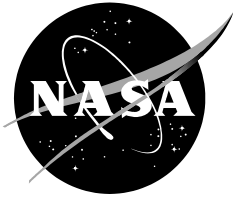


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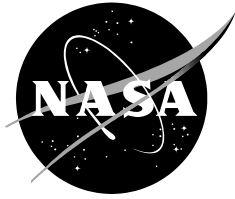
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Abstract— Traditional robotic structures have limitations in planetary exploration as their rigid structural joints are prone to damage in new and rough terrains. In contrast, robots based on tensegrity structures, composed of rods and tensile cables, offer a highly robust, lightweight, and energy efficient solution over traditional robots. In addition, tensegrity robots can be highly configurable by rearranging their topology of rods, cables, and motors. However, these highly configurable tensegrity robots pose a significant challenge for locomotion due to their complexity. This study investigates a control pattern for successful locomotion in tensegrity robots through an evolutionary algorithm. A twelve-rod hardware model is rapidly prototyped to utilize a new actuation method based on friction. A web-based physics simulation is created to model the twelve-rod tensegrity ball structure. Square-waves are used as control policies for the actuators of the tensegrity structure. Monte Carlo trials are run to find the most successful number of amplitudes for the square-wave control policy. From the trials' results, an evolutionary algorithm is implemented to find the most optimized solution for locomotion of the twelve-rod tensegrity structure. The software pattern coupled with the new friction based actuation method can serve as the basis for highly efficient tensegrity robots in space exploration.

Keywords— Robotics, Tensegrity, Evolutionary Algorithm, Machine Learning, NASA

Introduction

Tensegrity robots are a new field of robotics that diverge from the traditional sense of robotics. Traditional robotics relies on robots composed of rigid joints. Tensegrity structures, on the other hand, are composed of pure tension and compression elements as shown in Fig. 1 [12]. The lack of lever arms makes tensegrity structures resistant to force magnification in joints or other points of failure. The goal of these structures is to take part in low-cost planetary exploration [1]. In this task, tensegrities have numerous benefits to offer over traditional robots:

- **Highly Reconfigurable:** Topology of rods, cables, and motors can be changed to add new functionality.
- **Light-weight:** The structures are made of tubes/rods and cables/elastic lines.
- **Energy efficient:** Dynamic movement of the tensegrity structure results in efficient locomotion.
- **Scalability:** Composed of rods, cables, and actuators, the tensegrity structure can be scaled up in size without a significant cost difference.
- **Ease of Deployment:** The shock absorbent structure allows for a smoother landing on planetary missions.
- **Robust to failure:** The inherent tension network distributes harmful external forces to reduce the structural damage.

- **Locomotion techniques:** Evolutionary efforts have revealed that tensegrities can not only roll but also crawl, gallop, swim or flap wings depending on construction and need.

Tensegrity structures are a relatively modern concept, initially discovered in the 1960's by Buckminster Fuller [2] and the artist Kenneth Snelson [3]. For the first few decades, the majority of tensegrity related research was concerned with form-finding techniques, design, and analysis of the static structures [4].

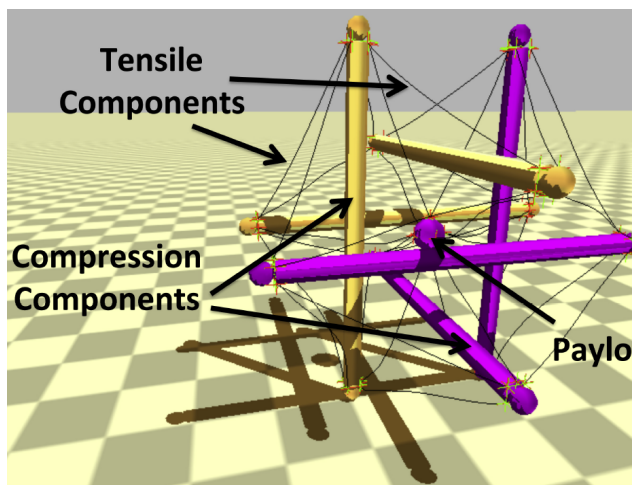


Fig. 1 Tensegrity structure is composed of tension and compression elements

More recent work has been done in the area of six-rod tensegrity structures. The six-rod design, as shown in Fig. 2 is one of the simplest designs that can behave as a “ball”. It is capable of rolling, changing shapes, and robust against failures. The study [5] explored the evolutionary efforts in the six-rod tensegrity structure and the study [6] used motor spindles to reel in the elastic cables.

