Developing Morphological Computation in Tensegrity Robots for Controllable Actuation

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ABSTRACT

Conventionally control can be achieved by attempting to simplify complex dynamics. The field of morphological computation explores how mechanical complexity can be advantageous. In this paper we demonstrate morphological computation in tensegrity robots. We present a novel approach to tensegrity actuation and explore the capabilities of our self-evolving system. Methods of finding desirable gaits through both hand selection and evolution are described and the effectiveness of the system is demonstrated by our robot's ability to pursue a moving target. We conclude with a discussion of a bootstrapped system with the potential of significantly reducing evolution time and need for user presence.

Categories and Subject Descriptors

I.2.9 [**Robotics**]: Propelling Mechanisms

Keywords

Morphological Computation; Tensegrity; Hill Climber; Bootstrapping

1. INTRODUCTION

Due to the ability of the natural world to deal with high levels of dynamic complexity, there has been resurgence in the implementation of natural systems in robotic design. The field of morphological computation [4] can allow for a decrease in the cost of control, allowing for individual components to react to each other instead of a central processor [7] [6] and allow for neural pathways that are interconnected to devote resources to higher level tasks. This can be seen in biological systems such as the tendinous network of the human hand [9].

Tensegrities, structures composed of rods for compression and strings for tension, are difficult to control by conventional means due to high levels of dynamic coupling. The majority of the development of locomotion in tensegrity robotics has been done through varying the resting lengths of springs [5]. Unfortunately, this approach leads to slow locomotion.

Much like tensegrities, many natural systems are inherently dynamic, involving a large number of degrees of freedom. These properties of living systems are accompanied by tight dynamic coupling between components [8] that are conventionally avoided in engineering. More predictable, kinematic systems, are easier to understand and implement.

What is then interesting to consider is how dynamically complex biological systems are able to attain controllability. Our exploration of tensegrity locomotion attempts to explain how controllability can be achieved through more dynamic methods. Through the use of a simple tensegrity structure, actuated with vibrational motors, and a mounted camera used as a sensing environment, we are able to achieve controllability allowing for the tensegrity to chase a moving target in real time. We begin the paper with a description of the design of our robot. We continue on to demonstrate the abilities of the evolved gaits, and conclude with a discussion of a bootstrapped system, which is able to evolve gaits without the need for the presence of a user.

2. FROM STRUCTURE TO ROBOT

Tensegrity structures can be found in various architectural foundations ranging from towers to camping tents. Tensegrities are also present in the biological realm, integrated into the structure of cellular cytoskeletons [10] and proteins [2].

While conventional approaches to tensegrity locomotion deal with dampening the dynamic complexity of the system, an emerging method of movement is actuation through vibration [3] [1]. Our approach exploits the dynamic movements of the tensegrity, vibrating the structure to produce locomotion. With the use of three vibrational motors attached to struts, we were able to gain locomotive control of the system. The struts were connected with springs and the completed robot is shown in Figure 1. With the ability of our tensegrity to achieve locomotion we demonstrate a novel way of exploiting dynamic complexity as an advantage in the actuation of our robot.

2.1 Design

Our tensegrity, VALTR (Vibrationally Actuated Locomotive Tensegrity Robot), is a 6-bar structure that is powered by vibration alone. 3 pager motors attached to 3 distinct struts of the robot are activated through the use of 2 Pololu microcontrollers attached to a 3V power source. Different oscillation frequencies were achieved by sending a

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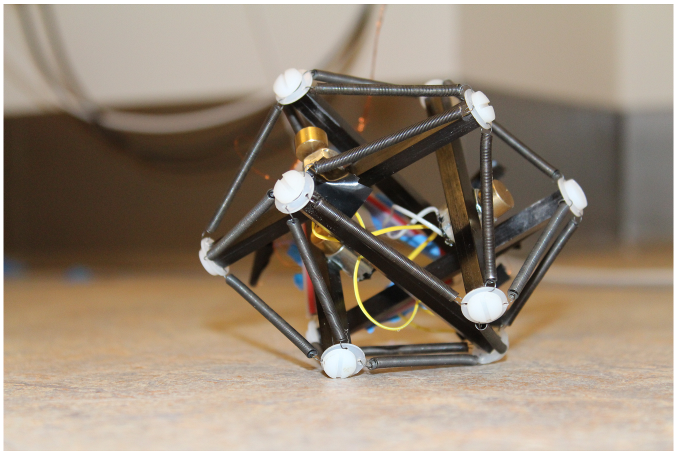

