Viability of Tensegrity Robots in Space Exploration

Cheng-yu Hong
Alice Agogino, Ed.
Edward A. Lee, Ed.

Electrical Engineering and Computer Sciences
University of California at Berkeley

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Eric Cheng-yu Hong

Project Advisor: Alice M. Agogino

Faculty Reader: Edward A. Lee

Master of Engineering

Department of Electrical Engineering and Computer Science

University of California, Berkeley

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Abstract

Robots in extraterrestrial exploration traditionally faced difficulties in surface landings and flexible locomotion. Our project explored the viability of building robots around the tensegrity structural concept, which allows greater shock absorbance and flexibility by using isolated components held together through continuous tension. The study was separated into two parts: a physical prototype of a Super Ball tensegrity robot to test manufacturing viability and impact resilience in combination with a software simulation model to test control strategies and design concepts, such as position and number of actuators. This paper focused on the robustness of using software simulation models to predict the behavior of complex physical structures, such as the Super Ball tensegrity robot. Results included controlled locomotion simulations from a custom framework built on top of Bullet, a real-time physics simulation software, and initial rolling movement with a physical prototype. Software simulation models provided useful results for preliminary viability assessments, but should not replace physical prototyping, especially for complex structures. In conclusion, tensegrity robots could become promising alternatives to traditional rigid robots, which are more fragile and less flexible.

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Contents

1 Introduction

1.1 Tensegrity Robotics

Robots in extraterrestrial exploration traditionally faced difficulties in surface landings and flexible locomotion. Our project explored a potential solution to the problem: building robots around the tensegrity structural concept [1]. Tensegrity structures are composed of isolated rigid components held together through continuous tension, similar to how a camping tent holds its shape through the tension in the strings. This structural principle also frequently appears in nature, as shown from the tension-compression interactions between bones, muscles, and connective tissues. The tensegrity structure allows greater shock absorbance and flexibility compared to rigid connections in currently used exploratory robots, such as the Mars Rover [2].

Because of their structural resiliency and efficient usage of space, tensegrity structures have received increasing interest in the field of robotics over recent years. Shibata and Hirai's study on implementing rolling locomotion on spherical tensegrity structures in 2009 paved the way for additional applications [3]. One of the most complex tensegrity robots at the time of this writing was the IsoTens developed by the Cornell Creative Machines Lab. The IsoTens robot was capable of rolling locomotion, which made it "significantly faster than all other tensegrity robots" [4].

Different from the existing competition, the Berkeley Emergent Space Tensegrities (BEST) project focuses on developing tensegrity robots for space exploration. Despraz's paper "Super Ball Bot – Structures for Planetary Landing and Exploration" gives an overview of the current progress in controlling tensegrity robots, with specific focus on extraterrestrial exploration. As noted in the paper, tensegrity robotics and control are fairly new research areas with great potential for further development in tools and techniques [5].

1.2 Project Goals

The current study aims to answer two questions: the viability of using tensegrity robots in space exploration and the robustness of using software simulation models to predict the behavior of complex physical structures, such as NASA's "Super Ball Bot" [6]. The first question would be evaluated by comparing the strengths and weaknesses of using tensegrity concepts versus rigid structures. The major strengths of tensegrity robots are weight-to-strength ratio, impact resilience, and flexibility while the weaknesses are difficulty of control algorithms and increased payload motion during locomotion. The question of software simulation prediction accuracy would be evaluated from the strength of the correlation between the simulation environment and the physical world. Some of the discrepancies include assumptions in friction, drag forces, and the deformation of materials in the software model.

To approach the two problems, we built two physical prototypes of six-rod ball-shaped tensegrities and developed software simulation models using the NASA Tensegrity Robotics Toolkit (NTRT) [7]. The physical prototype would provide insights to weight-to-strength ratio and impact resilience from stress and drop tests, and flexibility and payload motion from locomotion tests. The software models would allow for quick preliminary assessments with software simulations, and enable correlation analysis with the physical world. The software framework would also provide a simple way to test control algorithms by tweaking the parameters and quickly see the outcome of the alterations.

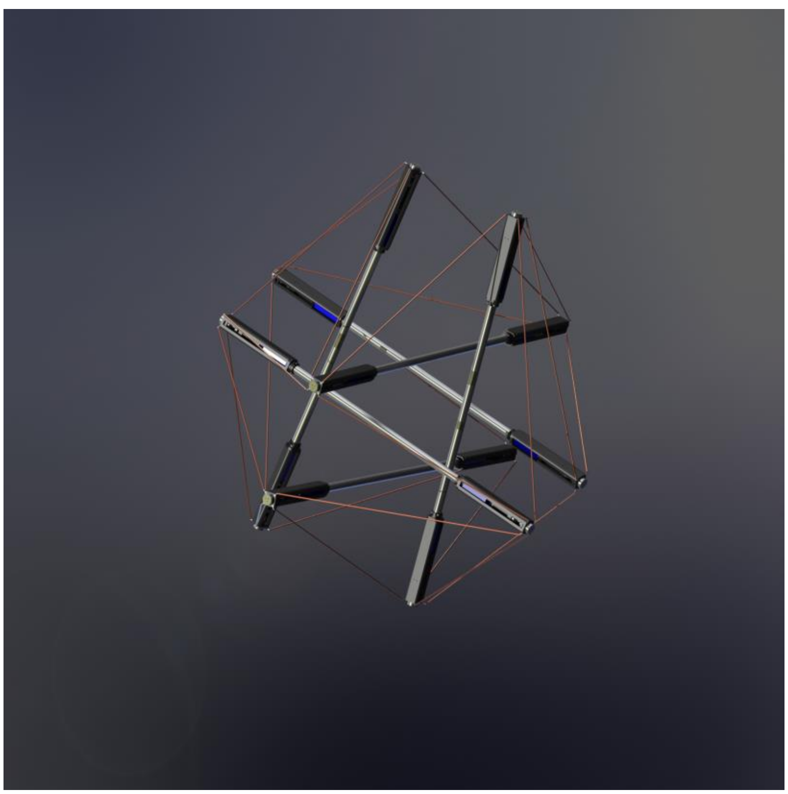


Figure 1: Six-Rod Tensegrity Structure [8]

2 Project Overview

The Berkeley Emergent Space Tensegrities (BEST) project was split into three major components: the design and manufacturing of a single rod in the tensegrity robot prototype for eventual space exploration, the construction and testing of a six-rod wooden design capable of rolling motion, and the development of a software simulation package with potential control algorithms for locomotion. The UC Berkeley Master of Engineering capstone group – Justino Calangi, Yangxin Chen, Cheng-yu Hong, Yuejia Liu, and Dizhou Lu – focused on the first and third components and was correspondingly associated into two groups, the Mechatronics Group and the Controls Group, based on technical expertise of the individual. The second component, the "Tensegrity Kit", was developed by graduate mentor Kyunam Kim and the BEST lab undergraduate team – Terence Cho, Borna Dehghani, Deaho Moon, Laqshya Taneja, and Aliakbar Toghyan. I will showcase the major deliverables from the Mechatronics Group and the "Tensegrity Kit" team, but will delve into more detail on the methods and results of the Controls Group, where I had direct participation.