This paper focuses on the twelve-rod tensegrity robots and a new form of actuation through friction that allows for a better distribution of force throughout the tension network. This paper is organized as follows: Section II gives details about the twelve-rod hardware tensegrity robot used in this paper. The approach for simulation of the tensegrity structure is discussed in section III. Section IV shows the approach for the control policy

for the tensegrity robot and section V discusses the evolutionary algorithm to optimize the locomotion of the tensegrity. Section VI presents experimental results. Section VII ends the paper with conclusions.

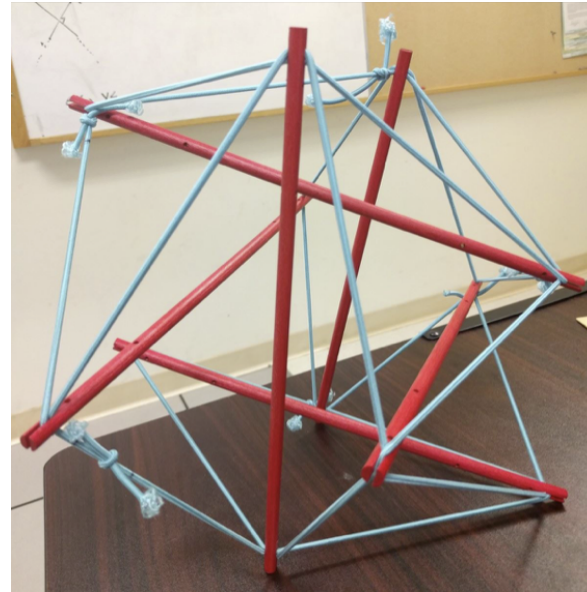


Fig. 2 Six-rod tensegrity structure is one of the simplest designs that can behave as a “ball”

Target Tensegrity Platform

One of the goals of this research is to rapidly prototype the tensegrity ball structures. The low-cost “Tensegritoy” hardware kit is used to build twelve-rod tensegrity ball structures. The Tensegritoy kit includes wooden rods with groves on end and cables to connect all the rods. The cables are actuated using Pololu continuous rotation servos [7]. The continuous rotation servo is a motor that spins without limit.

Structure

The structure of the twelve-rod tensegrity ball structure used in this paper is shown in Fig. 3. Each rod is a lightweight 12-inch wooden unit. Each rod has associated elastic cables to connect with the rest of the structure. At the end of each node is a node cap to secure the cables. Each node in the twelve-rod structure is connected to 3 other nodes. This setup allows for only one

possible angle in which the servo actuator could connect.

The indirect connection of rods through cables results in a continuous tension network just like the six-rod ball structure. Each node is interconnected with other rods through three different cables. When the structure is symmetrical, it allows for the ease of rolling. In contrast, when force is applied, it deforms, and the force is distributed throughout the tension network [12].

