New Approaches to Mechanizing Tensegrity Structures

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ABSTRACT

Tensegrities are unique geometry-based forms with complex distributed behaviour difficult to describe mathematically. Actuating them requires comprehensive knowledge of their action under stress. This paper discusses various ways to actuate tensegrity structures and to manipulate them simply and efficiently. The design strategies center on modular tensegrity construction with controllable tensegral articulations. We describe helical tensegrity masts, segmented tensegrity masts, integrated hubs, bistable tensegrity-prism 3D hubs, telescoping appendages, and interpenetrating modules. Systems built from independent tensegrity modules can form rugged complex three-dimensional linkages that are functional, controllable and energy efficient.

INTRODUCTION

Tensegrity based robots offer many advantages for operating in extreme environments but it can be challenging to design actuated tensegrity structures that are capable of the versatile behaviours required to navigate diverse terrains. We present a set of novel design principles for creating modular tensegrity structures to accomplish this. Individual tensegrity modules have high prestress, making them fairly resistant to deformation. The modules are connected using a variety of tensegral joints, with control lines allowing energy-efficient control over movement at the tensegral joint. This is the first published description of tensegrity design principles developed by one of us through decades of experimentation (Flemons 2007; Flemons 2012a). Employing biomimetic modeling has allowed the creation of relatively simple (non-fractal) tensegrity models that capture force transmission patterns in human and animal movements. We look forward to collaborative work on applying these design principles to tensegrity robotics. Further work is needed on topics such as kinematic analysis, actuation patterns, materials selection and assembly methods. Devising nodal end caps that allow individual tension members to be provisionally tensioned and the structure to be then fine tuned like an instrument would allow for rapid prototyping and optimization of the mechanism.

A *tensegrity* (tensional integrity) is an endoskeletal structure that maintains dynamic stability by isolating compression elements within a tensional matrix. Tensegrities mediate all static and dynamic forces through the prestressed tension system, and can act as dynamically tuned resonating structures. A force exerted upon a tensegrity structure is almost instantly dispersed and spread throughout the entire form. One of the chief strengths of tensegrities is their robustness; if a tensegrity suffers local damage, the structure as a whole can continue to function in a slightly degraded manner.

Tensegrity structures are extremely strong and resilient for their weight. No additional material components are needed to handle shear or torque forces because tensegrities only transmit tension and compression forces. Additionally, a tensegrity structure makes multiple paths available to dissipate forces and maintain integrity. The geometry of the tension net is a dispersion tree – as a force moves through a tensegrity it converges upon a hub where one or more compression members are constrained by multiple tension members. Thus forces have many available paths to follow, both through the tension network along the periphery of the structure and also cutting chordally through the structure by axially loading the compression components.

A tensegrity is a *self-supporting* tensile system that is not dependent on external supports or an external gravity field. Thus it cannot include lever arms or fixed fulcrums. All tensegrities are tension structures but not all tension structures are tensegrities. It is true that a circus tent holds its shape by balancing the compressive forces in the poles with the tension forces carried by the tent fabric and rope cables, but it is not a tensegrity because the whole structure relies on pinning the cables and the poles to the ground. Similarly, a spider web relies on the support of a tree branch; a struggling fly transmits forces throughout the web, alerting the spider, but ultimately the forces are dissipated and resolved by the branch. Many manmade structures employ a tension network to maintain stability – for example sailing rigs, suspension bridges, and radio and TV masts – but these are not tensegrities because they rely on a separate structure for grounding and stability.

Anthony Pugh (1976) gives a detailed taxonomy of tensegrity forms. In a pure tensegrity, struts are not in direct contact with each other but Skelton and de Oliveira (2009) propose an expanded typology of tensegrities that allows two or more struts to be in point-to-point contact. A class 2 tensegrity has two struts in contact at their nodal ends, a class 3 tensegrity has three struts intersecting and so on. In practice, strut and line congestion at the nodal ends mean that few useful designs involve more than two struts touching, and such contact never transmits torque or shear forces across the node.