2.1 Tensegrity Rod Prototype

The "Super Ball Bot" project focused on designing and testing particular elements of a single rod in the tensegrity structure, which included six rods and twenty-four elastic strings [6]. In the final prototype, the rods and strings would be assembled in a spherical formation following the six-rod tensegrity structure (**Figure 1**). The six-rod tensegrity was chosen as the main robotic structure for the prototypes and simulations because it is the simplest tensegrity structure capable of rolling movement.

Our team designed and manufactured several elements of a single rod, such as the battery holder, the custom connector, and the shock absorber. A close-up of a single rod and the individual components designed by our team are shown in **Figure 2**.

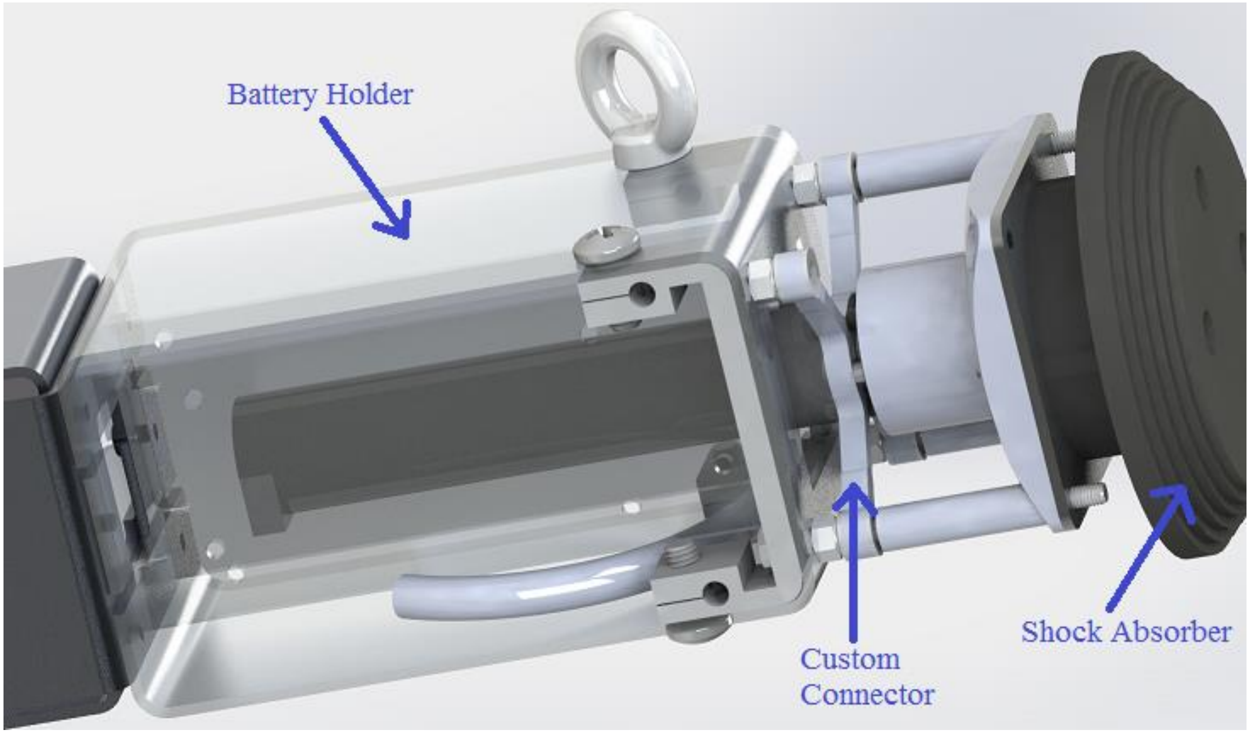


Figure 2: Single Rod with Components Designed by Capstone Team [9]

The design of each component of the rod included a hand-drawn sketch, several computer-aided design (CAD) models, and a manufacturing blueprint to specify how to manufacture the component. Each design went through up to thirty-two iterations based on feedback from doctorate mentors and mechanical/electrical engineers from NASA. Additionally, the team rigorously followed the manufacturing design principles and optimized the models based on numerical analysis from professional software such as Matlab and ANSYS. As a result, the final product included high-quality designs that were easy to modify and manufacture.

2.2 Six-Rod Tensegrity Kit

Since the design following strict physical and manufacturing standards required substantial amounts of time even for minor modifications, the BEST team built a simpler prototype using wooden rods, Firgelli linear actuators, and a LEGO Mindstorms EV3 microcontroller to control the actuators [10][11]. This design allowed rapid modifications and tests based on the software simulations. The prototype is illustrated in **Figure 3**.

