Proof-of-concept Designs for the Assembly of Modular Dynamic Tensegrities into Easily Deployable Structures

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Abstract

Dynamic tensegrity robots are inspired by tensegrity structures in architecture; arrangements of rigid rods and flexible elements allow the robots to deform. This work proposes the use of multiple, modular, tensegrity robots that can move and compliantly connect to assemble larger, compliant, lightweight, strong structures and scaffolding. The focus is on proof-of-concept designs for the modular robots themselves and their docking mechanisms, which can allow the easy deployment of structures in unstructured environments. These mechanisms include (electro)magnets to allow each individual robot to connect and disconnect on cue. An exciting direction is the design of specific module and structure designs to fit the mission at hand. For example, this work highlights how the considered three bar structures could stack to form a column or deform on one side to create an arch. A critical component of future work will involve the development of algorithms for automatic design and layout of modules in structures.

1. Introduction

This work proposes the development of modular, dynamic tensegrity structures, which have the capability to self-actuate, deform and then connect to form a larger structure. In the context of this objective, this paper investigates and evaluates one possible direction for connecting modular dynamic tensegrities. Multiple alternative docking mechanisms were considered given the literature (Zhang et al. 2017). A versatile option identified corresponded to electromagnets, which still raise some concerns in terms of: a) the strength of the connection that they can provide and b) the potentially stringent requirements for the proximity of the nodes before connection can be achieved. In terms of the first concern, this work provides the results of tests regarding the strength of the links achieved between pairs of modular tensegrities connected by electromagnets as well as measurements regarding the ability to deform while connected. Both of these aspects are crucial to success in a real-world scenario.

1.a. Benefits of Modular Dynamic Tensegrities

Due to their efficient design, tensegrity-shaped robots are generally inexpensive and more flexible than traditional rigid robots. These traits along with other advantages, such as low weight, compliance, etc, give them unique applications (Skelton et al. 2001). Inspired by similar structures in nature, tensegrities have been and can be applied to many man-made structures (Ingber 1998; Levin 2002). Their uses include: temporary bridges, columns, arches, and other scaffolding. These uses are similar to their application in architecture given that the distribution of forces in tensegrities allow them to be resistant to external impact (Heartney 2009; Gilewski et al. 2015; Pars 2016).

In an unknown, unstructured environment, such as a planetary surface, the use of modular tensegrities can be invaluable. Tensegrity-based exploration strategies and designs are already being tested for planetary exploration (Agogino et al. 2013; SunSpiral et al. 2013). Given their minimalistic design, tensegrities allow for the deployment of many more modules for the same cost compared to traditional, rigid, heavy robots. This makes them ideal for modularization since it makes it possible to deploy multiple instances during a mission and for each machine to both deform individually or manipulate itself to connect to the next. Furthermore, tensegrities naturally absorb impact well and can be dropped from space with fewer aids to slow them down (Caluwaerts et al. 2014). On the surface, their ability to connect and disconnect allows them to be very flexible in application. They could use their numbers to quickly clean ducts (Friesen et al. 2014) or explore the unfamiliar terrain (Furuya 1992). In emergency situations the modules could connect to form temporary structures or perform search and rescue missions.

1.b. Challenges of Modular Dynamic Tensegrities

A significant portion of previous work in tensegrities involves six-bar structures. An example of the shape can be seen in Figure 1a. While these have their uses, when modularization is concerned, the geometry of three-bars give them unique advantages. An example of this includes forming any temporary structure that requires a pole-like shape such as columns or bridges. When forming a column, three-bar tensegrities could simply stack together; if six-bar tensegrities were stacked, the resulting structure would be wider and less uniform. Furthermore, modular robots require duplicates to function at full capacity. The simpler structure of three-bars typically allow for fewer parts than other tensegrities. This can reduce costs and allow for more robots to be deployed at one time. In this model, the majority of the cost involved is the 9 linear actuators; a six-bar model would require 24 linear actuators.

Towards exploring modular dynamic tensegrities, this work built on top of designs aimed at rapid prototyping of cable-driven tensegrities (Kim et al. 2014), which employed elastic cords, carbon fiber bars and linear actuators. An example structure built given this design is available in Figure 1b below.