Tensegral and non-tensegral elements can be combined to form a *hybrid structure* but the advantages of the tensegrity approach may not be fully realized. For example, tensegrity masts can replace rigid components in a traditional articulated-rigid-body design. This offers the advantages of substantially reducing weight while increasing the resilience of the structure. However, the concentration of forces at the connections between tensegral and rigid components makes the hybrid structure likely to fail at the interface. Such concentration of forces does not occur in a pure tensegrity structure, instead every component is integrated into the whole such that a local stress is passed globally through the system. A tensegrity structure is compliant throughout and deforms in response to forces exerted on it.

TRIANGULATION IN TENSEGRITY STRUCTURES

Man-made tensegrity structures have only existed since the middle of the 20th century. The contentious history of the invention is reviewed by Jáuregui (2004). For decades, the principles that govern tensegrity assembly were investigated by only a few, notably the inventor and architect Buckminster Fuller and his former student and artist Kenneth Snelson. Fuller's designs include self-supporting geodesic domes that enclose vast spaces. Snelson created giant sculptures consisting of metal tubes and wire cables. While these creations differ, both are types of stable structures possessing no degrees of freedom and a limited range of oscillatory motion. These complex geometric forms are constrained through complete triangulation of the tensional envelope that encloses them. As discussed below, tensegral joints can be created as breaks in the triangulation.

Snelson designed his famous tensegrity sculptures with careful consideration of triangulation, as explained in Snelson (undated). These fully-triangulated tensegrities bear close resemblance to plants in how they support themselves. Like plants, they lack joints and their range of motion is reduced to oscillations generated by external forces such as wind. They sway slightly but do not collapse unless there is catastrophic failure of the tensional triangulation.

Snelson (undated) describes how he creates a surface triangulation out of struts and tension lines. We supplement Snelson's presentation by deriving a formula for the number of tension lines given the number of struts. As discussed by Eppstein (2017), Euler's Formula states that in a planar triangulation

$$number\_of\_vertices - number\_of\_edges + number\_of\_triangles = 2$$

From this we derive that a fully triangulated tensegrity with k struts contains $5k$-6 tension lines and $4k$-4 triangles. Two types of triangles are illustrated in Snelson (undated). The red type 1 *tension/compression triangles* are formed by one strut and two tension lines. The green type 2 *tension-only triangles* are formed by three tension lines. Each strut participates in the formation of two tension/compression triangles, yielding a total of $2k$ such triangles. The remaining $2k$-4 triangles are tension-only triangles. For example, the six strut tensegrity in Figure 11 has k=6 so the number of tension lines is 5(6)-6 = 24 and the number of triangles is 4(6)-4 = 20. Of these 20 triangles, 12 are tension/compression and 8 are tension-only. As a second example, pages 18 and 22 of Snelson (undated) show how to use *draw* and *sling* tension lines to link three 3-prisms into a column. The resulting column has k=9 so the number of tension lines is 5(9)-6 = 39 and the number of triangles is 4(9)-4 = 32. Of these 32 triangles, 18 are tension/compression and 14 are tension-only.

DESIGNING TENSEGRAL LINKAGES

Creating successful tensegrity articulations requires finding robust strategies for linking tensegrity modules together. The tensegrity modules must be linked into a larger system that articulates while still maintaining redundant force-transmission paths through the global tension network that connects the modules.

A tensegrity joint is really a disjoint. It is a failure or relaxation of the tensional triangulation that stabilizes the structure. Control of tensegral disjunctions differs markedly from control of traditional joints. In a traditional mechanism, revolute and prismatic joints are solid components in revolving or sliding contact. The joints are rigidly constrained to allow for very precise movement within a narrow range of tolerances. Control over range of motion and degrees of freedom is paramount and compliance can be a problem. In contrast, a tensegrity is always provisionally compliant, depending on the degree of prestress created by the current loading of the system. This means that tensegrity joints are not rigid affairs. It is not possible to isolate and manage forces by limiting their dispersal to individual components – forces repercuss through the entire structure. Any force exerted on a tensegrity has a universal effect, propagating almost immediately to all parts of the structure. The only way to stabilize a compliant joint is to add tension to the entire system. Because the individual modules are already highly prestressed, multiple actuator lines become taut and further stiffen the entire mechanism.