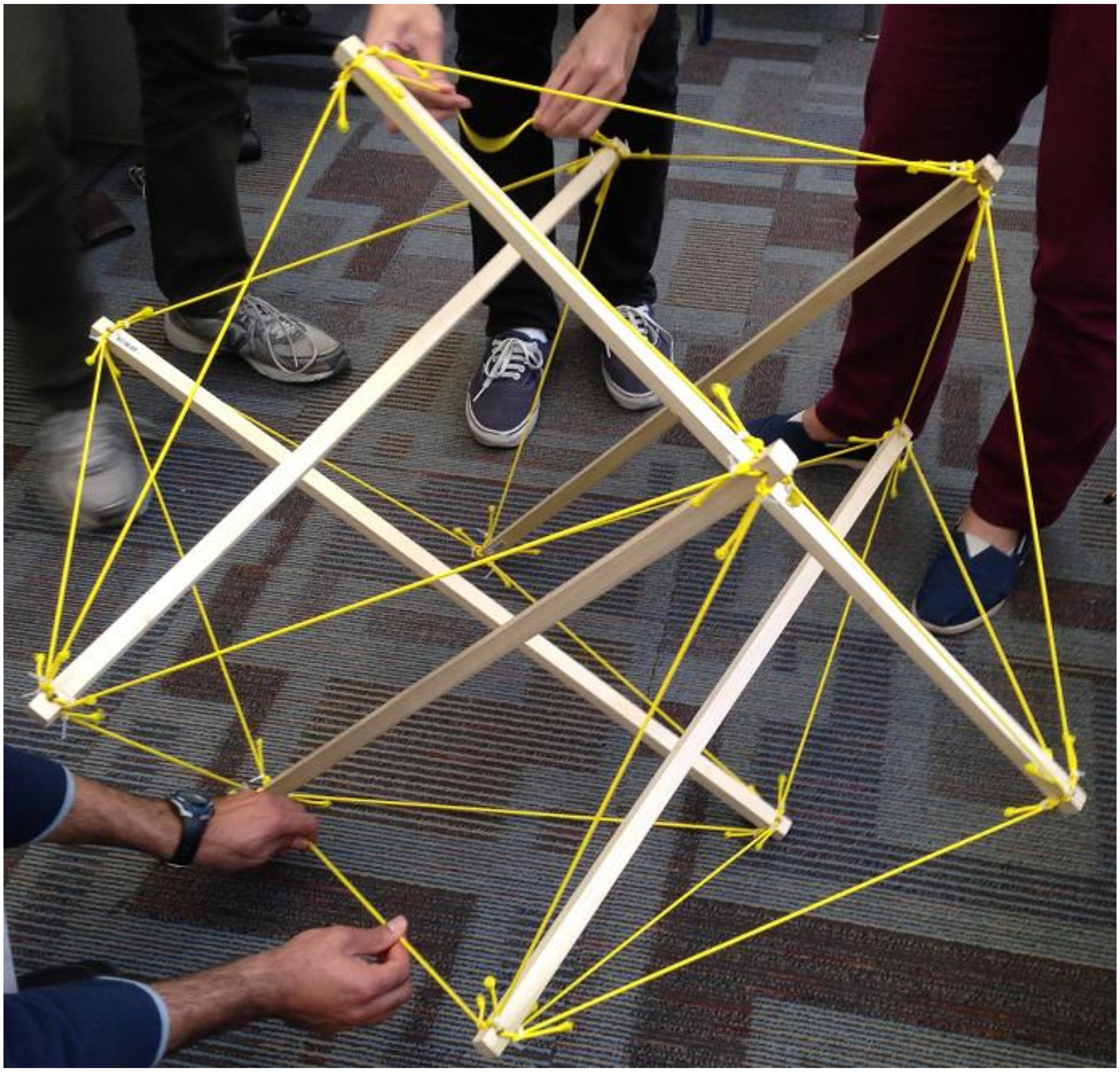


Figure 3: “Tensegrity Kit” Prototype

The current prototype includes linear actuators on the elastic strings to control their lengths. Using triangular wave actuations on eight of the twenty-four strings, the team accomplished two-step rolling motion: starting with an equilateral triangle face touching the ground, moving to an isosceles triangle face, and ending in another equilateral triangle face. Since the six-rod tensegrity structure is rotationally symmetrical about the center, it should be fairly straightforward to generalize the two-step motion to any equilateral triangle orientation and accomplish continuous rolling motion. The “Tensegrity Kit” team worked closely with the Controls Group to hasten the process of finding good string combinations and actuation parameters.

2.3 NASA Tensegrity Robotics Toolkit

The software simulation component of the project focused on developing the NASA Tensegrity Robotics Toolkit (NTRT), a software physics simulation framework to simulate tensegrity structures and their interaction with the environment. The engine was built on top of the open source Bullet 3D Real-Time Multiphysics Library, which offered "state of the art collision detection, soft body and rigid body dynamics" used by numerous movie and game companies for realistic physical interactions [12]. The Bullet Library used an impulse and constraint-based engine to solve equations of motion, and provided the groundwork for rigid and soft body interactions, variable time stepping, and libraries for real-time graphics simulations.

The relevant computer programming classes used for the tensegrity implementation were the RigidBody class, the Muscle class, and the Controller class. The RigidBody class allowed the creation of the rods in the tensegrity structure, which were simplified to solid cylinders with predefined base radius, mass, length, and density. The Muscle class corresponded to cables that connect the rods, with predefined string constants, starting lengths, and rest lengths. The Controller class was utilized to dynamically control the string lengths during program runtime. The initial simulation parameters for the mass, lengths, and spring constants of the rods and cables are shown in **Table 1** below.

	Mass (g)	Length (m)	k (N/m)
Rods	192	0.9144	∞
Cables	52.8	0.5	100

Table 1: Initial Parameters Based on Tensegrity Kit Project

3 Methods and Results

3.1 Tensegrity Initialization

One issue with the previous framework was the code complexity involved in creating a new tensegrity structure in the program with a specified size and position. In order to create a simple six-rod tensegrity, the programmer had to manually find the three-dimensional coordinates for both ends of each of the six rods, which added up to thirty-six input parameters to calculate. The initialization procedure was greatly simplified by using the symmetry in the tensegrity structure. The new framework reduced the amount of input parameters to four: the three-dimensional coordinates of the center of mass and the radius of the tensegrity structure from the center to the end of a rod (**Figure 4**).