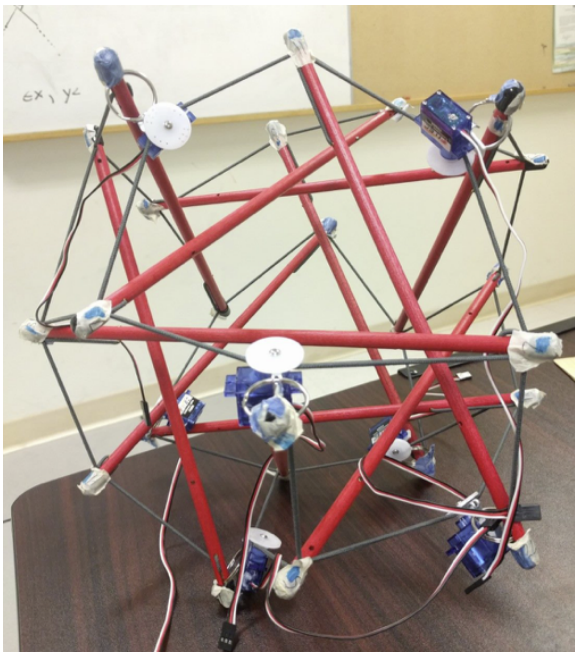


Fig. 3 In twelve-rod tensegrity ball structure each rod has associated elastic cables to connect to 3 other nodes.

Friction Actuation

As mentioned earlier, this research focuses on a new form of actuation through friction that provides better distribution of force throughout the tension network. A Pololu continuous rotation servo is attached to an associated node. Each servo has a rubber axle which is in contact with the elastic cable. The servo rotates to different positions along the elastic cable

through friction to deform the tensegrity ball structure. The servo can rotate in both directions at a certain speed specified by the servo controller. Fig. 4 shows the elastic cable highlighted in yellow and the continuous rotation servo.

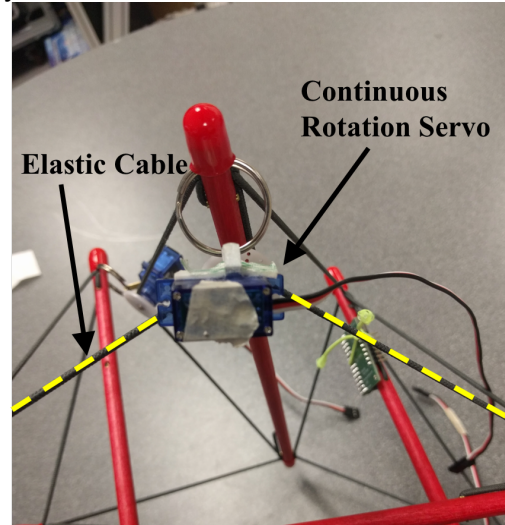


Fig. 4 The continuous rotation servo rotates to different positions along the elastic cable through friction to deform the tensegrity ball structure.

Simulation of Tensegrity Ball Structure

The tensegrity simulator is built on top of the open-source 3D Physics Engine Cannon.js [8]. Cannon.js is a rigid body simulation library that is commonly used in applications such as games. Cannon.js is used because of its built-in support for soft-bodied physics. This simulation serves to model tensegrity ball structures and test control algorithms. It is written in JavaScript and runs on any browser with rendering or game engine capabilities. Fig. 5 shows the visual representation of the web-based Tensegrity Simulator.