As illustrated in some of the following designs, it is best to create tensegral linkages between geometrically matching faces on the tensegrity modules. Each module has polygonal boundary faces defined by tension lines. Triangular faces should mate with triangular faces and squares should mate with squares. Complications arise from a mismatched linkage such as mating a triangle to a square or pentagon, because the forces that pass through the faces are not symmetrically distributed.

TENSEGRITY MECHANISMS WITH CONTROLLABLE TENSEGRAL LINKAGES

We illustrate six tensegrity designs using unactuated physical models. In the future we hope to create actuated prototypes.

1) Helical Tensegrity Mast

Figure 1 illustrates a tightly woven helical tensegrity mast with semi-elastic tension members. This mast is composed of stacked chiral prisms that create untriangulated rhombic facets. Multiple vertical control lines can be used to create sinuous snake like movement, as illustrated in the Flemons (2012b) video. To create a double ‘S’ in a 3 fold prism mast requires six actuator lines: three running freely from the bottom to the top and three attached from the bottom to half way up. Addition of lateral bands of adjustable tension lines allows the mast to extend its length from its resting state. A helical mast is stiffer and more integrated than the segmented mast discussed next and strictly speaking, there are no joints in a helical mast. But the rhombic weave pattern allows it to change shape as required by expanding and contracting like an accordion and also curving like a snake. It is possible to build this mast as a three legged scissor jack by aligning the modules' struts so that they touch but do not carry a compression load across their junction. Skelton and de Oliveriera's (2009) nomenclature would consider this a class 2 tensegrity. The struts meet end to end and hinge inward and outward from the axial centre of the mast. Vertical and lateral control lines can be used to telescope the mast longer or shorter, as illustrated below with Figure 8.

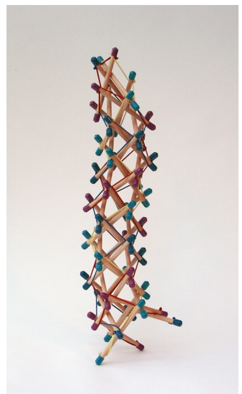

Figure 1. Helical tensegrity mast with six control lines creating an 's' curve.

2) Segmented Tensegrity Mast

This type of mast, illustrated in Figure 2, connects discrete stellated octahedral or tetrahedral tensegrities by means of a separate set of saddle slings. *Saddle slings* are tensioned dihedral rhombuses that connect to four stellated arms from two modules. When struts from two tensegrities are allowed to revolve around the sling connecting them together a universal revolute joint is created. Properly constrained a revolute joint can be reduced to one degree of freedom. A tensegral joint is never going to be completely constrained because the compliant nature of tensegrities means there is always some play in the system. A high prestress in the saddle sling can limit but not eliminate this.

Segmented tensegrity masts can be controlled and stabilized with four vertical lines that have the effect of tightening or loosening each vertical edge of the mast. The masts can also be controlled by cross-linked control lines in both planes, creating a bistable joint that uses less energy to shift from one configuration to the other. Combining this with vertical control lines gives a very fine degree of control to the mast.

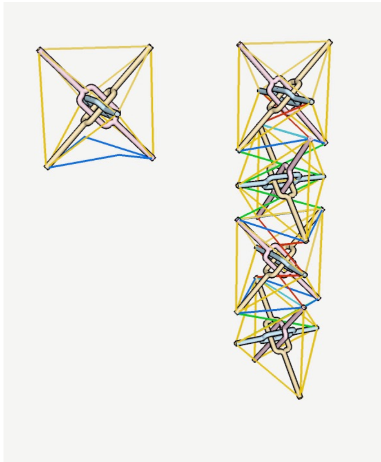

Figure 2. Tensegral octahedral units.
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Figure 3. Non-tensegral octahedral units. © 2017 Tom Flemons

To create a true tensegrity structure, a segmented tensegrity mast must be composed of units that are themselves tensegrities. For ease of construction, the physical model in Figure 3 uses a hybrid structure composed of tensegral linkages between rigid (non-tensegral) stellated octahedron forms. This hybrid structure loses some of the advantages of a tensegrity mechanism: maximal compliance with no shear, torque or bending forces. Figure 2 illustrates a fully tensegral mast composed of stellated octahedral tensegrity modules. Three interlinked chain-like components create a mutually free floating crossing of three struts.