Extending this design towards modular structures that can connect themselves poses multiple difficulties. For instance, the strategy employed to attach the elastic cords was to loop the ends through a hole in the carbon fiber bars and the linear actuators, then tie the ends together. It was difficult to manually tie the cord when it was fully stretched and the cord was prone to snapping. The carbon fiber tubes also posed difficulties. While lightweight and strong, carbon fiber is not easy to drill into. This made the process of creating precise holes in each tube challenging. Alternatives to this could include using different materials or tying the elastic cord to a modified version of the 3D printed endpoints.

Furthermore, the use of electromagnets for connecting pairs of tensegrities came with its own problems. These magnets constantly consume electricity to maintain their magnetic quality and easily heat up over time. The heat combined with the metallic surface makes it extremely difficult to attach the electromagnets to the endpoints, especially when the magnets are pointing directly downwards. Different alternatives were attempted including different types of glue and external attachment mechanisms. Significant quantities of glue were needed to hold the magnets to some degree of success.

1.c. Novelty

This work provides a proof-of-concept for a novel endpoint design allowing for the modularization of three-bar tensegrity robots. 3D printing is used to create these endpoints and allows for rapid prototyping of different models. Embedded in these endpoints are electromagnets, which enable the modules to attach and detach at will. In a practical application this would be important to the intentional connection of the corresponding points and the avoidance of accidental connections.

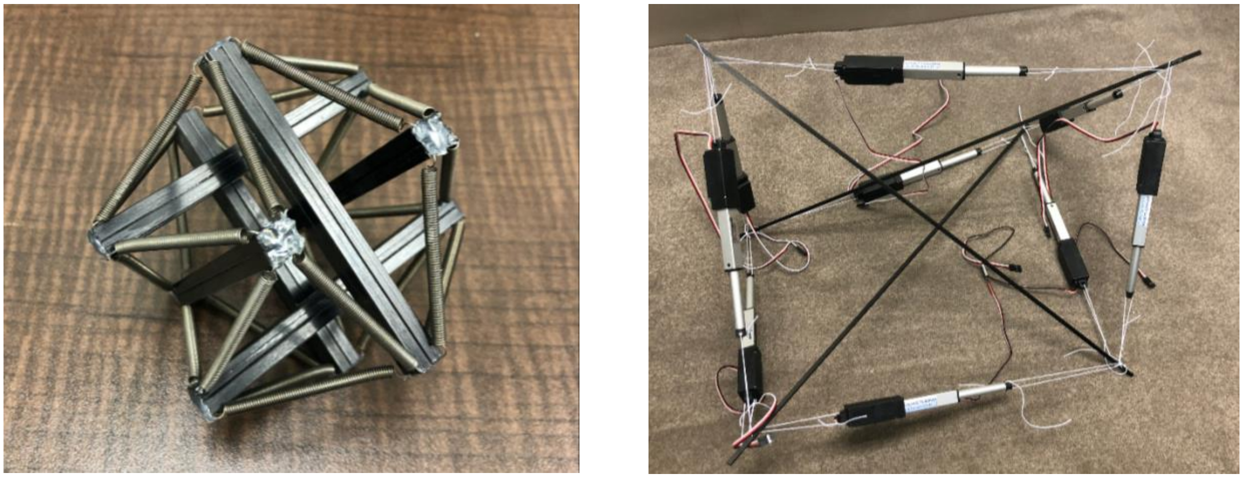

Figure 1- (a) Small six-bar model (b) Example of Tensegrity model

2. Proof-of-Concept Module

To test the modularization of tensegrities, two three-bar tensegrities were created to serve as the main structures. During construction of the tensegrities, two different types of square carbon fiber tubes were used (one for each tensegrity). This was done to determine if the endpoints could still align and withstand a loss in homogeneity. For each tensegrity, three rods were connected with nine “strands.” Each “strand” is composed of a linear actuator connected at each end to elastic cord tied to the ends of the rods. Two pairs of triangles are created by 6 of the strands. The remaining three are stretched across the bars to connect the triangles.