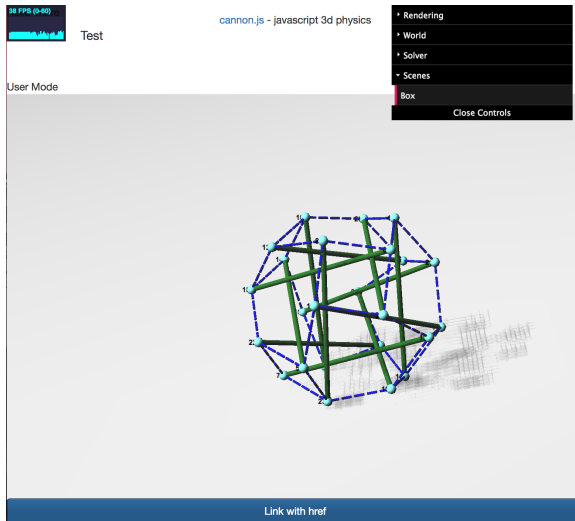


Fig. 5 Web-based tensegrity simulator is built using Cannon.js

The hardware specifications of the tensegrity are applied in software for simulation. The twelve-rod tensegrity consists of 24 nodes that have the same relative coordinates as the geometry of a truncated octahedron. In addition to geometry, the weight and size of these structures are applied in the simulation. The size of the structure is modeled from the 12-inch wooden rod dimensions. The overall weight of the tensegrity structure is measured, and in simulation, this weight is distributed between the node bodies. Each node is assigned a mass of 17.5 grams in the simulation. Similar to the NASA Tensegrity Robotics Toolkit simulation, the cables of the tensegrity robot are assigned zero mass; therefore, the cables will not interact in the physics world [9] and are used for visual purposes only. While the cables do not physically interact with the rest of the structure, spring mechanics are still applied to each node. For the spring mechanics, we defined the spring constant. Aside from the previously mentioned specifications, default values of the physics engine are used, such as gravity.

Control Policy

With a functioning simulation, the next step is to implement a control policy for the tensegrity locomotion. A control policy is a way the different servos in the tensegrity structure are actuated. The goal of a control policy for a tensegrity structure is to simulate continuous rolling motion [10].

Square Waves

Previous research works explored various periodic functions such as sine waves and square waves as control policies [6] [10]. Specifically, each actuator follows a periodic function. These works relied on an actuation method that would physically reel in the cables through a motor spindle. As a result, the various periodic functions would determine the actuation length of the cables for each actuator at a certain time. This research uses a new actuation method that moves along the cables rather than physically lengthening or shortening the cables. A periodic function is assigned to each servo to determine the velocity at a certain time. This project explores square waves as the periodic function. The square wave gives both the speed of the associated servo and the direction in which it spins, at a certain time.

Fig. 6 shows an example square wave that is assigned to a certain servo. The y-axis shows the relative velocity of the servo, positive and negative indicating opposite directions. The x-axis indicates the time in seconds. Each square wave pattern consists of a set number of cycles; in this case, there are three unique cycles, each one containing amplitudes with the same magnitude but different directions. The area under the square wave pattern is zero, resulting in the shape of the tensegrity restoring after every full completion of the periodic function. After each period (9 seconds, in this case), the whole periodic function repeats indefinitely.

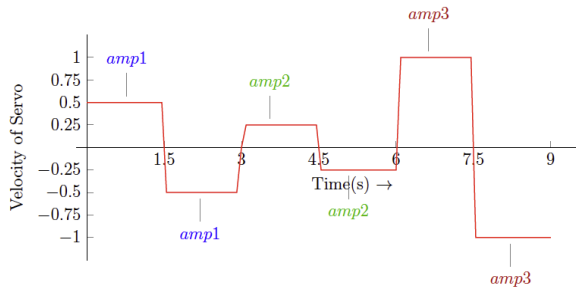


Fig. 6 Square wave pattern of the servo velocity

Determining Number of Amplitudes for Square Wave

Since each periodic square wave can have an arbitrary amount of amplitudes, simulations are run to determine the best number of amplitudes. Specifically, two, four, six, eight, and ten amplitudes are tested separately with a Monte Carlo Simulation of 2000 trials. Within each of these trials, 12 motors are assigned random square-waves for the twelve-rod tensegrity robot. The control policy is tested for 60 seconds, and the displacement of the tensegrity robot is recorded.

The top ten displacements for each amplitude in Monte Carlo simulations are used for statistical analysis. The analysis of the variance between the different amplitude groups with an F-test resulted in an F-value of 141.59. The corresponding F-test static P-value is 6.99E-25. There is sufficient evidence to conclude that at least one of the means for the displacement with its corresponding amplitude is different from the others. Analysis of the box plot from Fig. 7, shows that four amplitudes performed better in terms of displacement in comparison to the other amplitudes.

