Final Report
Super Ball Bot - Structures for Planetary Landing and Exploration
for the
NASA Innovative Advanced Concepts (NIAC) Program

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1 Executive Summary

Small, light-weight and low-cost missions will become increasingly important to NASA’s exploration goals. Ideally teams of small, collapsable, light weight robots, will be conveniently packed during launch and would reliably separate and unpack at their destination. Such robots will allow rapid, reliable in-situ exploration of hazardous destination such as Titan, where imprecise terrain knowledge and unstable precipitation cycles make single-robot exploration problematic. Unfortunately landing lightweight conventional robots is difficult with current technology. Current robot designs are delicate, requiring a complex combination of devices such as parachutes, retrorockets and impact balloons to minimize impact forces and to place a robot in a proper orientation. Instead we propose to develop a radically different robot based on a “tensegrity” structure and built purely with tensile and compression elements. Such robots can be both a landing and a mobility platform allowing for dramatically simpler mission profile and reduced costs. These multi-purpose robots can be light-weight, compactly stored and deployed, absorb strong impacts, are redundant against single-point failures, can recover from different landing orientations and can provide surface mobility. These properties allow for unique mission profiles that can be carried out with low cost and high reliability (see Figure 1). We believe tensegrity robot technology can play a critical role in future planetary exploration.

Figure 1: Tensegrity structures are composed of pure compression and tension elements. They can be lightweight, reliable, deployable, and efficient to manipulate. Mission Scenario - Tightly packed set of tensegrities, expand, spread out, fall to surface of moon, then safely bounce on impact. The same tensegrity structure which cushioned the landing is then used for mobility to explore moons such as Titan and small asteroids.

Our Phase I study explored: 1) Feasibility of applying tensegrities to a low-cost, high science return mission to Saturn’s moon Titan. 2) Ability to control these oscillatory structures through evolutionary and central pattern generator based algorithms. 3) Effectiveness of tensegrities as a landing and mobility platform. These studies resulted in three important conclusions:
1. Tensegrities can be an effective landing and mobility platform for a Titan mission. A tensegrity mission can have a high mass fraction between science payload and overall weight (as measured at atmospheric entry) due to its dual use as a landing system (like an airbag) and as a system for surface mobility. As a result, tensegrity based missions can be cheaper and open up new forms of surface exploration that take advantage of their natural tolerance to impacts.

2. We demonstrated in our physics based simulator that tensegrity probes can be controlled effectively with evolutionary and dynamical algorithms resulting in robust smooth rolling motion over a variety of terrains.

3. Using multiple analysis and simulation tools we showed that Tensegrities are a very robust landing platform, and can protect delicate payloads from a landing impact of 15 m/s (and possibly beyond). This was further confirmed by performing drop tests on multiple physical prototypes.

Figure 2: Tensegrity Evaluations. Phase I study showed: A) That tensegrities can be controlled for mobility, B) That our partially actuated hardware prototype can be efficiently stowed and deployed (with greater stowage efficiency when fully actuated), and C) analytical and physical drop tests confirm that the probe can serve as an effective landing platform.

These results are summarized in Figure 2. The top-left figure shows a tensegrity in simulation rolling over uneven terrain using our control algorithms. The top-right figures shows a hardware tensegrity prototype using its own actuation to stow and deploy (better stowage is possible with full actuation). The bottom figures shows the drop test of a prototype landing at speeds equivalent to terminal velocity on Titan.
2 Introduction

2.1 Mission Concept

Tenegritity robots can facilitate an intriguing low-cost planetary exploration mission profile (see Figure 1) comprising of the following stages: 1) A set of tenegritity robots can be squeezed into a small launch platform; 2) After initial atmospheric entry and ejection of the heat shield, they can automatically spring away from each other when released at their destination. 3) They “bounce” on impact reducing the need for final descent equipment, such as airbags; and 4) They can reorient themselves from landed position without addition reorientation hardware and efficiently move from scattered initial positions to perform sensor measurements; 5) They can survive significant falls and are resistant to being stuck, simplifying route planning and allowing for more aggressive exploration in the pursuit of science.