Table 1- List of Components Used

Component	Quantity
Linear Actuator	9
1 mm Elastic Cord	NA
10mm x 10mm Square Carbon Fiber Tube	3
3mm x 3mm Square Carbon Fiber Tube	3
Arduino Uno	2
Breadboard	1
Power Supply	1
PLA Plastic (For Endpoints)	NA
Electromagnets	6

2.a. Alignment of Modules

For a three bar tensegrity, such as the one discussed in this work, the electromagnets are placed on each of the ends of the bars. While six strands form the edges of two triangle, six magnets form the vertices. Each triangle aligns and connects to a triangle on the next tensegrity using electromagnets. On the ground the tensegrities are held up by three points. When transitioning to the next connected tensegrity, the triangle on the other end of this tensegrity is rotated by thirty degrees (Pinaud et al. 2004). Since each end triangle is equilateral, the adjacent tensegrity can be rotated around to fit the previous triangle in three ways and one way will always have three points touching the ground. In this way, an indefinite number of tensegrities can be linked and stably sit on a flat surface with three points touching. It should be noted however that as the actuators change the lengths, the equilateral triangles could change and thus complicate the connection. The general geometry can be seen in Figure 2.

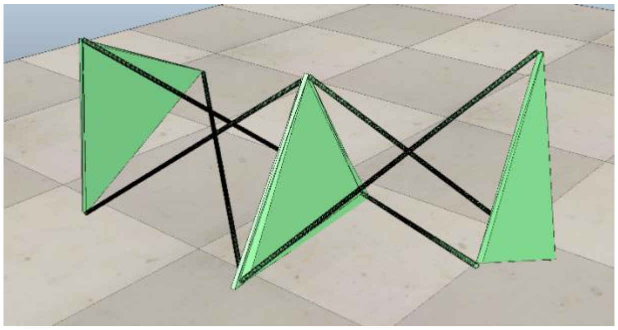

Figure 2- Simulated alignment of two tensegrities

Theoretically it would be possible to align two tensegrities with minimum changes in the actuators with two identical robots. In the simulation it was only necessary to contract one strand for each module. Unfortunately, it is difficult to construct tensegrities identically when manually building them. This is partially due to the elastic cords stretching and making it difficult to maintain the same length in each part of the structure. Thus, in this implementation each elastic cord was manually balanced to form tensegrities that behaved as similarly as possible. As seem in Figure 3, the alignment was not perfect so several actuators were contracted on each tensegrity to correct for it.

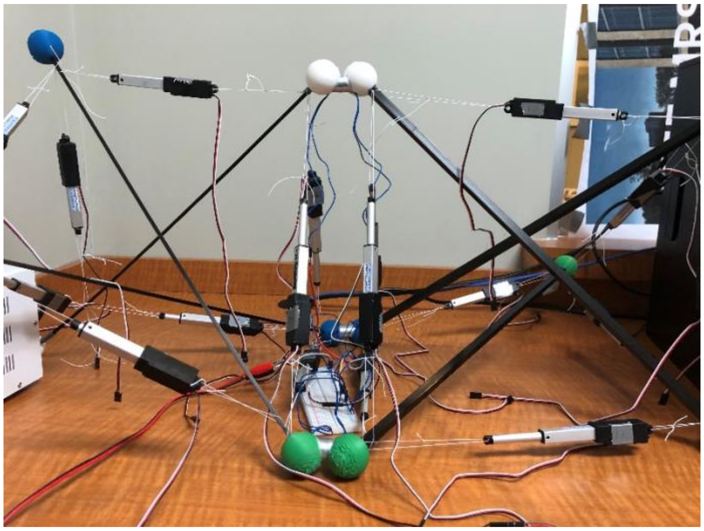

Figure 3- Tensegrities connected by magnets

2.b. Attachment Design and Implementation

At the end of each rod is a 3D printed "endpoint." These were designed to hold the magnets that allow for modulation as well as to connect to the rigid body components of the corresponding tensegrity. 3D printing was chosen for its customizability and easy replaceability. The CAD models for the prints are shown in Figure 4a and 4b. Each endpoint has a slot to insert the carbon fiber and a circular notch to place electromagnets. Furthermore, the circular notch is placed at an angle to allow for the magnets to feasibly touch each other.