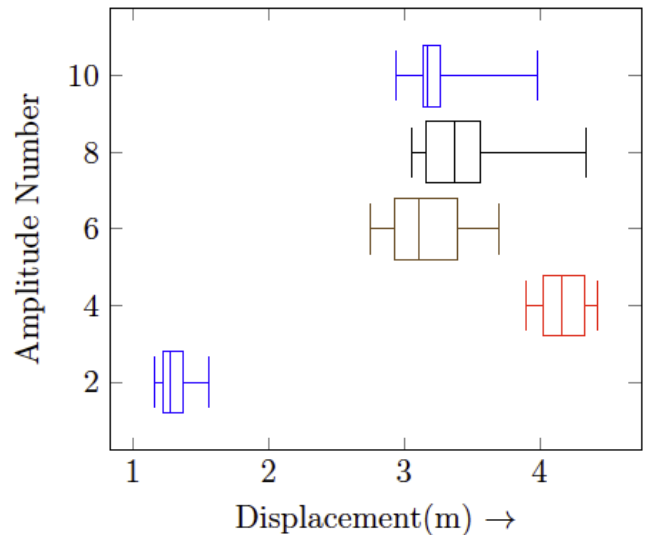


Fig. 7 Tensegrity displacements for various amplitudes are simulated using a Monte Carlo simulation of 2000 trials

Evolutionary Algorithm

Associating different square waves to the different motors provides a challenge that is beyond the scope of a hand-coded solution. As a result, this paper uses an evolutionary algorithm to figure out the best combination of square waves for a successful locomotion control policy. An evolutionary algorithm is a heuristic optimization algorithm using techniques inspired by mechanisms of organic evolution such as mutation and fitness selection to find an optimal configuration for a specific system within specific constraints [11].

In the twelve-rod structure, there are 24 different nodes for possible motor placement. Of these 24 different possible motor placement positions, 12 are selected in a manner that respects the symmetry of the twelve-rod structure. This section explores the use of an evolutionary algorithm to determine a set of control parameters that leads to the desired behavior.

Fitness Function

A key component of an evolutionary algorithm is a fitness function. The fitness function serves to evaluate each

chromosome within the population. The fitness function, in this case, is the measure of the displacement, in meters, of the tensegrity robot from its start point to its end point after 60 seconds [12]. This fitness is next assigned to the respective chromosome, and this helps in determining the successful chromosomes. The following function determines the fitness value:

$$f = d(S_1, S_2, S_3, \dots, S_{12})$$

where d is the distance traveled, and S_i represents a square wave associated with a motor.

Mutation Function

Another component of the evolutionary algorithm is the mutation function. The mutation function serves to randomly alter chromosomes to create new solutions based on successful ones. Specifically, the mutation function alters the square waves of each control policy chromosome. Since each control policy has 12 associated square waves, each of these square waves is mutated. The resulting mutation serves as a new chromosome.

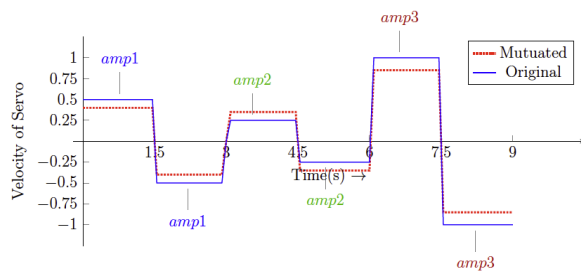


Fig. 8 Mutation of servo square wave results in a new chromosome

Fig. 8 shows an example of the mutation function. The original square wave belonging to a certain control policy is altered. Each pair of amplitudes are shifted through a Gaussian distribution where the standard deviation is 0.1, and the mean is the amplitude.

Algorithm

This paper implements a centralized evolutionary algorithm instead of a cooperative coevolutionary algorithm [1]. The goal is to maximize fitness. In this NASA/TM—2017-219718

implementation, a population consists of n randomly created chromosomes. Each of these chromosomes has 12 different square waves assigned to the 12 motors. The simulation evaluates all of the n chromosomes and ranks the chromosomes in ascending order based on the fitness value. After a round of evolution, the worst k control policies are replaced by mutated versions of the best $n-k$ policies. This paper does not use the reproduction and crossover genetic algorithm operators. This process of evolution runs for g number of generations.