Once on the surface, tensegrity robots can perform an array of scientific analysis including soil and atmospheric composition, surface imagery and microscopic analysis. To further reduce complexity, sensors can be suspended on the interior of the tensegrity on cables attached to the nodes, or when appropriate even to the nodes themselves so that the sensors can be moved with movements of the structure itself, eliminating the need for separate sensor arms. In addition environmental analysis can be performed in-situ at the landing site, at different local locations, or even at distant locations given a tensegrity robot’s potential for efficient locomotion. The biggest advantages of this mission profile are:

1. The structure of the robot itself provides capability for deployment, landing (EDL), and mobility, reducing complexity, risk, and mass compared to using three separate systems.
2. Tensegrity robots are light-weight and can be packed tightly, reducing cost;
3. Multiple robots speed up science return and reduce risk.
4. Flexibility of robot allows design reuse, reducing mission project risk.

2.2 Reusability, Redundancy, Reliability

This mission concept has three fundamental desirable properties 1) Design Reusability - The core design of a tensegrity robot is simply composed of off-the-shelf rods, cables and actuators. All instances of these components are nearly identical and do not have to be custom machined, significantly reducing design complexity and project risk. In addition, using the same basic components of rods and actuators, many different morphologies are possible, with different landing and mobility characteristics that can be tailored to different missions. 2) Redundancy - Due to their light-weight and collapsibility, multiple tensegrity robots can be packed together and deployed, then land and carry out their mission independently. In addition, individual tensegrities are robust against actuator failure, as performance gracefully degrades as the number of failures increases. 3) Reliability - Structural components can be made robust since they undergo pure linear tension and
Figure 3: **Tensegrity Structure.** Tensegrities are composed of pure tension and pure compression elements (e.g. cables and rods) as seen in this picture of a tensegrity robot from our physics based tensegrity simulator. They are light-weight, energy-efficient and robust to failures.

compression, reducing sheer and bending forces. In addition, the flexible nature of its movements allows the tensegrity robot to recover from awkward landing positions, being stuck, or even falling or rolling from significant heights.

### 2.3 Enabling the Mission

While tensegrities have the potential to dramatically reduce the cost and increase the reliability of robotic missions, significant technology development is still needed to enable such missions. Our study has made large strides towards showing that a tensegrity landing and mobility platform is feasible by showing that:

1. Tensegrities can be an effective landing and mobility platform for a Titan mission. A tensegrity mission can have a high mass fraction between science payload and overall weight (as measured at atmospheric entry) due to its dual use as a landing system (like an airbag) and as a system for surface mobility. As a result, tensegrity based missions can be cheaper and open up new forms of surface exploration that take advantage of their natural tolerance to impacts.

2. We demonstrated in our physics based simulator that tensegrity probes can be controlled effectively with evolutionary and dynamical algorithms resulting in robust smooth rolling motion over a variety of terrains.

3. Using multiple analysis and simulation tools we showed that Tensegrities are a very robust landing platform, and can protect delicate payloads from a landing impact of 15 m/s (and possibly beyond). This was further confirmed by performing drop tests on multiple physical prototypes.

These results served our Phase I study goals of showing that our tensegrity landing and mobility platform is theoretically possible and relevant to NASA.
3 Organization of this Report

The goal of this final report is to detail all of our activities related to our Phase I study. This report is organized as follows:

- Section 4 - A summary the basics of tensegrity robotics including their unique structure and possible control methods.
- Section 5 - A summary of our three key findings from our Phase I study as they relate to our three original research goals for this study.
- Section 6 - A detailed description of a notional mission to Titan describing both the mission and advantages a tensegrity probe has over traditional alternatives for landing and mobility.
- Section 7 - A detailed description how to control a tensegrity robot using evolutionary algorithms, including performance experiments in simulation showing how these algorithms are robust to numerous challenges.
- Section 8 - A detailed description of how dynamical controls and neuroscience inspired central pattern generators may be applied to tensegrity robotics.
- Section 9 - A detailed description of our initial hardware prototype designed to show deployment and landing characteristics along with a feasibility study for actuated tensegrities.
- Section 10 - A detailed analysis of the effectiveness of a tensegrity as a landing platform. This section includes analysis from a physics engine, an Euler-Lagrange solver, drop tests of a hardware tensegrity with payload, and drop tests of an actuated tensegrity probe. We also analyze the accuracy of the simulators.
- Section 11 - An outline of future work and the next steps required to mature this concept to Technology Readiness Level (TRL) 3-4.

