Locomotion of a Tensegrity Robot via Dynamically Coupled Modules

John Rieffel[1], Ryan James Stuk[1], Francisco J. Valero-Cuevas[1] and Hod Lipson[1]
[1] Computational Synthesis Laboratory, Cornell University, Ithaca NY
rieffel@cornell.edu

Abstract

Tensegrity structures - dynamically stable systems consisting of disjoint rigid elements (rods) connected by tensile elements (strings) - are an intriguing robotic platform due to their relatively high strength-to-weight ratio, resilience to deformation, and collapsability. Furthermore, the homogeneity of the rigid elements lends itself to a modular design . However, for any such design which requires centralized control, as the scale of these robots increases, inter-modular communication becomes a challenge (not just in terms of logistics, but also in the risk of tangled wires during locomotion). An alternative proposed here is to treat each module as a completely autonomous agent, with no explicit inter-modular communication between them. Rather, the only information transmitted and received between modules is through the tension on their respective strings. As such, locomotion arises through the complex interplay of dynamical forces throughout the structure. In this extended abstract we describe a design for such a system, present an assembled model, and describe a means by which controllers can be evolved in order to produce locomotion.

Introduction

The word *tensegrity*, a concatenation of *tensile integrity* was coined by Buckminster Fuller to describe structures first developed by the sculptor Kenneth Snelson in 1948 (Fuller, 1975). Broadly speaking, a tensegrity structure is a set of disjoint rigid elements (rods) whose endpoints are connected by tensile elements (strings), and which maintains its shape due to the synergy between the compressive forces on its rods and the complementary forces in its cables, as shown in Figure 1. Such structures are *pre-stress stable*, in the sense that, in equilibrium, each rigid element is under compression and each tensile element is under tension, and that the structure has a tendency to return to its stable configuration after subjected to any moderate temporary perturbation (Connelly and Back, 1998).

These principles of tensegrity can be found in a variety of man made and natural objects, ranging from free-standing camping tents and geodesic domes to the cellular cytoskeleton and even the structure of proteins (Ingber, 1998).

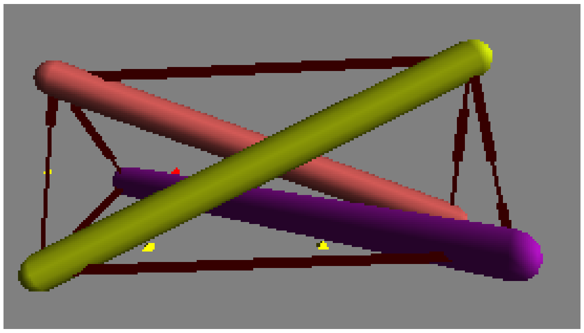

Figure 1: A simple three-bar tensegrity structure

Challenges in Tensegrity Robotics

Recent attention has been paid to the control and manipulation of tensegrity structures. Skelton *et al.* have been able to demonstrate both active vibration damping (Chan et al., 2004) and open-loop control of simple structures. More recently, Paul *et al.* demonstrated an ability to produce static and dynamic gaits for 3- and 4-bar tensegrity robots via evolutionary optimization, and implemented these gaits on a physical robot (Paul et al., 2006). Related work demonstrated how the overall stability of these structures results in beneficial resilience and redundancy of control mechanisms (Paul et al., 2005).

The physical implementation of tensegrity-based robots is a double-edged sword. On one hand the homogeneity of the rigid elements allows for a high degree of modularity: each rod can contain identical sets of sensors and actuators – the parts of a 10-bar tensegrity could be identical to those of a 3-bar one.

On the other hand, any solution which relies upon centralized control of the robot faces a crucial problem: that of communication between modules. As the number of modules increases, the lines of communication (quite literally) increase, bringing with them the risk of tangles.

Rather than resort to potentially expensive and time consuming solutions to inter-modular communication such as wireless technology, we propose a simpler alternative: to do away with the notion of explicit inter-modular communication completely - replacing locomotion via centralized control with locomotion which emerges purely as a consequence of the distributed dynamics of the system.

Decentralized Control of Dynamically Coupled Modules

The resilience of tensegrity structures is due in large part to their pre-stress stability: any perturbation in one section of the structure results in a corresponding redistribution and rebalancing of compressive and tensile forces throughout the structure (Ingber, 1998).

We can harness this intrinsic dynamic coupling of elements as a means of inter-modular communication. Provided a module were capable of measuring changes in its *local* force vectors, such as the tension of its cables, it would be capable of sensing distal stimuli. Correspondingly, if a module were capable of manipulating its local force vectors, it would able to *affect* the behavior of distant modules.

In principle, therefore, it is possible to program individual modular controllers which exploit this dynamical coupling in order to produce complex behaviors such as locomotion. Such a system could certainly be said to be performing *morphological computation*. In the remainder of this extended abstract we will describe our design of such a system.