Machine learning algorithms have been used to find control strategies for locomotion of such a segmented tensegrity mast (Tietz et al 2013; Mirletz et al 2014). Figure 12 illustrates with simulation of a tetraspine robot crawling over a wall.

3) Integrated Hub

Many tensegrity modules provide multiple faces and facets which can be used as hubs. For example, the six strut expanded octahedron tensegrity (Figure 11) has three fold symmetry; prism-based appendages can be extended from any face or facet.

Masts based on octahedral symmetry can sprout appendages from any face. As illustrated in Figure 4, a robot resembling an octopus can be built from a central hub with appendages based on helical or segmented masts.

A hub can function like a pelvis in a vertebrate biped or quadruped, integrating a flexible spinal mast with a pair of jointed legs (Figure 5). Similarly a quadruped can be constructed using these basic modules and modifying them as needed (Figure 6). It is tempting to closely mimic biologic structures when designing tensegrity robots that are meant to resemble vertebrates (bipeds or quadrupeds) but practically this can prove to be difficult. The attempts illustrated here are crude low resolution simulations and it may be more useful to design mechanisms that perform similar functions but only superficially resemble living beings.

Figure 4. Integrated hub.

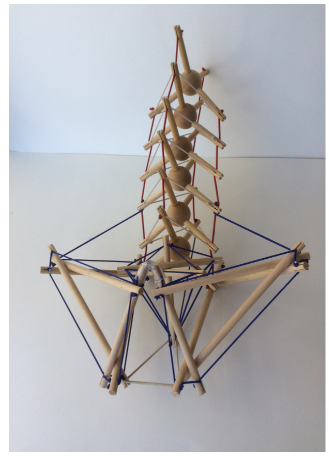


Figure 5. Tensegrity pelvis with spine.

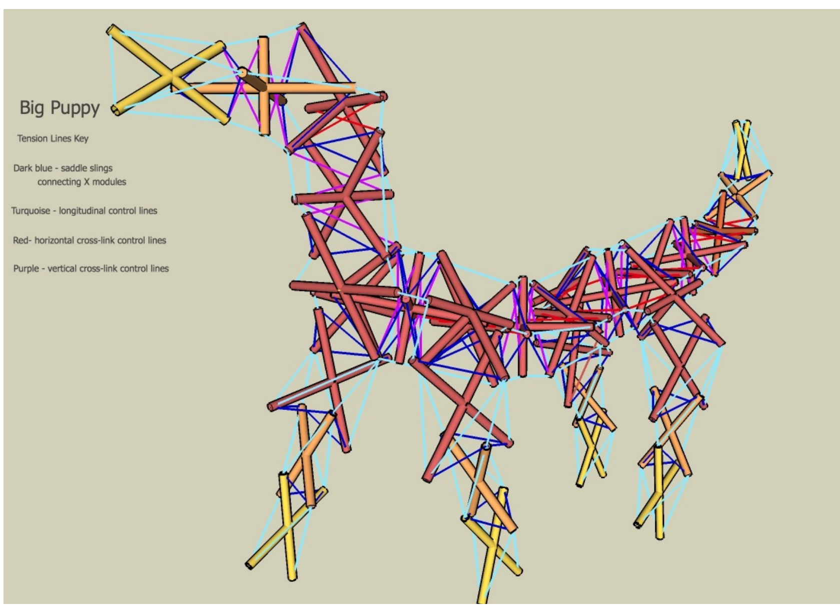


Figure 6. Modular tensegrity construction in the Big Puppy. Dark blue: saddle slings connecting X modules. Turquoise: longitudinal control lines. Red: horizontal cross-link control lines. Purple: vertical cross-link control lines.