Combined, these results form a strong picture of how a tensegrity robot can be used as an effective landing and mobility platform.
4 Background on Tensegrity Robotics

4.1 Tensegrity Structures

Tensegrity structures are composed of axially loaded compression elements encompassed within a network of tensional elements, and thus each element experiences either pure linear compression or pure tension. As a result, individual elements can be extremely lightweight as there are no bending or shear forces that must be resisted. An actively controlled tensegrity structure can be packed into small launch volumes and deployed when required. Active motion in tensegrity structures can be performed with minimal energy expenditure since actuators work linearly along the load paths in the tension elements, avoiding the torques caused by long lever arms of traditional robotic designs.

A unique property of tensegrity structures is how they can internally distribute forces. As there are no lever arms, forces do not magnify into joints or other common points of failure. Rather, externally applied forces distribute through the structure via multiple load paths, creating a system level robustness and tolerance to forces applied from any direction. Thus tensegrity structures can be easily reoriented in gravity fields and are ideally suited for operation in dynamic environments where contact forces cannot always be predicted. Likewise, tensesgities can be robust to the failure of individual actuation elements, resulting in a gradual reduction of overall workspace, rather than the loss of entire ranges of motion which are common in serial manipulators.

Figure 4: **Tensegrity Structures.** Left: NASA Ames simulation of tensegrity showing compression and tension elements. Right: Prototype tensegrity robot at NASA Ames. For the prototype actuation is performed with electric motors and pulleys that change the length of tension elements. Future models may use simple mechanisms to change cable length such as electro-elastomers.
4.2 Tensegrity and Biology

One of the most intriguing aspects of tensegrity structures is that they are being discovered in many aspects of biological systems. This property is being discovered at all scales, from the cytoskeleton of individual cells [29] to mammalian physiology [36]. Emerging biomechanical theories are shifting focus from bone-centric models to fascial-centric models. [36, 14] Fascia is the connective tissue in our bodies (including muscles, ligaments, tendons, etc.), and forms a continuous web of tension, even surrounding and supporting the bones which, unlike our traditional robots, have no rigid connections between them. [45] This new view is challenging the common sense view of our skeletal structure as the primary load bearing elements of our bodies. In the emerging biotensegrity model, bones are still under compression, but they are not passing compressive loads to each other, rather it is the continuous tension network of fascia (muscles, ligaments, tendons) that is the primary load path for forces passing through the body [35]. Recent anatomical research through fresh dissections (i.e. without preserving the cadaver, a process which changes the fascia) [44] is providing evidence of the global network of continuous connective tissue that manages force transfers in the body [45]. Tensegrity structures are a good model for this body-wide tension network. [18]

![Figure 5: Tensegrity models of the spine showing how vertebrae float without touching, image courtesy of Tom Flemons (copyright 2006) [18]](image)

4.3 Tensegrity Control

Tensegrity structures are a fairly modern concept, having been initially explored in the 1960’s by Buckminster Fuller [19] and the artist Kenneth Snelson [66, 65]. For the first few decades, the majority of tensegrity related research was concerned with form-finding techniques [78, 39, 69, 79] and the design and analysis of static structures [3, 31, 64]. Research into control of tensegrity structures was initiated in the mid-1990’s, with initial efforts at formalizing the dynamics of tensegrity structures only recently emerging [64]. The very properties that make tensegrities ideal for physical interaction with the environment (compliance, multi-path load distribution, non-linear dynamics, etc) also present significant challenges to traditional control approaches. A recent review [73] shows that there are still many open problems in actively controlling tensegrities. We believe that modern advances in control algorithms based on central pattern generators and distributed learning and genetic algorithms will be key elements in controlling tensegrity robots.
4.3.1 Control Based on Genetic Algorithms

Instead of defining a control policy directly, genetic algorithms can be used to “learn” a control policy. It does this through an iterative cycle, where in simulation a control policy is run and evaluated, and this evaluation is fed back into the genetic algorithm so that it can improve the control policy. Genetic algorithms have the following advantages:

1. Complex, nonlinear control policies can be learned.
2. Underlying physics of dynamics does not need to be known.
3. Control policies can be learned from scratch or optimal parameters of existing control policies can be learned.
4. Distributed learning can be used to scale to larger tensegrities and to speed up learning.

Genetic algorithms can learn very complex, nonlinear control policies without the need to characterize the physics behind the control policy. Recent advances in distributed genetic algorithms applied to control tasks have produced robust learning algorithms that are a perfect match for tensegrity control [17, 23, 12, 68, 75, 72, 1, 71, 25]. Through these methods, each component can individually learn a control policy that decides how to actuate its individual node in such a way that global performance is maximized.