Data: Population of n control policies

Result: Evolved control policies for locomotion of twelve-rod tensegrity structure initialize generation 0 with n control policies;

forall Generations **do**

forall Control Policies **do**

 Evaluate Fitness;

end

 sort population by fitness;

 eliminate worst k control policies from population;

for $i = 0 \dots k$ **do**

 new chromosome = mutation of one of $n-k$ best control

policies;

 add new chromosome to population;

end

end

Algorithm 1 Centralized Evolution Algorithm

Experimental Results

Outcome of Evolutionary Algorithm

In order to test the results of the centralized evolutionary algorithm, simulations are run on the tensegrity simulator. Each population consisted of 50 control policies. Each of the control policies is implemented for 60 seconds, after which the associated fitness value is recorded. At the end of each evolution, the 45 worst control policies are eliminated and replaced by mutations of the best five control policies. This process is run for 50 generations. Fig. 9 shows a graphical representation of the progression of the evolutionary algorithm. At the end of the 50th generation, the best fitness value is 5.43 meters in 60 seconds.

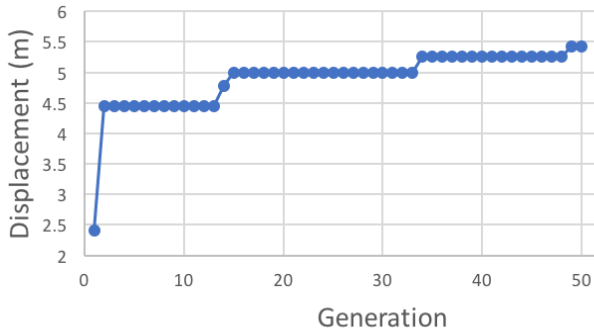


Fig. 9 Tensegrity displacement for 50 generations

Fig. 10 shows the visual representation of the rolling motion of the tensegrity structure. The first square shows the structure deforming from symmetry. The second and third square shows the intermediary steps of the rolling process. The structure retains its symmetry in the fourth square. This process repeats itself continuously. This repetitive process of rolling reflects the periodic square waves used as the control policy.

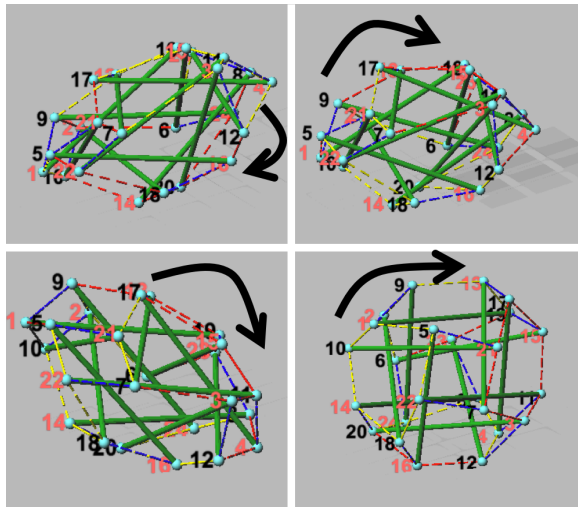


Fig. 10 The continuous rolling motion of twelve-rod tensegrity ball structure

Conclusions

This paper shows a control pattern for successful locomotion in twelve-rod tensegrity structures through an evolutionary algorithm. To simulate the twelve-rod tensegrity, a web-based physics simulation is used. Each actuator is controlled by an associated square-wave. Monte Carlo trials are run to find the most successful number of amplitudes for the square-wave. Results show that four amplitudes performed better in terms of displacement in comparison to the other amplitudes for the twelve-rod tensegrity structure. Using a four-amplitude square-wave, an evolutionary algorithm is implemented to find the most optimized solution for locomotion of the twelve-rod tensegrity structure. The results from the evolutionary algorithm at the end of the 50th generation was 5.43 meters in 60 seconds. This result shows evolutionary efforts for twelve-rod tensegrity robots have potential for future space exploration locomotion. The next step would be to implement the patterns established in the software to the twelve-rod hardware tensegrity robot. Additionally, in order to make the software closer to reality, spring noise should be added as well.

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