Module Design

In order to realize such a dynamically coupled modular tensegrity robot we must first design modules capable of sensing and affecting their local tension. In our case, central to this function is the Robotis AX-12 servo motor (www.tribotix.com), which is capable of continuous rotation and, more importantly, contains an integrated load sensor. As a consequence, it is capable of serving as both sensor and actuator. Each servo is then coupled with a simple touch sensor and battery pack to form an element end-piece. Figure 2 contains a schematic of this package, and Figure 3 shows its physical implementation.

Each full modular element consists of two of these servo payloads connected by a hollow nylon rod, as shown in Figure 4. Concentrating the payload at the endpoints in this manner improves clearances between modules, and allows for the creation of larger structures by simply using a longer connecting rod.

Modules are then connected together using nylon string as the tensile elements. The schematic of a complete 3-bar robot is shown in Figure 5, and the corresponding physical robot is shown in Figure 6.

The simplicity and flexibility of this modular system allows us to scale to larger structures with more elements relatively easily.

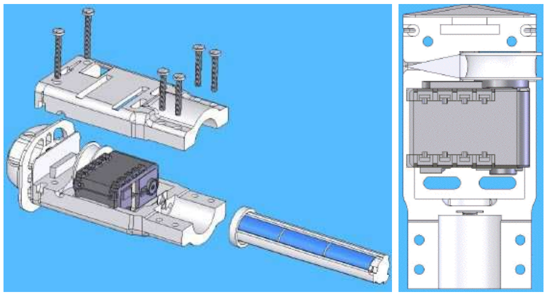

Figure 2: Schematic for one end of a tensegrity element

Controller Discovery

While relying on the coupled dynamics of the tensegrity modules described above solves the issue of inter-modular communication, it complicates the task of control. In order to achieve locomotion, for instance, each module's controller may need to be out of phase or, in the extreme, each module may require an entirely unique controller.

Given the complexity of the task, we have chosen to use evolutionary optimization over analytical approaches. In this method, each module's controller consists of a simple 2-layer neural network whose inputs are the forces measured on each servo, and whose outputs are a consequential desired rest length for each string. Given the destructive nature of in-situ evolution, controllers are evaluated in simulation (using the Open Dynamics Engine, in a manner similar to (Paul et al., 2006) before being transferred to the physical robot.

A movie showing an initial result of locomotion can be found at the author's web site (http://www.mae.cornell.edu/rieffel/).

Conclusion

In our ongoing research we are exploring a means of locomotion in tensegrity robots which arises from the complex coupled dynamics of multiple independent modules, whose only means of communication is the propagation of force throughout the structure. In the particular design described above, each modular structural element is capable of sensing the tension at each endpoint, and of reactively affecting forces through the structure by activating the connecting strings. As such, centralized control is replaced by the de-centralized, emergent collective behavior of the modules. Armed with this hardware, and with a corresponding simulated robot, we are presently evolving the modular controllers in order to produce locomotion.

References

Chan, W. L., Arbelaez, D., Bossens, F., and Skelton, R. E.: 2004, Active vibration control of a three-stage tensegrity structure, in *Proceedings of SPIE 11th Annual International Symposium on Smart Structures and Materials.*

Figure 3: The physical assembly of the module end in Figure 2

Figure 4: A complete module

Figure 5: CAD model of a complete modular tensegrity robot

Connelly, R. and Back, A.: 1998, Mathematics and tensegrity, *American Scientist* 86

Fuller, R. B.: 1975, *Synergetics—Explorations in the Geometry of Thinking*, Macmillan Publishing Co

Ingber, D. E.: 1998, The architecture of life, *Scientific American*

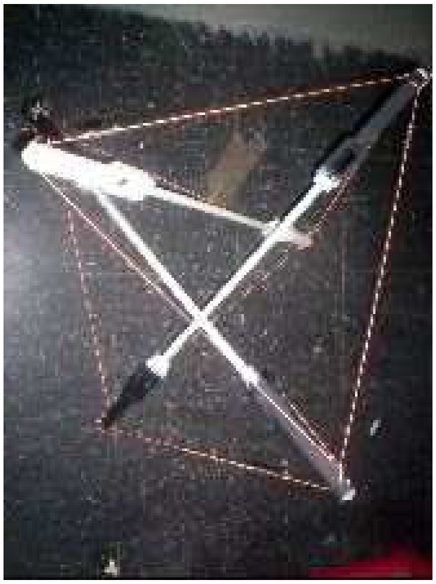

Figure 6: The fully assembled modular tensegrity robot

Paul, C., Valero-Cuevas, F. J., and Lipson, H.: 2005, Redundancy in the control of robots with highly coupled mechanical structures, in *Int. Conf. on Intelligent Robots and Systems*, pp 802–808

Paul, C., Valero-Cuevas, F. J., and Lipson, H.: 2006, Design and control of tensegrity robots for locomotion, *IEEE Transactions on Robotics* 22(5)