4.3.2 Control Based on Central Pattern Generators

Central pattern generators (CPGs) are neural circuits found in both invertebrate and vertebrate animals that can produce rhythmic patterns of neural activity without receiving rhythmic inputs. CPGs have been studied from a biological perspective and have been used extensively in robotics [26], especially for walking and other locomotion research (swimming, slithering, flying, etc). They use the term “central” to indicate that rhythms of the CPG are not driven by sensory input, but are self-generated. CPGs are the fundamental building blocks for the locomotor neural circuits both in invertebrate and vertebrate animals, and are also key to other fundamental rhythmic activities such as chewing, breathing, and digesting. In fact, recent research [16] has shown a close relationship between CPG’s and motion primitives in the spine which enable both rhythmic and discrete motions. Besides the biological inspiration, CPG’s present several interesting properties that are useful to robotic motion including distributed control, robustness to perturbations, the ability to deal with redundancies, fast control loops, and allowing modulation of locomotion by simple control signals.

The complex problem of agile locomotion of a robot can be greatly simplified if the structure and reactive controls of the robot provide a high level of locomotion competence. An inspiring goal is how decerebrated mammals can coordinate complex locomotion behavior without the involvement of their brains [54]. Due to the inherent uncertainty of operating in unstructured natural environments, modern robotic locomotion and manipulation research often focuses on compliant actuation. Tensegrity structures, which model the musculoskeletal system, extend this focus on compliance to the entire structure of the robot, providing desirable qualities such as variable stiffness, robustness to perturbations, and multi-path force distribution. Reactive controls draw
inspiration from numerous biological studies showing significant locomotor computation below the brain (for examples and reviews see: cockroaches [56], stick insects [10], and cats [76, 54]), we focus on maximizing the reactive competence of our robots by exploring the combination of compliant tensegrity structures with central pattern generator (CPG) controls [27]. A motivating intuition for pairing tensegrity robots with CPG networks is the similarity in the dynamics of physical forces propagating through a tensegrity structure with the dynamics of control patterns propagating through CPG networks.

Use of tensegrity robots for mobility was initiated in 2004-6 by papers from Masic [40], Aldrich [2], and Paul [52, 53]. Masic’s paper included an analytical study of tensegrity based locomotion via periodic waves in a worm-like tensegrity robot; Paul demonstrated mobility both in a physics based simulator and on a hardware prototype. As a result of studies showing the prevalence of tensegrity structures in nature such as cell structure [28] and anatomy [35, 55], and the challenges of controlling tensegrity structures using traditional approaches, the majority of the works in mobile tensegrity robotics have shown biological inspiration in their motivation, using evolutionary algorithms [51, 52, 53, 57, 58, 59, 30], neuroscience inspired CPGs [6, 4, 5], and biomimetic structures such as manta-ray wings [43], or caterpillars [58, 49, 47, 48]. (See also [60, 62, 32, 7, 41] for other works on the locomotion of tensegrity robots) While some work has continued in the analytical understanding of the dynamics of motion for tensegrity mobility [22], the dynamics of contact with the environment are not considered. Since contact dynamics greatly complicate the already difficult task of controller design, most work resulting in simulated or hardware demonstrations of mobility are using non-analytical approaches. This started with Paul’s [51, 52, 53] and Rieffel’s [57, 58, 59] work which used evolutionary algorithms to discover controllers that resulted in slow crawling and hopping motions. This was followed by Bliss’s work using CPGs to control the oscillatory motion of a robotic tensegrity manta ray wing for swimming [6, 4, 5]. Additionally, CPG-like equations have been used by Boxerbaum et al. to control a soft robot moving with peristalsis [8]. Boxerbaum’s and Bliss’ independent work both confirmed the validity of our approach to using CPGs to control mobile terrestrial tensegrity robots. Other work in our lab, not covered in this report, has also had great success at using CPG’s to control the locomotion of a tensegrity inspired ”spine” robot over a variety of terrains. [70]
5  Summary of Key Findings

The purpose of our study was to validate that the concept of a tensegrity robot landing platform is feasible and useful for real NASA space missions. This validation consisted of three important parts: 1) Define a notional mission to Titan which would provide driving mission requirements for the engineering analysis performed in the later sections. 2) Show that the complexities of non-linear and oscillatory control of a tensegrity robot could be overcome through the use of genetic algorithms and central pattern generators, and 3) Show that in simulation and partially on a hardware platform that a tensegrity robot is in fact a good landing platform capable of surviving a hard landing, protecting its payload, and then act as a mobility platform. We are glad to report that our results exceeded all expectations, thoroughly validating the overall tensegrity robot and landing platform concept.