4) **Bistable Tensegrity-prism 3D Hub**

Four 3-fold tensegrity prisms can be joined to form a bistable linkage. As shown in Figure 7, the hub scissors back and forth in a complex motion that involves rotation simultaneously along three axes. The triangular tensegrity prisms are loosely coupled in a four fold (rhombic) array that is bistable and wants to resolve into one of two dihedral forms. There are no fixed fulcrums, only tension members connected to the ends of four struts which radiate out into the rest of the mechanism. A saddle sling links the separate integral complexes – each prism is self supporting. This cluster of prisms defines a bistable rhombic hub that flips from one tetrahedral geometry to its opposite. As it does so, it creates two interconnected revolute hinges that fold at 90 degrees to each other. This linkage may prove useful in designing complex tensegrity joints in robotics and prosthetics as well as modelling complex joints in the body. Bistable joints allow for articulated segments to be controlled with minimal energy expenditure.

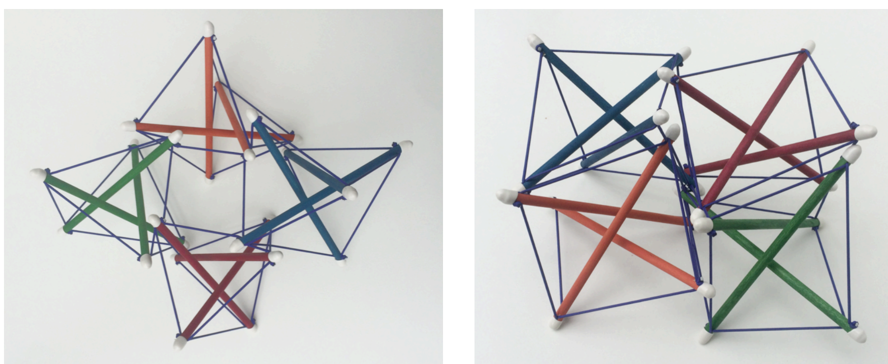
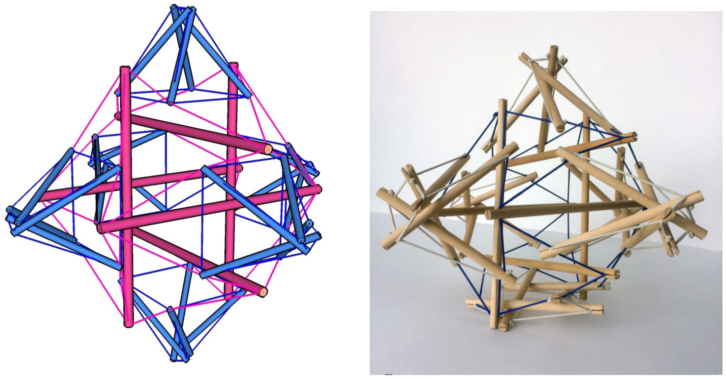


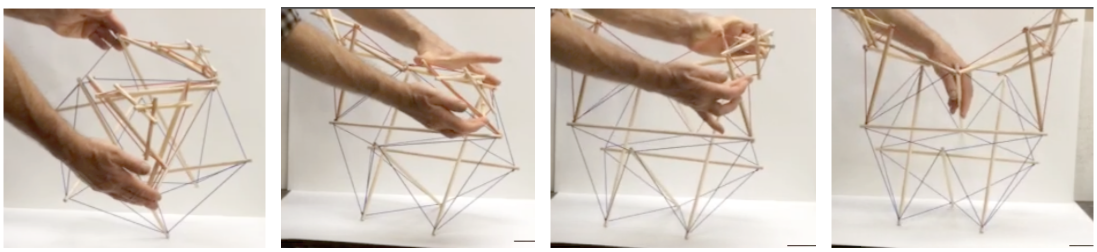
Figure 7. A bistable tensegrity-prism hub. The transition between these two stable states is a complex motion with rotation along three axes. © 2017 Tom Flemons

5) **Telescoping Appendages**

Telescoping appendages can extend and contract through simple actuation which can be used to propel the mechanism forward. As illustrated in Figure 8, telescoping appendages can be created by allowing prism struts to move freely along the tension lines they attach to.