In this implementation, two different thickness square carbon fiber tubes were used as bars. Therefore it was necessary to design two different types of endpoints to fit each. Furthermore, square tubes where chosen to stop the endpoints from slipping. This, however, limited the adjustability of the angle that the endpoints had relative to each other. In the future it may be wise to use round tubes with some other method to prevent slipping. A finished endpoint is shown in Figure 4c.

2.c. Powering and Control

Each three bar tensegrity is composed of nine linear actuators and can be controlled by a single Arduino. Currently, each Arduino is tethered to a computer for power. In further implementations each Arduino could be powered by a battery and suspended in the middle of a tensegrity. The magnets are powered by a power supply through a breadboard. These too can, theoretically, be moved to two separate boards suspended in a tensegrity or alternatively connected to the Arduino in order to be controlled automatically.

Figure 4- (a) Endpoint model for thinner-rod tensegrity
(b) Endpoint model for thicker-rod tensegrity (c) Endpoint with magnet inserted

3. Evaluation

3.a. Maximum Deformation

The linear actuators used in this implementation have values ranging from 40 to 150 with 40 being fully retracted and 150 being fully extended. This property was used to test the effect of moving the linear actuators on the strength of the magnets.

Each linear actuator was numbered from 1 to 18 with 1-9 being on one tensegrity and 10-18 on the other. Once the magnets were connected, the position of each linear actuator was recorded. Then a linear actuator's position was changed until a pair of endpoints disconnected or it reached the maximum change from the starting position. If the magnets detached, the position of the linear actuator was recorded. The actuator was then reset to test the next one. In Figure 5a, the initial position is shown. In Figure 5b, a linear actuator has contracted and thus disconnected the top joint.

Figure 5- (a) Tensegrities connected in initial position
(b) Tensegrities disconnected do to a change in a linear actuator

Table 2- Separation Points of Magnets Given Change in Linear Actuators

Linear Actuator	Initial Position	Separation Point	Net Change	Disconnected Joint
1	40	90	50	Green
2	150	70	-80	Green
3	40	SC*	NA	NA
4	40	150	110	Green
5	100	SC/SC	NA	NA
6	40	SC	NA	NA
7	80	SC/50	NA/-30	NA/White
8	40	SC	NA	NA
9	150	60	-90	White
10	150	SC	NA	NA
11	150	110	-40	White
12	40	SC	NA	NA
13	40	SC	NA	NA
14	150	SC	NA	NA
15	40	SC	NA	NA
16	40	SC	NA	NA
17	150	40	-110	White
18	40	SC	NA	NA

*SC = Stays Connected Once Aligned

3.b. Weight Support Tests

One test used to determine endpoints' ability to hold was to hold one tensegrity off the table, held in place by only the magnets connected to the other tensegrity. The magnets being able to hold a robot's weights using its own strength can be useful in many situations. This could range between finishing a task by reaching across a pit to forming a temporary bridge allowing humans or robots to travel across a chasm. Figure 6 depicts a tensegrity completely held off the table by another one through electromagnets. Here the left tensegrity is held down by hand because the weight of a single module is not enough to support another. If there was a third one connected to the left, it is likely that they would be able to hold the right tensegrity without additional weight.