5.1  Define Notional Titan Mission and Requirements

Section 6 provides full details on our notional mission, which is summarized here. Titans atmosphere, stable bodies of surface liquid and complex organics make it one of the most complex and Earth-like environments in the solar system. This tensegrity probe mission will build on the science returns from Huygens and answer many of the new and unresolved questions surrounding Titans ongoing organic processes, geologic history, atmosphere, and surface-atmosphere interactions. Upon arrival at Titan, the tightly packed tensegrity probes enter the atmosphere behind a heat shield until sufficiently slowed to avoid further thermal loads, at which point the heat shield is ejected and the probes separate and expand to fully deployed shock absorbing state. Without requiring parachutes or other landing device, each probe is projected to impact the surface at Titan’s terminal velocity of about 11 m/s, absorbing and distributing impact stresses while protecting its science payload. After the tensegrity probes bounce, roll, and finally come to a rest on the surface of Titan, the actuated tensegrity structure will then begin to function as the primary mobility system for these mobile probes. Once on the surface, a notional science payload containing an atmospheric package, an analytical chemistry package, and an imaging package can begin the probes science mission. Since each probe is equipped with a science payload, mission success is not entirely dependent on the survival of a single probe, and the deployment of only a few probes enables the distributed exploration of a planetary surface.

Our first analysis was to explore the possible packaging and deployment of the probe. We found that the basic structure could be fully flattened to a triangular shape with sides equal to the lengths of the rods. This approach leaves room in the middle of the payload, and can be fully deployed with actuated cables. Next, we investigated possible technologies to use for the three science packages: the atmospheric and meteorology package, the analytical chemistry package, and the imaging package. These were used to drive initial mass estimates and to scale the avionics, power, and structural support required for the mission. This resulted in an initial design that showed an overall system mass of 100kg, of which 70kg is productive scientific payload and associated avionics, while the remaining 30kg is dedicated to structure and actuation for deployment and mobility.

Using these numbers, we were able to show that an individual tensegrity probe has a significantly
lower EDL hardware overhead and increased science payload mass percentage when compared to similar planetary surface probe missions, increasing the potential for science return. We evaluate this by comparing the total system mass at the point of atmospheric entry with the mass of the rovers productive payload, which constitutes all the science instruments and associated avionics, power, and controllers. Compared with the Mars Exploration Rovers (MER) and Mars Science Laboratory (MSL) which had a science payload mass fraction of 18% for MER and 22% for MSL, we have shown that a tensegrity probe may be able to operate on Titan as a mobile probe with a science payload mass fraction of 50% due to the dual use of the tensegrity structure as for both EDL and surface mobility. While comparing Mars rovers to a Titan probe is not ideal, these are the closest existing missions which include surface mobility. Further analysis may drive this percentage higher as more efficient versions of the tensegrity lander are explored. By increasing the mass ratio of productive science payload vs total system mass, this approach helps drive down future mission costs by allowing smaller lighter missions with the full capabilities of EDL and surface mobility.

5.2 Developing Control Algorithms using Evolution and Central Pattern Generators

Sections 7 and 8 cover the controls work summarized here. Tensegrity robots have the potential to be fabulous mobility platforms as they can be light-weight, energy efficient, robust against failures, and can traverse across unfavorable terrains. However controlling these robots is difficult since there are many points of control, the controls interact in non-linear ways, and the structure as a whole is oscillatory. Using traditional control algorithms for mobile tensegrity robots is difficult and previous successful attempts have been limited to very slow static gaits, and evolutionary control of very simple structures. A real concern going into the Phase I study was that no reliable control could be found. Fortunately we have had tremendous success with evolutionary algorithms and later with dynamical and Central Pattern Generator based controls (see Figure 6).

We performed several tests of evolutionary control in a detailed physics simulation. Using open loop control, the evolutionary algorithm is able to find a control policy that allows the tensegrity robot to roll quickly in a smooth manner. These results were robust to adding small obstacles to the terrain and was even able to keep rolling after we cut one of the control cables.