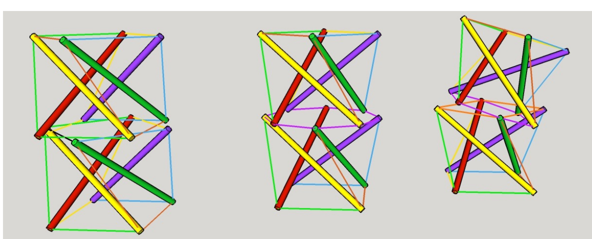


(a)



(b)

Figure 8. Telescoping appendages created by attaching tensegrity prisms to facets of a larger tensegrity. (a) Six telescoping appendages. (b) Appendages can extend and contract through simple actuation, illustrated here on two telescoping appendages in an unactuated prototype.



(a) (b)

Figure 9. (a) Revolute joint formed by a face bond between two four-strut prisms. (b) The hinging action of this joint.

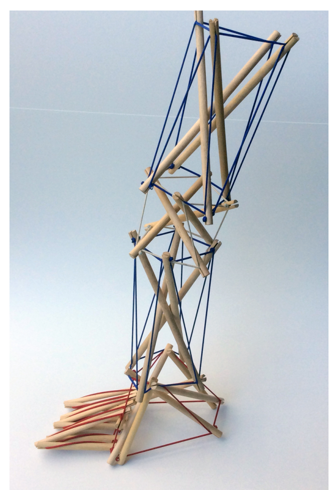


Figure 10. A tensegrity knee joint.

6) Interpenetrating Modules

Another type of revolute joint involves interpenetrating two four-fold tensegrity prisms such that degrees of freedom are limited. Figure 9 illustrates that modules can be interlinked to form something like a knee joint, and it is possible to constrain the rotation by trapping some lines to prevent hyperextension. Figure 10 details how a central prism's top and bottom facets can interface with two longer prisms representing leg components. A double hinge is created that has one degree of freedom without allowing hyperextension.

The above six tensegrity designs provide a versatile foundation for creating controllable articulating tensegrity systems. Designers may find ways of using these linkage techniques in conjunction with other tensegrity construction approaches such as Tachi's (2012) method of turning a surface mesh into a tensegrity, or Moghaddas and Choong's (2016) automated design of multilayer prism tensegrities.

EXISTING WORK ON MOBILIZING TENSEGRITY STRUCTURES

Stochastic tensegrity models of biomechanics

In the last 30 years researchers began to explore applications of the tensegrity principle to complex systems that move. In the 1980s Donald Ingber, a professor at Harvard Medical School, proposed that the cytoskeleton of the cell exhibits tensegral properties. He identified the microtubules that cross the volume of the cell and support the cell membrane as equivalent to islanded compression members in a tensegrity. Further he suggested that cells transmit information across their surfaces by means of mechanotransduction: cell shape alters due to changing composition and lengths of the microtubules, and the altered shape affects other cells embedded in the extracellular matrix (Ingber, Wang, Stamenovic 2014).

More generally orthopedic surgeon Stephen Levin proposed that all systems of living structure at every scale can be understood to behave like tensegrities. Fractal aggregates of cytotensegrities constellate into larger arrays of tensegral connections at ever increasing scales (Levin, 2006). From cells to tissues to organs to structural anatomy, a tensegrity explanation of biomechanics might provide a new paradigm for understanding movement in living structure, both plant and animal (Scarr, 2014). This theory is making inroads in the biological sciences, and a change in how biomechanists view anatomy is occurring. It has become possible to imagine complex articulating life forms moving tensegrally, and to design complex tensegrity mechanisms based upon this insight.

Mobilization by relaxing and restressing the triangulation

Some approaches to mechanizing tensegrity structures are focused on relaxing and restressing the inherent tensional triangulation.

In 2004 Cornell roboticists explored the possibility of generating movement by altering individual tension members of a three strut tensegrity prism (Paul, Roberts, Lipson, Cuevas, 2005). They linked two tensegrity cubes that pull themselves forwards by distorting the rhombic untriangulated facets of each cube. The structure is controlled by a series of linear actuators that alter the lengths of the tension lines defining the cubes. Actuation patterns from a learning algorithm allow the structure to slowly move forward. This structure is not a pure tensegrity system, due to the flexible sleeves used to connect struts from each cube.