Figure 1: Tensegrities consist of rigid elements (struts) connected with tensile elements (springs). Their shape is obtained through the interplay of these forces. Above is the fully constructed tensegrity robot with vibrational motors attached.

voltage value to the motors, allowing it to turn with varying speeds. Thin wires were connected to the motors, allowing the tensegrity to move with as little resistance as possible.

The struts were made from 6.35 mm graphite composite tubes that were cut to a length of 9.4 cm. The motors used were Precision Microdrives vibration motors, Model 312-107, which operate between 100 and 260 Hz. These motors were mounted to the flat outer surface of the graphite rods. Selection of springs was given the most consideration, as they would have the greatest affect on VALTR's morphology. The basic strategy in string selection was to try and produce the smallest number of natural frequencies. This was due to the assumption that small natural frequencies would lead to large displacement amplitudes, possibly allowing for the tensegrity to achieve rolling. With these considerations spring were chosen with a constant of 0.209 N/cm.

3. EVALUATION

The robots design was crafted specifically for the maximization of resonance. We proceed by quantifying the results of VALTR's vibrational motion. We explain how the system was evolved, and demonstrate our robots advanced capacity for controllability.

3.1 Setup

The robot was placed on a 91x61 cm table with a removable cork-board sheet as the surface. The specific board was used to provide enough friction for the tensegrity to move freely, but also allow for its base to grasp against the surface. Wooden borders surrounded the testing environment to guard the tensegrity from falling during trials. Thin wires were used to prevent the robot from being tethered by its connections and preventing its ability move with its greatest possible range.

A USB camera was mounted above the testing arena. Below we describe how the camera was used in the process of evaluation and how evolution of motion was achieved through the use of still images of the tensegrity. We then proceed to describe how the evolved motion and the mounted camera worked in tandem to create a system where our tensegrity could autonomously chase a moving target.

Figure 2: The process of measuring fitness by taking the difference between start and end positions is displayed.

3.2 Discovering Motion

3.2.1 *Evolution of Physical Systems*

While a virtual evolution of gaits may seem more practical, there are many problems associated with this approach. The dynamic complexity of the tensegrity does not allow for an accurate virtual representation of its dynamics. Attempting to implement virtually evolved gaits to the physical system does not provide similar results to evolving the gaits within the physical world. Embodied evolution allows us to address this issue [11], eliminating the problem of a reality gap.

3.2.2 *Hand Selected Gaits*

Our first process of selecting gaits was done through trial and error. By varying the voltages passed to the motors we were able to change the motion of the tensegrity. An "interactive" feature was implemented where voltage could be changed manually while the tensegrity was active, and the system would respond in real time. Two gaits were selected as "turning" gaits as they were most effective in rotating the tensegrity clockwise and counterclockwise.

3.2.3 *Evolution by Hill Climber*

A Hill Climber algorithm was used for the evolution of a forward propagating gate. Consisting of 10 individuals, a population was first chosen at random with the top half best-fit individuals continuing on to the next generation. Each individual (genotype) consisted of 3 loci, one for each motor voltage. Each genotype's loci were chosen randomly for the first population and were either mutated or re-evaluated for every successive generation.

With the use of a mounted camera we were able to take pictures of the tensegrity before and after a trial run. Images taken were first converted to black and white and then overlapped. The average difference in white pixels (the space the tensegrity occupied) was calculated and was used in the evaluation of the specific individual of the population 2.

By choosing individuals of the population that were able to travel the furthest distance within the allotted 7 seconds, a new population was then created with children of the survivors of the previous population slightly mutated. The new population was reassessed and new individuals were chosen to continue on to produce offspring. Figure 3 shows 25 generations of a 10 member population evolving over time.

