.nl/e-architecture.html.

[5] K. Snelson, "Kenneth Snelson; Art and Ideas," 2016. [Online]. Available: http://kennethsnelson.net/.

[6] M. Khazanov, J. Jocque and J. Rieffel, "Evolution of Locomotion on a Physical Tensegrity Robot," in *Fourteenth International Conference on the Synthesis and Simulation of Living Systems (ALIFE 14)*, New York, NY, 2014.

[7] K. C. J. Despraz, A. Iscen, A. P. Sabelhaus, J. Bruce, B. Schrauwen and V. SunSpiral, "Design and control of compliant tensegrity robots through simulation and hardware validation," *Journal of the Royal Society Interface,* vol. 11, no. 98, 2014.

[8] A. P. Sabelhaus, J. Bruce, K. Caluwaerts, P. Manovi, R. Firoozi, S. Dobi, A. M. Agogino and V. SunSpiral, "System Design and Locomotion of SUPERball, an Untethered Tensegrity Robot," in *IEEE 2015 International Conference on Robotics and Automation*, Seattle, WA., 2015.

[9] K. Kim, A. K. Agogino, A. Toghyan, D. Moon, L. Taneja and A. M. Agogino, "Robust learning of tensegrity robot control for locomotion through form-finding," in *IEEE 2015 International Conference on Intelligent Robots and Systems*, Hamburg, Germany, 2015.

[10] K. Kim, A. K. Agogino, A. Toghyan, D. Moon, L. Taneja, and A. M. Agogino, "Robust learning of tensegrity robot control for locomotion through form-finding," in *Intelligent Robots and Systems (IROS), 2015. IEEE Int. Conf. on.* IEEE, 2015, pp. 5824-5831.

[11] Pololu official webpage, "298:1 Micro Metal Gearmotor HPCB 12V with Extended Motor Shaft", viewed 7 September 2016, https://www.pololu.com/product/3056

[12] Sparkfun official webpage, "Pro Micro & Fio V3 Hookup Guide", viewed 6 September 2016,<https://learn.sparkfun.com/tutorials/pro-micro--fio-v3-hookup-guide

[13] M. Shibata, F. Saijyo, and S. Hirai, "Crawling by body deformation of tensegrity structure robots," in *Robotics and Automation (ICRA), 2009. IEEE Int. Conf. on*. IEEE, 2009, pp. 4375-4380.

[14] NASA Tensegrity Robotics Toolkit, [Online]. Available: https://ti.arc.nasa.gov/tech/asr/intelligent-robotics/tensegrity/NTRT/

[15] L-H. Chen, K. Kim, E. Tang, K. Li, R. House, E. Jung, A. M. Agogino, A. K. Agogino, and V. Sunspiral, "Soft spherical tensegrity robot design using rod-centered actuation and control," in *ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2016)*. ASME, 2016.

[16] XOZZOX Design Consult – the art and engineering of tensegrity structures. http://www.xozzox.com/index.html/