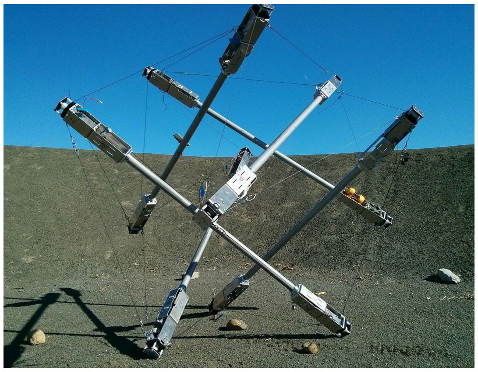


Figure 11. The NASA Superball Bot moves using actuators that change cable length. The compliance of the tensegrity structure absorbs landing impact.
From Wikimedia Commons, posted by Vytas SunSpiral Oct. 2014.

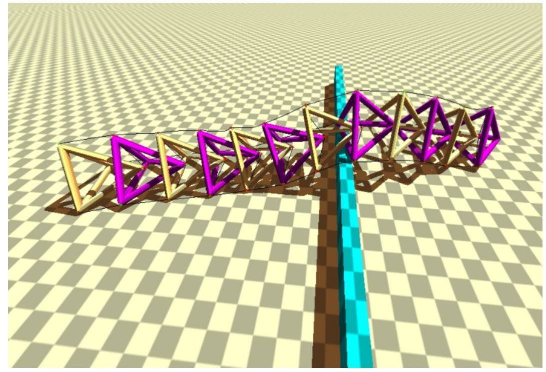


Figure 12. Simulation of a tetraspine tensegrity robot crawling over a wall.
From Wikimedia Commons, posted by Vytas SunSpiral Oct. 2014.

In 2008 a team of NASA roboticists, engineers and computer scientists led by Vytas Sunspiral designed and built a perambulating six strut tensegrity robot that employed this strategy (Caluwaerts et al 2014). The Superball Bot in Figure 11 is a compliant faceted expanded octahedron tensegrity that employs a distributed control system. A machine learning algorithm enables the robot to learn how to initiate movement in a desired direction. The tensional triangulation is relaxed, causing the robot to fall into a new stable arrangement and generating movement in the process. It is akin to an inflatable ball that can deflate all or a segment of itself, creating slack or under-pressure in the system. Re-inflating the ball from behind causes it move forward into a new position. There is energy cost to this: constantly reducing the global tension in a system loses energy that cannot be completely recovered when re-stressing the system.

In recent work, Rieffel and Mouret (2017) describe a new approach for actuating a tensegrity robot of this type. Their robot has the same connectivity as in Figure 11, but with springs instead of cables and with three vibrators glued to three of the struts. The structure is small, easy to assemble, and resilient. It discovers new gaits using a highly efficient machine learning algorithm that is able to harness the inherent resonance of the structure in order to make it "walk".

Mobilization through tensegrity articulations

A modular approach to tensegrity construction may allow more efficient mechanization than is possible by relaxing and restressing the triangulation. An articulating robot like a snake or quadruped can be created using a secondary tension system to link discrete tensegrity modules that each have their own fixed prestress. Tensegrity modules joined together by separately tensioned connecting slings can be actuated by a third set of control lines. This introduces a means to control multiple degrees of freedom and a wide range of motion.

Advantages to this method may include simpler actuation, less energy expended and a simpler algorithm to control the tensegrity linkages. As each module is separately pretensioned, the joints connecting them can remain compliant. An arm with a gripper capable of precision grasping needs to be non compliant, but the joints that allow it to move and rotate need to be flexible and loosely coupled. This method solves for both specifications.

Tensegrity mobilization of this type has been explored in simulations of tensegrity-spine robots controlled through central pattern generators (Tietz et al 2013; Mirletz et al 2014); see Figure 12. Similarly Friesen et al (2013) have interlinked two tetrahedral structures tensegrally to form a unique duct climbing robot that can manipulate its way through and around duct work.