The data shows an increase in maximum fitness over the first 25 generation. After the maximum is achieved, fur-

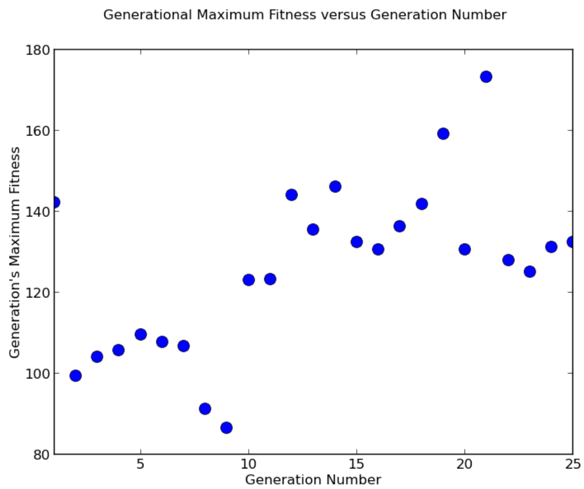

Figure 3: 25 generations of the hill climber evolution are shown. Individuals were assessed based on distance traveled and top performers continued onto the next population.

ther evaluations of the similar frequencies prove to be less successful.

The largest difficulty faced during evolution was the constant need for a manual reset of the system. After each trial the tensegrity would need to be physically moved to its initial location. Other than the repositioning of the robot there was no other necessity for a user. Naturally, this prompted a desire for an automated process in the resetting of the tensegrity. At first an omnidirectional treadmill was considered. When this proved impractical the feasibility of a mechanical arm was put into question. The solution to repositioning was found in the capabilities of the tensegrity itself, using its newly developed ability to navigate.

3.2.4 Navigation

By attaining gaits that were able to produce clockwise, counterclockwise, and forward locomotion in the tensegrity we were able to steer the tensegrity towards a destination. Using left and right arrow keys we were able to turn the tensegrity and press forward when we desired for forward motion towards a target. Once the controllability of the tensegrity had reached this level we proceeded to create a completely autonomous system.

The first step in our automation process was the development of a tracking system. By placing colored markers at three points of the tensegrities upper surface we were able to include a directional property in our system. The different colors were detected and an angle was calculated between the measured angle of the forward vector of the tensegrity and the vector from the center of our robot to the target. Figure 4 shows the tensegrity placed into an environment with a yellow ball acting as the target.

By implementing the state machine shown in Figure 5 our robot was able to track a moving target. VALTR would first calculate the angle between his forward vector and the target. If the angle was below -30 degrees or above 30 degrees, our state machine would either choose to turn clockwise or counterclockwise. Only when in the 60 degree range between -30 and 30 would the robot locomote forward towards the target. When the tensegrity was switching from one movement to another it would stop momentarily so that its components could settle. Once the tensegrity was less than a specified distance away from the target the process would conclude.

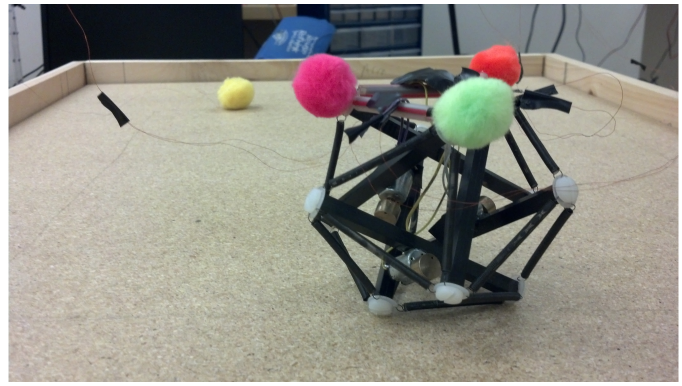

Figure 4: Our tensegrity robot with colored markers used for tracking and navigation. The yellow ball is used as movable target, which the tensegrity is able to pursue.