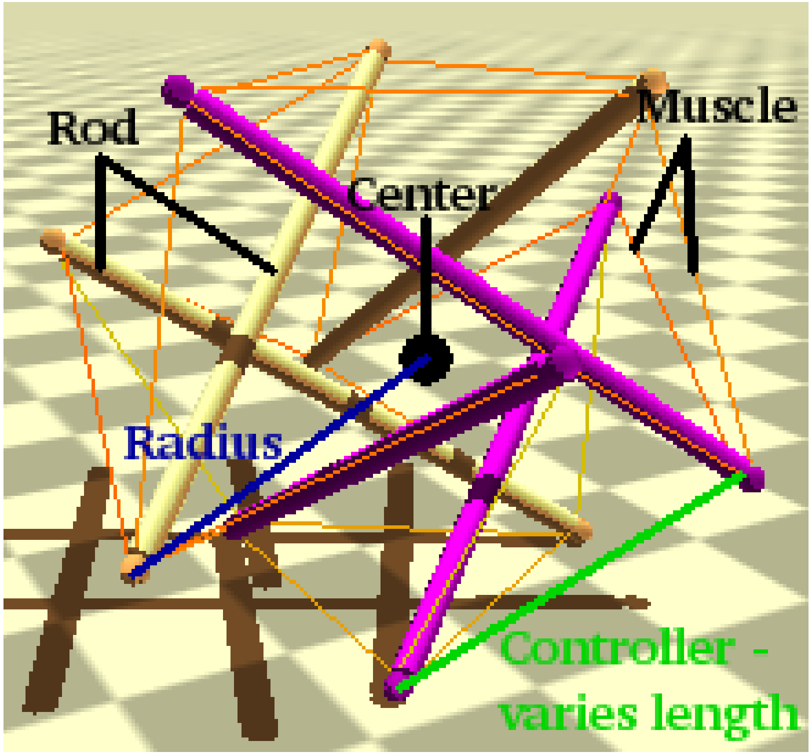
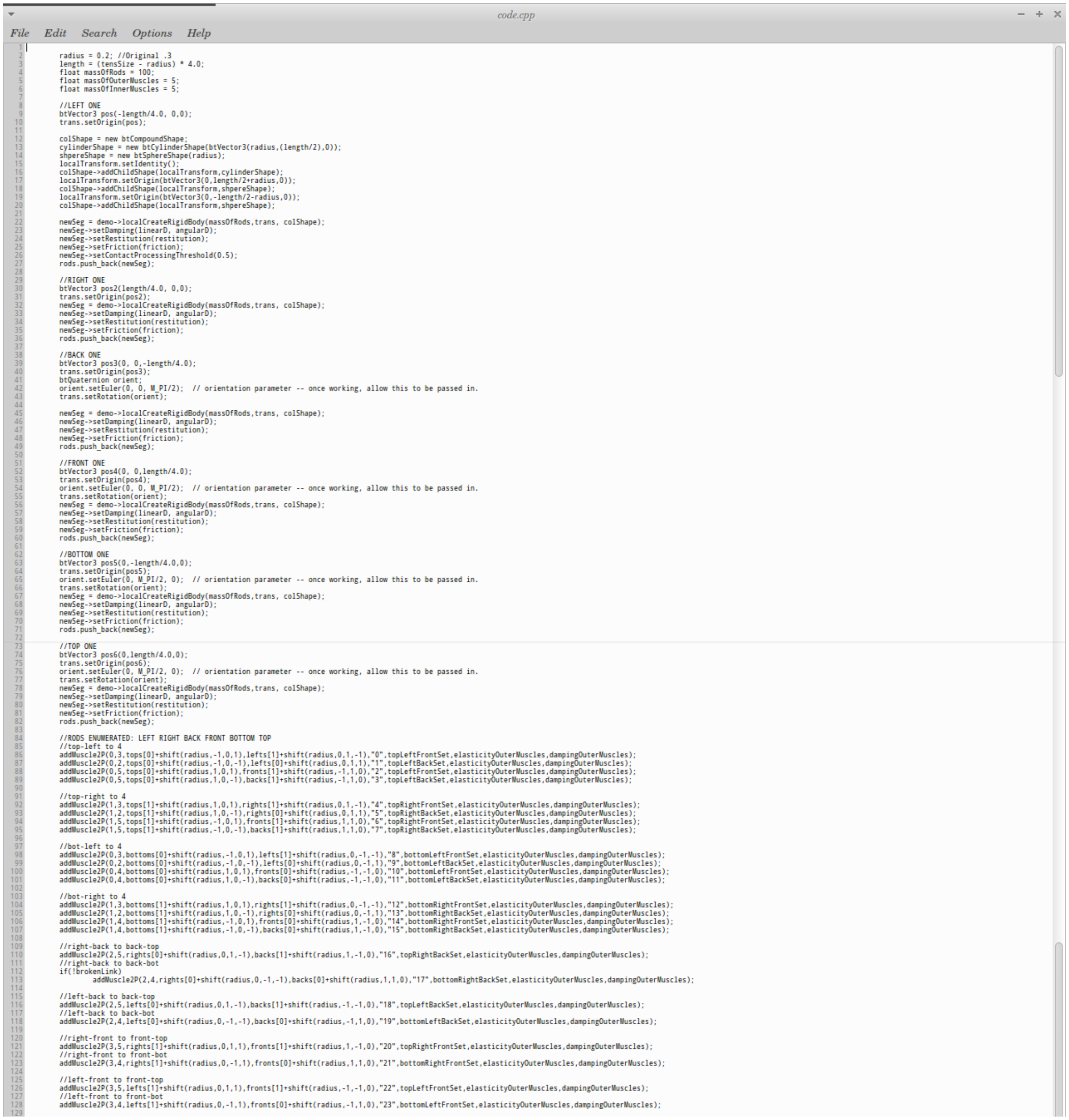