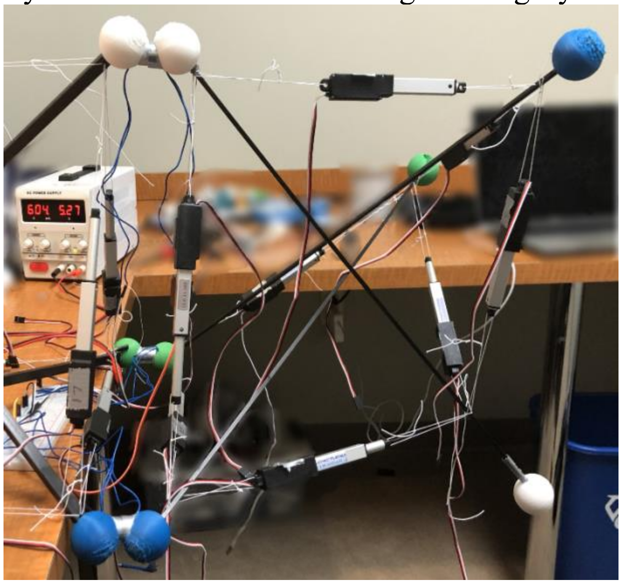

Figure 6- Tensegrity held by magnets off table

Another important test is the ability to hold tensegrities up vertically. This vastly increases the possible applications of modular tensegrities. By stacking, the robots could potentially form support columns or arches for a structure (Ashwear et al. 2016). In Figure 7, two tensegrities are stacked vertically. On the top most triangle of 7a, the side with the white endpoint is clearly higher than the others. This is done intentionally to form the base of an arch.

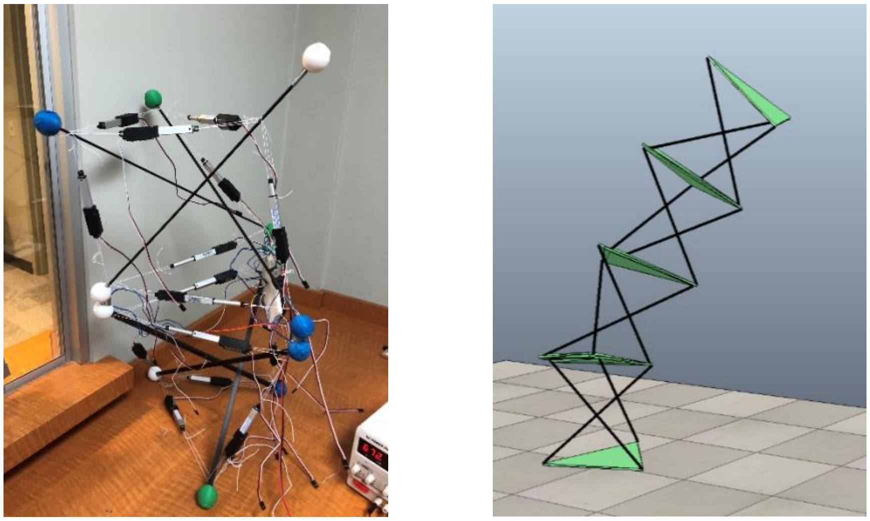

Figure 7- (a) Tensegrities stacked vertically and held by magnets to form the base of an arch (b) Simulated base of an arch

If multiple tensegrities stacked together it is possible to form a full arch potentially capable of supporting other parts. Alternatively, when stacked with all linear actuators extended, the tensegrities would form a column.

Conclusion and Future Improvements

This work provides the groundwork for modular three-bar tensegrities that can connect to one another. As a proof-of-concept design, the tensegrities build in this experiment achieved this objective through the use of electromagnets. They were able to attach and deform to the desired shape. Furthermore, simulations are used to demonstrate that several practical formations are feasible with three-bar tensegrities, such as bridges, columns, and arches. These uses could allow a more advanced set of similar robots to be deployed in unstructured environments, such as a planetary body.

In the current iteration, the magnets cannot be perfectly aligned so that an approaching tensegrity will not be able to connect on its own. The electromagnets are only able to join when within a few millimeters and at the perfect angle from one another. Nevertheless, there are still practical uses of tensegrities that need an outside force to assemble. For example, a person or a mechanical hand could connect the modules, then the tensegrities could actuate to obtain the desired structure.

Although the electromagnets were effective in holding the tensegrities together they constantly consumed electricity and heated up after prolong usage. In future work, alternative connections that passively connect the robots could be used in tandem with the electromagnets. Once the electromagnets are close enough to connect the modules they could be turned off to allow the passive connections to keep them together. For example, one idea considered was to add a ring to hold the modules in place once connected by magnet. This could increase the flexibility of the joint, but make it more difficult to accomplish tasks such as for a module to hold another from a platform.

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