CONCLUSION

The properties of tensegrities can be advantageous or disadvantageous, depending on circumstances. Their compliance can be a feature or a problem depending on requirements. The advantages of robust, light weight construction must be weighed against issues like strut and line congestion, complexity of assembly, and the need to develop complex machine learning algorithms to discover control strategies. The global nature of tensegrities presents unique problems, including the necessity to consider the behavior of the whole mechanism when designing individual sections.

Tensegral robotic designs might be of use in situations where weight, energy requirements, and robustness are important considerations. These include harsh and challenging environments encountered in space exploration, as well as hazardous sites such as Fukushima or the Hanford Nuclear depository in Washington State.

Experimental bio-tensegrity model building by Flemons from 1981 to the present has led to the discovery of a number of new ways to connect discrete tensegrities, and to create joints that can articulate. In collaboration with a new generation of engineers, roboticists and computer scientists it may now be feasible to design complex tensegrity robots to perform similar functions as bipeds or quadrupeds (Figure 13 and Figure 14).

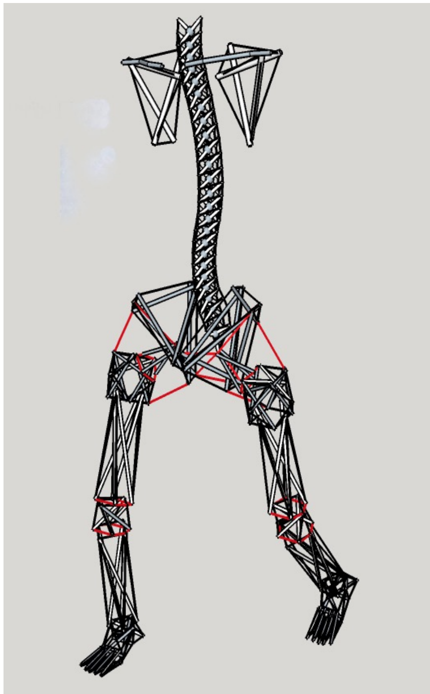


Figure 13. Modular tensegrity design for a tensegrity biped.
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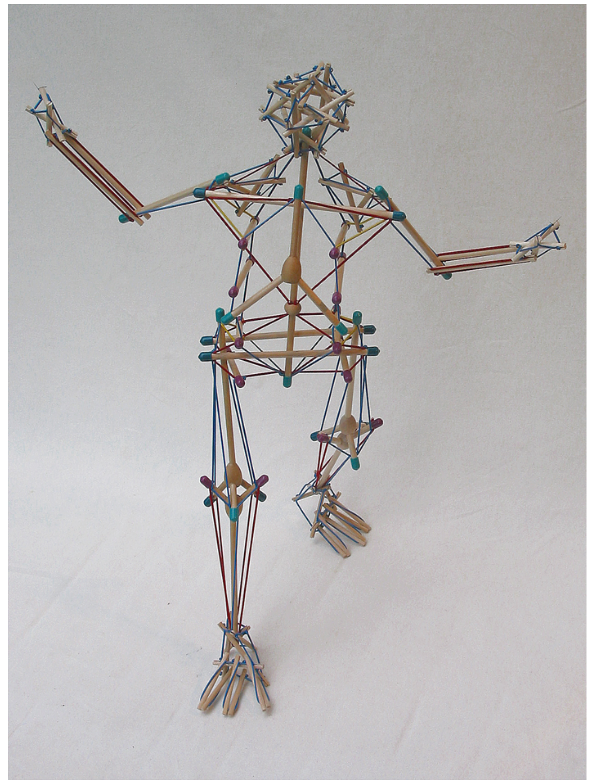

Figure 14. Complete tensegrity biped.
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To fully realize the potential of these tensegrity design principles, a mathematical characterization of the kinematics and kinetics of tensegral joints should be developed. Mathematical analysis is difficult because movement anywhere in a tensegrity structure causes a compliant response throughout the entire structure and any local structural change affects the kinematics of the entire structure. Computational power will continue to increase allowing the use of extremely high degree polynomial systems to analyze compliant mechanisms and tensegrity systems (McCarthy, 2011).

The details as always are bedeviling but the great potential of tensegrity mechanisms will undoubtably make it worth the effort to get it right.

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