The controls used by our evolutionary methods were a simple form of semi-distributed oscillatory control: All the actuations were controlled through sine waves synchronized through their relative phase shifts. These controls proved to be robust and sufficient for our goals of having our tensegrity platform roll smoothly. These controls also gave excellent examples and insight into what fundamental dynamics were required for fast smooth motion. On the other hand, a major limitation of these evolved controls is that they do not provide a means to direct or steer the motion of the tensegrity probe. Rather, a control law is learned which can be abstracted, but which does not allow reactive changes of direction. To develop steerable controls we took the insights gained from the evolved controllers and hand crafted reactive dynamical controllers that used a variety of simulated sensor feedbacks to enable steerable rolling. This approach was very successful and was
Figure 6: **Tensegrity Dynamics.** Tensegrity is able to achieve smooth rolling motion. This rolling is accomplished solely by changing the length of the cables. Our learned control policies produce rolling that is also dynamical as the tensegrity does not stop to setup next roll action. This type of rolling can be fast and highly efficient.

Figure 7: **Dynamical and Central Pattern Generator Based Control.** Our dynamical controls allows tensegrity to climb over moderate hills.
shown to work on a variety of terrains, including moderate hills (Figure 7). But, this approach relied on significant amounts of sensor feedback which may be difficult to implement, so we wanted to find a hybrid approach that enabled steering while using a minimum amount of sensor feedback. Central Pattern Generators (CPG’s) are able to store complex gait cycles in their network dynamics allowing for a significant reduction of sensor feedback required. We explored a variety of ways to use this property and to combine it with aspects of the dynamical controls approach to enable steering. The best result found so far uses the hand-coded dynamical controller as a trainer to learn the parameters for a Hybrid CPG which combines Hopf oscillators and Inverse Kinematics.

5.3 Verification in Simulation and Hardware

Section 9 covers details of our hardware prototype, and Section 10 covers analysis, simulation, and actual hardware drop tests at Titan terminal velocity to confirm the possibility of using these structures for landing platforms. We believe that this is the first such analysis showing the characteristics of tensegrity structures during planetary landing. In all these experiments, our Phase I study verified the suitability of a tensegrity robot as a landing and mobility platform in the following three ways:

1. We verified that actuation for compact storage and deployment is possible in a hardware tensegrity probe.

2. We verified that our actuated prototype tensegrity probe remained structurally sound and could continue to operate after landing.

3. We verified that a tensegrity structure could protect a delicate payload, landing at impact speeds of 15 m/s (and possibly higher, pending future analysis).

Our first hardware prototype was build with hollow aluminum rods with the actuators mounted inside the rods for protection. The cables were a mixture of springs and high tension synthetic cables. This prototype was only partially actuated, with six motors, and was able to demonstrate shape change from a compact form to a fully deployed shock absorbing shape. With full actuation it would be able to achieve an even more compact shape when stored. To test the robustness of the design we dropped the probe 10m, as shown in Figure 8. Dropped from this height at earth gravity the probe landed at Titan Terminal Velocity, and it easily survived the fall and was still functional afterwards, as was shown by its ability to still change shape between its collapsed and deployed states. A useful insight from this test was that the motors should have mechanical brakes on them for the landing impact, as they were slightly back driven during landing.

Since the first prototype was only composed of the basic structure and did not contain a central payload, we also extensively analyzed how the landing forces would impact a payload in two simulators: our tensegrity simulator which uses the Bullet Physics Engine, and a hand-built Euler-Lagrange (E-L) simulator based on algorithms developed by Robert Skelton. We used these two simulators because they both have strengths and weaknesses. The Bullet simulator is the most general purpose, allowing us to explore control algorithms and complex environmental interactions, but it is an iterative discrete solver that we were concerned might not be providing accurate answers. The E-L solver, on the other hand, has a much stronger analytical basis and provides very
accurate answers, but is limited because some of the nodes (i.e. rod ends) must be constrained and locked into place.

Using these tools, we compared the forces on a “naked” payload surrounded with the equivalent of a few inches of foam, with a payload located in the center of a 1 meter diameter tensegrity structure. The results shown in Figure 9 (left) show that the payload in the structure has dramatically reduced peak accelerations after an impact of 15 m/s (which is beyond the actual Titan terminal velocity of 11.4 m/s). Compared to the Huygens probe, we were landing at 3 times the velocity, but the payload experienced half the impact forces. In addition the position measurements show that while it is elastic, the tensegrity structure settles quickly after landing.

These payload simulation results were supported by further drop tests with another prototype probe made of wood, plastic and elastomers. In this test, an egg was suspended in the middle of the tensegrity probe, which had no actuators, and was then dropped from a height of 10 meters (See Figure 9 right). The landing speed of the structure was thus about 14 m/s, and an egg can be expected to break at about 1.7 m/s, showing a significant amount of payload protection provided by the tensegrity structure.
Simulated Landing Performance at 15 m/s

Payload (falling sphere)  Payload with Tensegrity

Position

Acceleration

900 m/s²  125 m/s²

86% Reduction in Landing Forces With Tensegrity!