3.2.5 Semi-Autonomous Evolution

With a system that is autonomous, we began to incorporate this feature into the evolution of our robot. Instead of having a user place the tensegrity back to its initial location after each evaluation of an individual, the tensegrity was able to reposition itself autonomously. This significantly reduced the need for user interference. The problem of tangled wires still remained, but no manual repositioning of the robot was necessary during the evolution process.

Our next step to completely eliminate the necessity for user interference is the development of a wireless system. Work currently being done includes a wireless implementation of the tensegrity robot.

3.2.6 A Bootstrapped Implementation

The autonomous navigation of our system spurred the idea for a bootstrapped evolutionary process. While the bootstrapped design has not been fully completed it assumes that when we find better forward propagating gaits we will be able to implement them in the navigational frequencies that return our robot to its original position. In this way the process of evolution will decrease in time because the forward propagation gait will improve, repositioning the robot at a faster and faster rate. The problem with this implementation is that "forward" gaits are currently non-directional. They are achieved by finding gaits that produce the furthest distance traveled and then the forward vector is accommodated for through hardcoding. Currently, we are redeveloping the system to include directional vectors that accompany the distance and speed of our current evaluation process.

4. CONCLUSIONS

Tensegrities have begun to grow in popularity in the field of soft robotics. Their morphology allows for an incredibly versatile range of motion and malleability. While tensegri-

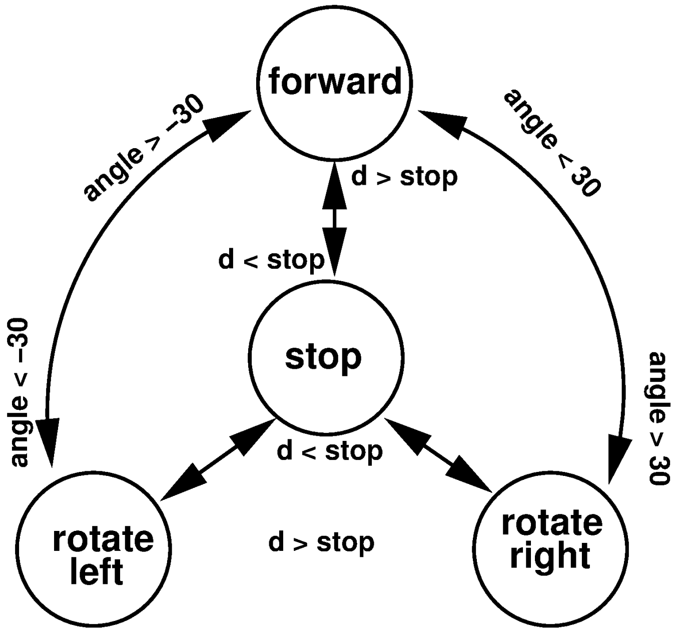

Figure 5: Above is a state machine implemented in the navigation process. Depending on the distance from the target and the angle between the robots forward vector and the vector which points in the direction of the target, the robot is able to change its gaits to either turn clockwise, counterclockwise, or propagate forward.

ties have been most commonly actuated through processes that suppress the resonance of the structures, our approach was to exploit their dynamic complexity, actuating the tensegrity through vibration only. This exploitation of mechanical complexity allows us to further implement morphological computation, in which a greater dynamic coupling can decrease the cost of control. Through the implementation of a tracking system and evolved gaits for directional propagation, our robot is able to achieve robust and agile controllability accompanied by impressive speeds.

Our ability to control the robot has not only led to the creation of an autonomously navigable system, but also an autonomous evolution process. By combining controllable locomotion with the self-positioning provided by the tracking system, our robot is able to perform evaluations and reposition itself without the need for human interference. With a bootstrapped evolution process we will be able to implement the gaits of the most fit individuals directly into our navigational abilities and repositioning speeds. We believe this bootstrapped evolution system to be the first of its kind implemented in physical robotics. Given the vast applications of tensegrity robotics ranging from biomedical devices to search-and-rescue operations, our hope is that this autonomous self-improving evolution system can both advance the locomotive abilities of tensegrity robotics as well as the evolutionary process of dynamically complex systems. In this way we can push the boundaries of technology, our understanding of living systems, and our interaction with the natural world.

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