Figure 4: Initialized Six-rod Spherical Tensegrity

Although the new framework allowed less fine-grain tuning, it kept the parameters that were most frequently changed and significantly reduced the time needed to program a working simulation. It also lessened the amount of time required for the structure to reach equilibrium at the beginning of the simulations, since the computed rod and cable lengths from the radius are typically closer to equilibrium than manually defined values. The screenshots below illustrates the reduction in code changing from the old initialization framework (**Figure 5**) to the new one (**Figure 6**).




```
	radius = 0.2; //Original .3
	length = (tensSize - radius) * 4.0;
	float massOfRods = 100;
	float massOfOuterMuscles = 5;
	float massOfInnerMuscles = 5;

	//LEFT ONE
	btVector3 pos(-length/4.0, 0,0);
	trans.setOrigin(pos);

	colShape = new btCompoundShape;
	cylinderShape = new btCylinderShape(btVector3(radius,(length/2),0));
	shpereShape = new btSphereShape(radius);
	localTransform.setIdentity();
	colShape->addChildShape(localTransform,cylinderShape);
	localTransform.setOrigin(btVector3(0,length/2+radius,0));
	colShape->addChildShape(localTransform,shpereShape);
	localTransform.setOrigin(btVector3(0,-length/2-radius,0));
	colShape->addChildShape(localTransform,shpereShape);

	newSeg = demo->localCreateRigidBody(massOfRods,trans, colShape);
	newSeg->setDamping(linearD, angularD);
	newSeg->setRestitution(restitution);
	newSeg->setFriction(friction);
	newSeg->setContactProcessingThreshold(0.5);
	rods.push_back(newSeg);

	//RIGHT ONE
	btVector3 pos2(length/4.0, 0,0);
	trans.setOrigin(pos2);
	newSeg = demo->localCreateRigidBody(massOfRods,trans, colShape);
	newSeg->setDamping(linearD, angularD);
	newSeg->setRestitution(restitution);
	newSeg->setFriction(friction);
	rods.push_back(newSeg);

	//BACK ONE
	btVector3 pos3(0, 0,-length/4.0);
	trans.setOrigin(pos3);
	btQuaternion orient;
	orient.setEuler(0, 0, M_PI/2);  // orientation parameter -- once working, allow this to be passed in.
	trans.setRotation(orient);

	newSeg = demo->localCreateRigidBody(massOfRods,trans, colShape);
	newSeg->setDamping(linearD, angularD);
	newSeg->setRestitution(restitution);
	newSeg->setFriction(friction);
	rods.push_back(newSeg);

	//FRONT ONE
	btVector3 pos4(0, 0,length/4.0);
	trans.setOrigin(pos4);
	orient.setEuler(0, 0, M_PI/2);  // orientation parameter -- once working, allow this to be passed in.
	trans.setRotation(orient);
	newSeg = demo->localCreateRigidBody(massOfRods,trans, colShape);
	newSeg->setDamping(linearD, angularD);
	newSeg->setRestitution(restitution);
	newSeg->setFriction(friction);
	rods.push_back(newSeg);

	//BOTTOM ONE
	btVector3 pos5(0,-length/4.0,0);
	trans.setOrigin(pos5);
	orient.setEuler(0, M_PI/2, 0);  // orientation parameter -- once working, allow this to be passed in.
	trans.setRotation(orient);
	newSeg = demo->localCreateRigidBody(massOfRods,trans, colShape);
	newSeg->setDamping(linearD, angularD);
	newSeg->setRestitution(restitution);
	newSeg->setFriction(friction);
	rods.push_back(newSeg);

	//TOP ONE
	btVector3 pos6(0,length/4.0,0);
	trans.setOrigin(pos6);
	orient.setEuler(0, M_PI/2, 0);  // orientation parameter -- once working, allow this to be passed in.
	trans.setRotation(orient);
	newSeg = demo->localCreateRigidBody(massOfRods,trans, colShape);
	newSeg->setDamping(linearD, angularD);
	newSeg->setRestitution(restitution);
	newSeg->setFriction(friction);
	rods.push_back(newSeg);

	//RODS ENUMERATED: LEFT RIGHT BACK FRONT BOTTOM TOP
	//top-left to 4
	addMuscle2P(0,3,tops[0]+shift(radius,-1,0,1),lefts[1]+shift(radius,0,1,-1),"0",topLeftFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(0,2,tops[0]+shift(radius,-1,0,-1),lefts[0]+shift(radius,0,1,1),"1",topLeftBackSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(0,5,tops[0]+shift(radius,1,0,1),fronts[1]+shift(radius,-1,1,0),"2",topLeftFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(0,5,tops[0]+shift(radius,1,0,-1),backs[1]+shift(radius,-1,1,0),"3",topLeftBackSet,elasticityOuterMuscles,dampingOuterMuscles);

	//top-right to 4
	addMuscle2P(1,3,tops[1]+shift(radius,1,0,1),rights[1]+shift(radius,0,1,-1),"4",topRightFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(1,2,tops[1]+shift(radius,1,0,-1),rights[0]+shift(radius,0,1,1),"5",topRightBackSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(1,5,tops[1]+shift(radius,-1,0,1),fronts[1]+shift(radius,1,1,0),"6",topRightFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(1,5,tops[1]+shift(radius,-1,0,-1),backs[1]+shift(radius,1,1,0),"7",topRightBackSet,elasticityOuterMuscles,dampingOuterMuscles);

	//bot-left to 4
	addMuscle2P(0,3,bottoms[0]+shift(radius,-1,0,1),lefts[1]+shift(radius,0,-1,-1),"8",bottomLeftFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(0,2,bottoms[0]+shift(radius,-1,0,-1),lefts[0]+shift(radius,0,-1,1),"9",bottomLeftBackSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(0,4,bottoms[0]+shift(radius,1,0,1),fronts[0]+shift(radius,-1,-1,0),"10",bottomLeftFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(0,4,bottoms[0]+shift(radius,1,0,-1),backs[0]+shift(radius,-1,-1,0),"11",bottomLeftBackSet,elasticityOuterMuscles,dampingOuterMuscles);

	//bot-right to 4
	addMuscle2P(1,3,bottoms[1]+shift(radius,1,0,1),rights[1]+shift(radius,0,-1,-1),"12",bottomRightFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(1,2,bottoms[1]+shift(radius,1,0,-1),rights[0]+shift(radius,0,-1,1),"13",bottomRightBackSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(1,4,bottoms[1]+shift(radius,-1,0,1),fronts[0]+shift(radius,1,-1,0),"14",bottomRightFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	addMuscle2P(1,4,bottoms[1]+shift(radius,-1,0,-1),backs[0]+shift(radius,1,-1,0),"15",bottomRightBackSet,elasticityOuterMuscles,dampingOuterMuscles);

	//right-back to back-top
	addMuscle2P(2,5,rights[0]+shift(radius,0,1,-1),backs[1]+shift(radius,1,-1,0),"16",topRightBackSet,elasticityOuterMuscles,dampingOuterMuscles);
	//right-back to back-bot
	if(!brokenLink)
		addMuscle2P(2,4,rights[0]+shift(radius,0,-1,-1),backs[0]+shift(radius,1,1,0),"17",bottomRightBackSet,elasticityOuterMuscles,dampingOuterMuscles);

	//left-back to back-top
	addMuscle2P(2,5,lefts[0]+shift(radius,0,1,-1),backs[1]+shift(radius,-1,-1,0),"18",topLeftBackSet,elasticityOuterMuscles,dampingOuterMuscles);
	//left-back to back-bot
	addMuscle2P(2,4,lefts[0]+shift(radius,0,-1,-1),backs[0]+shift(radius,-1,1,0),"19",bottomLeftBackSet,elasticityOuterMuscles,dampingOuterMuscles);

	//right-front to front-top
	addMuscle2P(3,5,rights[1]+shift(radius,0,1,1),fronts[1]+shift(radius,1,-1,0),"20",topRightFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	//right-front to front-bot
	addMuscle2P(3,4,rights[1]+shift(radius,0,-1,1),fronts[0]+shift(radius,1,1,0),"21",bottomRightFrontSet,elasticityOuterMuscles,dampingOuterMuscles);

	//left-front to front-top
	addMuscle2P(3,5,lefts[1]+shift(radius,0,1,1),fronts[1]+shift(radius,-1,-1,0),"22",topLeftFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
	//left-front to front-bot
	addMuscle2P(3,4,lefts[1]+shift(radius,0,-1,1),fronts[0]+shift(radius,-1,1,0),"23",bottomLeftFrontSet,elasticityOuterMuscles,dampingOuterMuscles);
```

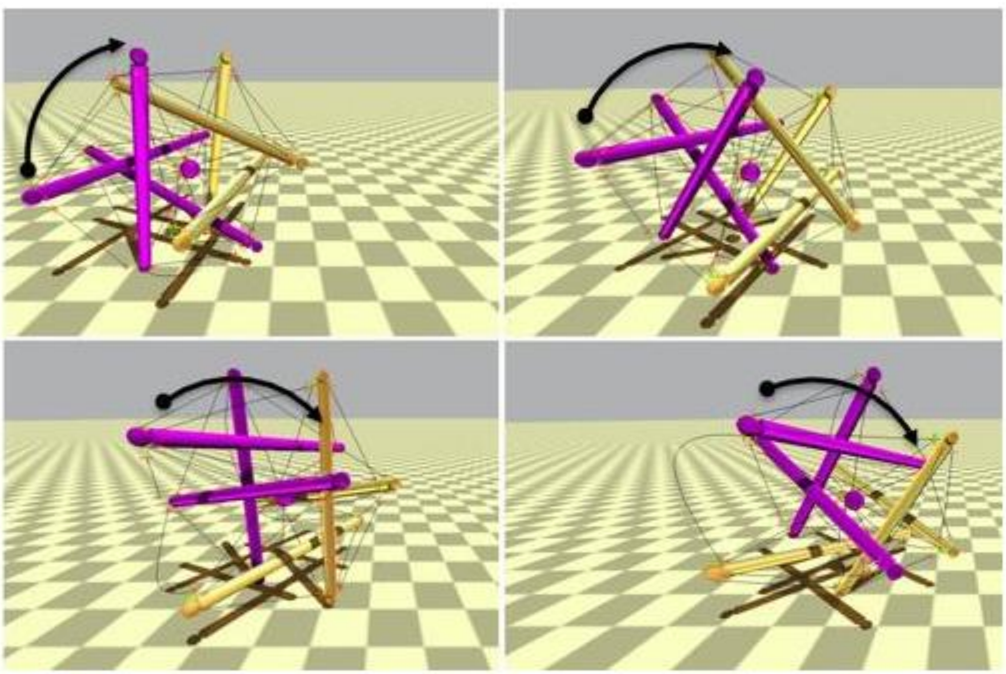
Figure 5: Old Initialization Framework

```cpp
btVector3 location(0,3,0);
btVector3 rotation(0,0.6,0.8);
btVector3 speed(0,0,0);
double tensRadius = 3.0;
ManhattanToyBig* tensCon = new ManhattanToyBig(pdemo,location,rotation,speed,"TensControl",tensRadius);
```

Figure 6: New Initialization Framework

3.2 Dynamic Control of Tensegrity Robots

The unique structure and interconnections of a tensegrity body complicated locomotion control, as a force applied to any point in a tensegrity structure would be transmitted through the whole tensional network. Traditional control strategies for rigid bodies were not well adapted for the tensegrity robots because their responses to impulses were non-linear and oscillatory [5]. Therefore, new control strategies had to be developed.