Payload experiences landing forces equivalent to 2.1 m/s (Huygens = 4.7 m/s)

Figure 9: Validation as Landing Platform.

6 Tensegrity Probes for a Notional Mission to Titan

Low-cost yet highly capable planetary entry probes have the potential to revolutionize science return even at today’s modest space budgets. However, it is nearly impossible to imagine such probes being built with traditional rigid robotics and traditional landing systems due to the high weight, complexity, and high mission control costs of these systems. A novel probe concept based on tensegrity structures can overcome many of these limitations. The core tensegrity structure is entirely formed out of tensile components (cables) and compression components (light-weight rods) to create a tensile network. Our concept is to develop a tensegrity probe in which the tensile network can be actively controlled to enable compact stowage for launch followed by deployment upon landing. Due to their natural compliance and structural force distribution properties, tensegrity probes can safely absorb significant impact forces, enabling high speed Entry, Descent, and Landing (EDL) scenarios where the probe itself acts much like an airbag. However, unlike an airbag which must be discarded after a single use, the tensegrity probe can actively control its shape to provide compliant rolling mobility while still maintaining its ability to safely absorb impact shocks that might occur during exploration. This combination of functions from a single structure enables compact and light-weight planetary exploration missions with the capabilities of traditional wheeled rovers, but with the mass and cost similar or less than a stationary probe.

In this paper we evaluate tensegrity probes on the basis of the EDL phase performance of the probe in the context of a mission to Titan. Titan’s atmosphere, stable bodies of surface liquid and complex organics make it one of the most complex and Earth-like environments in the solar system. This tensegrity probe mission will build on the science returns from Huygens and answer many of the new and unresolved questions surrounding Titan’s ongoing organic processes, geologic history, atmosphere, and surface-atmosphere interactions. Upon arrival at Titan, the tightly packed tensegrity probes will separate from the spacecraft and expand to fully deployed shock absorbing state. Without requiring parachutes, each probe is projected to impact the surface at about 11 m/s, absorbing and distributing impact stresses while protecting its science payload. As the tensegrity
probes bounce, roll, and finally come to a rest on the surface of Titan, the actuated tensegrity structure will then begin to function as the primary mobility system for these mobile probes. Once on the surface, a notional science payload containing an atmospheric package, an analytical chemistry package, and an imaging package can begin the probes’ science mission. Since each probe is equipped with a science payload, mission success is not entirely dependent on the survival of a single probe, and the deployment of only a few probes enables the distributed exploration of a planetary surface.

An individual tensegrity probe has a significantly lower EDL hardware overhead and increased science payload mass percentage when compared to similar planetary surface probe missions, increasing the potential for science return. We evaluate this by comparing the total system mass at the point of atmospheric entry with the mass of the rovers productive payload, which constitutes all the science instruments and associated avionics, power, and controllers. Compared with the Mars Exploration Rovers (MER) and Mars Science Laboratory (MSL) which had a science payload mass fraction of 18% for MER and 22% for MSL, we have shown that a tensegrity probe may be able to operate on Titan as a mobile probe with a science payload mass fraction of 50% due to the dual use of the tensegrity structure as for both EDL and surface mobility. Further analysis may drive this percentage higher as more efficient versions of the tensegrity lander are explored. By increasing the mass ratio of productive science payload vs total system mass, this approach helps drive down future mission costs by allowing smaller lighter missions with the full capabilities of EDL and surface mobility.

A key quality of these probes is their ability to shock-protect core systems (science payloads, avionics, and actuators), even when landing at relatively high speeds. We will discuss analytical, simulated, and experimental results of terminal velocity landing events to show how the impact forces are distributed through the structure and reduce the internal stress at any one point within the probe. We will then discuss how these results are guiding engineering choices for actuation and material properties of the tensegrity probe and our ongoing efforts to develop and test physical prototypes. Given the multi-function use of the tensegrity probe, we will then describe how the structure can also enable mobility for exploration of a landing site. Finally, the tensegrity probe is directly compared to other EDL and mobility solutions with a focus on cost, complexity, delivered science payload, and robustness.