The Super Ball Bot tensegrity structure can achieve a smooth rolling motion, accomplished solely by changing cable length. The NASA Ames research team's learned control policies produce rolling that is also dynamical, since the tensegrity structure does not need to stop to set up its next roll action. This type of rolling can be fast and highly efficient.
(Source: NASA Ames Research Center)

Figure 7: Tensegrity Locomotion Control by Changing Cable Lengths [13]

The main goal for locomotion control is to move the tensegrity robot via internal forces from actuators within the structure, without aid from and sometimes even counter to external forces such as gravity. An intuitive and mechanically viable way to accomplish this task is to shift the center of mass by expanding and contracting cables or rods within the tensegrity, thus pushing the robot to fall in the desired direction. In regards to the physical prototypes, it is easier to implement actuators that shift the lengths of the soft cables rather than the rigid rods. Since two major goals of the simulations are to replicate observations from the physical robots and suggest potential actuation strategies, the software simulations mainly focus on cable actuations similar to those in the "Tensegrity Kit" physical prototype.

The past approach in simulation was to use a machine learning strategy to maximize the distance traveled by the tensegrity robot. The open-loop control policy was based on sinusoidal actuators controlling the rest length l of the springs based on the function $l(t) = A\sin(wt + \Phi) + l_0$, where A, w, Φ, and l_0 were coevolved within an evolutionary framework [14]. Although this approach was capable of learning a rolling gait after around 10,000 learning iterations, the resulting control algorithm was difficult to replicate in the physical prototype and even other simulation frameworks using rigorous mathematical approaches [15]. The actuators also could not be dynamically modified with parameter inputs during simulation to fine-tune the effects.

We developed a framework to allow for dynamic control of actuation parameters during simulation runtime. Since actuators in the physical world do not match given control signals instantaneously, a basic position control loop was implemented to simulate the delay between receiving the control signal and moving the motor to the desired position. Given the desired length of a single string, the string would expand or contract based on a predefined motor speed and the amount of time passed. The equation is shown below (L_{i+1} = length at next timestep, L_i = length at current timestep, L_d = desired length, M = motor speed, dt = change in time):

$$L_{i+1} = L_i + \text{sign}(L_d - L_i)*M*dt$$

As shown in the equation, the actual length of a cable at a particular timestep (L_i) is not necessarily equivalent to the desired length of the cable (L_d). This is an attempt to simulate actuation behavior in the real world. The graph in **Figure 8** illustrates how the desired and actual lengths resemble each other but do not perfectly match up. In particular, the actual length never reaches the maximum and minimum lengths specified by the desired triangular wave because of the motor delay.

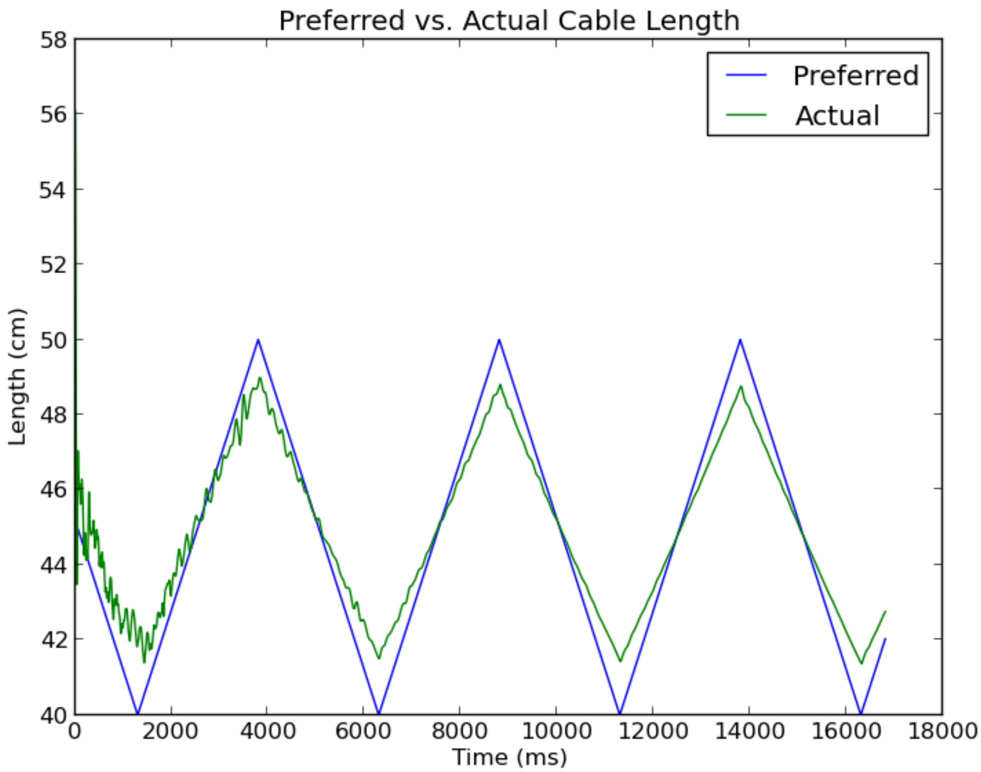
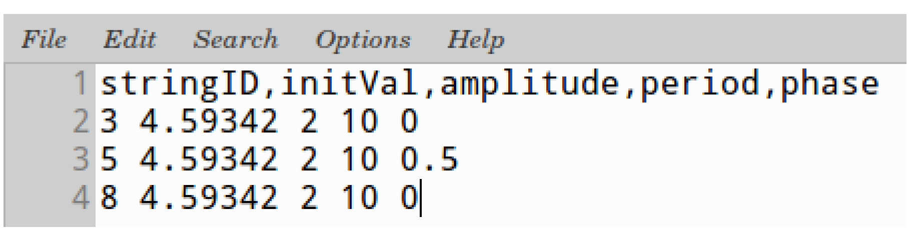


Figure 8: Preferred vs. Actual Cable Length

The real-time control of the cable actuations was done by parsing a text file that could be modified by the user or a program before or while running the simulation. The text file specified the function parameters – initial value, amplitude, period, and phase – for a triangular or sin wave that described the desired lengths of the cables at specific simulation times. The contents of an example text file is shown below in **Figure 9**.



Note: Values from line 2 onwards are space-separated, following the order specified in the comma-separated parameters in line 1.

Figure 9: Input Text File Specifying Cable Actuation Parameters

3.3 Tensegrity Rolling Using Three-String Actuation

Using the above controls framework, the effects of tuning various string actuation parameters were observed in simulation. In particular, the simulation model realized rolling locomotion by actuating only three of the twenty-four cables at any given timeframe. Three cable actuation stemmed from the idea to actuate as few actuators as possible and still accomplish rolling movement so power consumption is minimized. One and two cable actuations were also attempted in simulation; however, the robot did not show promising movement without significant actuation speed and power not available in the current physical motors.

To figure out the optimal combination of three cables, the simulation was run with all possible three-string combinations using triangular wave actuation parameters similar to that of the linear actuators in the "Tensegrity Kit" physical prototype. The exact parameters were an initial value of 50 centimeters, amplitude of 20 centimeters, and period of 10 seconds. In addition, the phases of the triangular waves were also methodologically altered. For each combination of three-strings, four simulations were run: one with phases in sync and three with one of the string actuations in antiphase (one wave is at the maximum amplitude when the other waves are at the minimum amplitude). Successful rolling simulations were accomplished by actuating one cable from the equilateral triangle base and two cables from the top of the structure. Snapshots from the associated rolling simulation are shown in **Figure 10**.

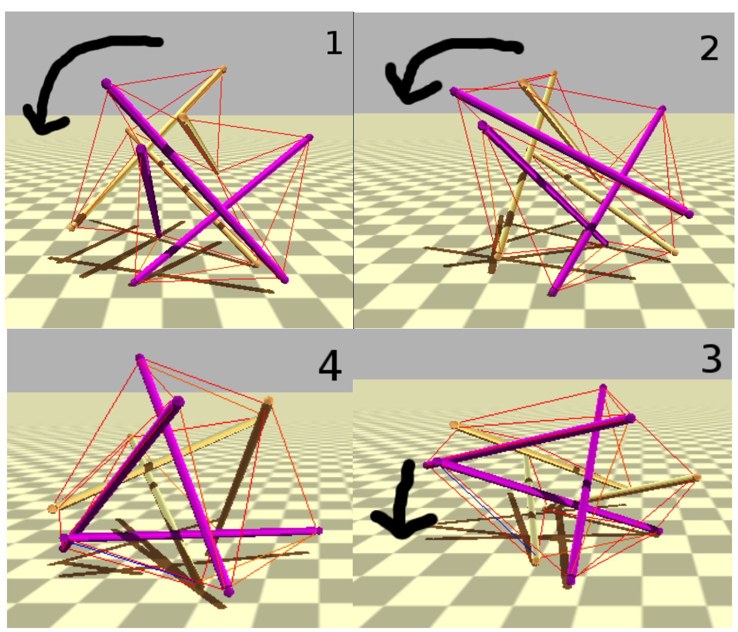


Figure 10: Rolling Simulation Using Three-String Actuation

3.4 Physical Prototype Tests – Nine and Five-String Actuations

With the simulation framework described above, our team tested various control strategies and compared the results with the "Tensegrity Kit" physical prototype to confirm their validity. A physical six-rod tensegrity prototype built using wooden rods was actuated by contracting a subset of the twenty-four linear actuators controlling the lengths of the strings. The three-cable control strategy that succeeded in the software simulation did not produce enough momentum to produce rolling movement in the physical prototype. Therefore, a new control strategy that actuated nine cables was proposed to increase the shift in center of mass and move the robot.

The control algorithm utilizing contractions in nine of the twenty-four strings allowed the physical robot to accomplish a two-step rolling motion. The robot was able to start in a stable configuration with an equilateral triangle face touching the ground, rotate to a relatively less stable isosceles triangle face, and end in a different stable equilateral triangle face. The results of the two-step motion were replicated in the NASA Tensegrity Robotics Toolkit. Frames from the rolling motion video are shown below in **Figure 11**.

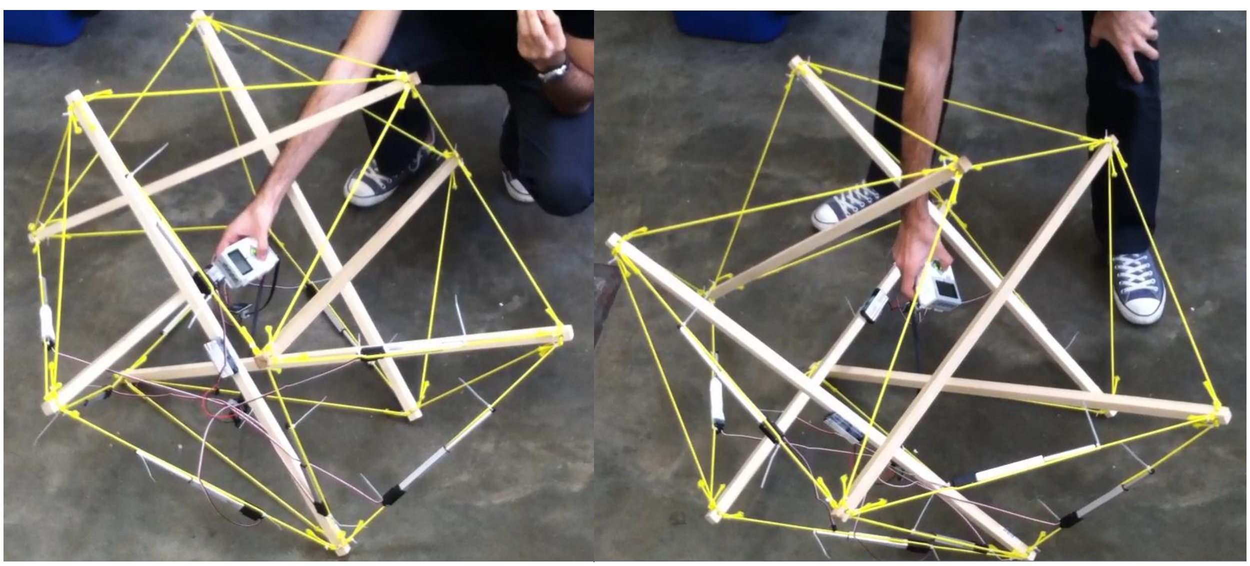


Figure 11: Rolling Motion of Physical Prototype

From the physically proven nine-cable actuation, the team was able to find a more efficient actuation strategy using only five of the nine actuators in the simulation. The positional values of the structural center of mass for the five-actuator rolling motion are graphed in **Figure 12**. The five-cable actuation strategy also succeeded in the physical prototype after modifications to make the linear actuators more effective. Furthermore, by using the symmetry in the tensegrity structure, we were able to implement continuous rolling motion in the software simulation [16].

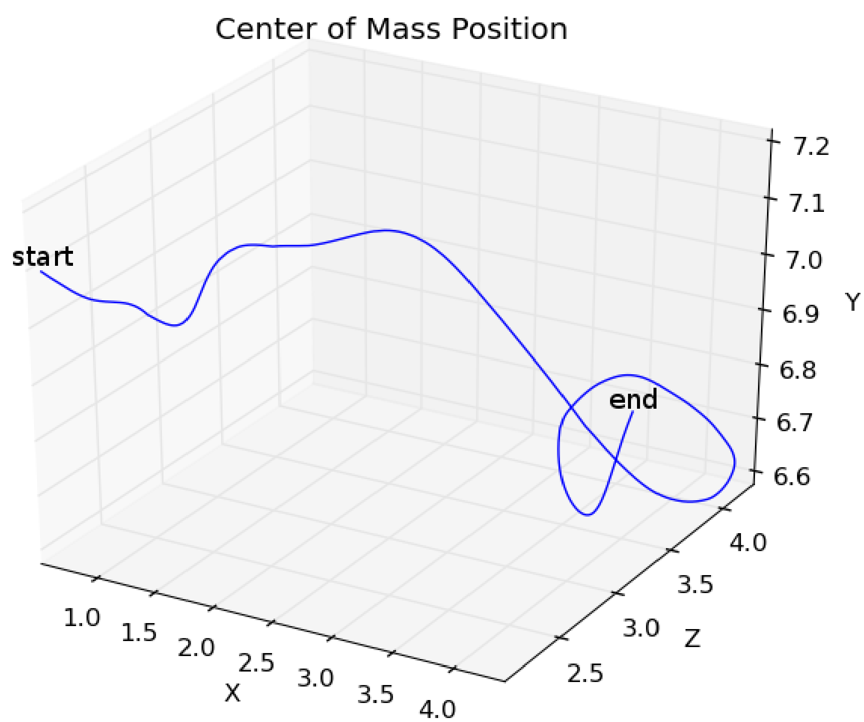


Figure 12: Center of Mass Position for Five Actuator Two-Step Motion

4 Discussion

4.1 Physical Prototype and Simulation Differences

One major difference between the physical prototype and the software simulation was the effect of external forces. The simulation framework utilized a simplified model that disregarded air drag and assumed a constant friction from the floor. The air drag proved to be a negligible factor in physical tests; however, the friction from the floor was significantly higher in the physical tests and altered depending on the motion of the rods and cables. The simulation constants are shown in **Table 2** below.

Property	Value	Units
Gravity	-10	m/s^2
Ground Friction Coeff.	2.7	---
Single Time Step (dt)	1.0	Ms

Table 2: Simulation Constants

Another difference between the two models was the behavior of the actuators. The simulation assumed that the actuators had negligible mass in the computations. This proved to not be the case in the physical tests. The mass from the actuators noticeably weighted down the structure and shifted the center of mass, making it easier to roll in one direction compared to the opposite direction depending on the actuator placements. Additionally, the linear actuators expanded and contracted at a fixed maximum speed no matter how stretched or compressed the cables in the simulations. Those simulation approximations made it more difficult for the physical prototype to replicate the success in the software.

Despite the differences between the physical prototype and the simulations, the “Tensegrity Kit” team replicated the two-step motion in the simulation with the physical structure by actuating nine of the twenty-four cables, and later five of the twenty-four cables. The parallel results in the physical prototype validated the usage of software simulations to conduct initial tests and hasten the development process.

However, the physical prototype actuated five cables to accomplish the same motion as actuating three cables in the simulation. Furthermore, the tensegrity prototype was never able to accomplish continuous rolling locomotion by merely controlling the lengths of five cables as in the software simulation. Nevertheless, the capacity for the physical structure to move at all was a promising beginning for more complex locomotion of the tensegrity structure.

4.2 Software Simulation Robustness for Tensegrity

Previous work on control for tensegrity robots utilized evolutionary algorithms to “learn” the actuation parameters. Atil Iscen et al. [14], Ken Caluwaerts et al. [17] and Chandana Paul et al. [18] had all developed evolutionary algorithms that successfully simulated robust rolling motion in software. Atil Iscen et al. used “an open-loop control policy based on sinusoidal actuators coevolved in order to maximize the distance traveled by the tensegrity robot” [5]. Ken Caluwaerts et al. proposed “a closed-loop control strategy based on reservoir computing […] to generate [signals] using a central pattern generator (CPG) and evolve parameters of a neural network” [5].

However, control strategies developed by evolutionary algorithms were complicated to realize in physical structures, since the actuation parameters might differ greatly for similar motions, such as rolling left and rolling right, or change multiple times within a second. Consequently, prior physical prototypes had not been able to replicate the rolling motions in simulation.

A major goal for the Controls Group was to accomplish the same movements using simpler motions that could be easily realized in a linear actuator. We had not yet reached the goal of continuous rolling motion in the physical prototype. However, the two-step rolling motion we did accomplish proved the viability of moving the tensegrity robot with simple linear string actuations.

For the most part, software simulations were consistent with the physical tests on tensegrity dynamic motion. However, there were instances when the tensegrity model in simulation would vibrate without any visible forces. This could be a software bug in the simulation program, and we are currently attempting to fix the issue.

There were also simulation behaviors that were difficult or impossible to replicate in the physical prototype. For instance, the software tensegrity model would break apart when a combination of strings were stretched beyond four times their original rest length. However, the motors in the physical prototype could not apply enough force to replicate the behavior.

Despite the shortcomings of software simulation to exactly replicate the physical environment, it approximates real-world interactions well enough to provide useful preliminary analysis. Simulations were also valuable in providing initial actuation parameters to test. Additionally, physical locations that are impractical to do prototype tests, such as the environment on Titan, can be simulated in software.

5 Conclusion

This capstone project provided initial assessments on the viability of developing and controlling tensegrity robots for use in extraterrestrial exploration. The single-rod physical prototype designed by the Mechatronics Group proved the manufacturing viability and impact resilience of the tensegrity structure. The six-rod wooden prototype illustrated the viability of moving the tensegrity robot with linear actuators. The software simulation results provided support for the capability of continuous rolling motion on both Earth and Titan.

In respect to space exploration, the research combining tensegrity and robotics is still in its infancy stages. As mentioned in this report, progress is still being made for rolling locomotion of a physical prototype on a flat surface under Earth's gravity. The NASA team working on the development projects eight more years of research, design, and tests before the product is ready for the launch to Titan.

Software simulations of the robot experienced greater success in rolling locomotion. However, further developments are required to produce control strategies that can be implemented in a physical prototype. Control algorithms for other tensegrity motions, such as compression and bouncing, are also works in progress for the simulation. The NASA Tensegrity Robotics Toolkit also has the capability to change the material properties of the rods and cables, which can be further explored to produce the optimal movements.

Tensegrity robots have so far proved to be promising replacements to rigid robots based on the initial research and prototypes. The reduced weight and increased flexibility and impact resilience from using the tensegrity structure suggest exciting potential in the future of robotics and extraterrestrial exploration.

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Thesis: Viability of Tensegrity Robots in Space Exploration

Student Name: Eric Cheng-yu Hong

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Approved by:

1. Capstone Project Advisor:

Signature: ___________________________ Date _____________

Print Name/Department: Alice M. Agogino / ME

2. Faculty Committee Member #2:

Signature: ___________________________ Date _____________

Print Name/Department: Edward A. Lee / EECS