6.1 Notional Titan Mission

NASA’s 50 year history of planetary exploration mission development and execution has followed a carefully formulated processes involving the evaluation of existing technology, confirmed and theoretical understanding of our solar system, and detailed reconnaissance strategies for the development of follow-on missions to capitalize on new discoveries and current hypotheses. To increase opportunity for future missions, innovative new tensegrity based probes are undergoing development at NASA Ames Research Center to serve as capable atmospheric entry, descent and landing hardware, as well as primary mobility hardware facilitating surface exploration and experimentation. The study of planetary exploration tensegrity probes through advanced simulation and analysis, has yielded initial results with regard to impact behavior and surface motion capabilities. With a better understanding of the benefits and strengths of tensegrity structures in the context of a planetary exploration mission, new mission concepts and operational procedures which utilize
these new facilities can be explored and further developed.

The delivery of in-situ science instruments to the surface of a planetary body requires hardware specific to the Entry, Descent, and Landing (EDL) phase of the mission. The support equipment used to deliver these instruments can be large, complex and expensive [42]. Low-cost, highly capable planetary entry probes utilizing novel new tensegrity based hardware designed for EDL and surface mobility accomplishes this task in a manner enabling new mission profiles and increasing the science return to mission cost ratio. The first advantage of a tensegrity probe is that it can be packed into an efficient flat package. For the designs explored so far we show that a large ”spherical” tensegrity can pack down to a flat triangle. Other structures which will be studied in the future may have even more efficient packing capabilities.

A tensegrity based probe mission targeting the surface of Titan will be able to land without the aid of parachutes or retro-thrusters, instead using its tensegrity structure, consisting of rigid linear struts interconnected with tensile string-like elements, the probe will absorb and distribute the impact stress of a terminal velocity landing, causing the probe to bounce and eventually come to a rest in a manner similar to the airbag system first used on the Mars Pathfinder mission [67]. This same tensile structure used for EDL is then also used to initiate a rolling motion to steer the probe across the surface in an efficient, collision tolerant manner benefiting operations during a time and power constrained mission. As the tensegrity probe rolls across the surface, the science payload remains shielded by the robust tensegrity structure, this allows the vehicle to move quickly even in an environment filled with obstacles. When the probe arrives at scientifically interesting sites, modulation of the tension in the structure can position the science payload carried at its center, lowering the payload allows it to sample from the surface or lifting it to an exposed, unobstructed view of the cloud cover permits atmospheric measurement. The dual use of the tensegrity structure for EDL equipment and mobility hardware can safely deliver science instruments to a planetary surface while reducing vehicle complexity and mass and increasing science opportunity and operational capability.

6.2 Benefits of Tensegrity Structures for Mission

Tensegrities have a number of beneficial properties including:

- **Light-weight**: Forces align axially with components and shocks distribute through the tensegrity, allowing tensegrities to be made of light-weight tubes/rods and cables/elastic lines.

- **Compact Storage**: Tensegrity structures can be packed into compact forms for launch and deployed to a functional configuration prior to landing. This deployment uses the same actuation system that will later provide mobility.

- **Energy efficient**: Through the use of elastic tensile components and dynamical gaits, efficient movement is possible.

- **Robust to failures**: Tensegrities are naturally distributed systems and can gracefully degrade performance in the event of actuation or structural failure.

- **Capable of unique modes of locomotion**: Tensegrities can roll, crawl, gallop, swim or flap wings depending on construction and need.
- **Impact tolerant and compliant**: Since forces are distributed upon impact, they can fall or bump into things at moderate speed. In addition, their compliance ensures that they do minimal damage to objects they contact.

- **Naturally distributed control**: Characteristics of force propagation in tensegrities allows effective local controllers.

The last property is the most subtle but important. In “traditional” robots, distributed controls becomes messy due to the need to communicate global state information to all the controllers with high precision, and thus often undermines the very promise of distribution. Fundamentally, this stems from the fact that a rigidly connected structure will magnify forces internally through leverage, and will accumulate force into joints. Thus, the actions of a local distributed controller can have disproportionate global consequences. These consequences can require a certain amount of global coordination and state management, undermining the value of the local controller. Tensegrity structures are different, due to the tension network, there is no leverage in the structure. Thus, forces *diffuse* through the structure, rather than accumulate in joints. As a result, actions by a local controller diffuse through the structure, integrating with all the other local controllers. While any one local controller will impact the structure globally, that impact is locality relevant and not magnified via leverage. Thus, the structure enables true distributed control, because local actions stay (predominately) local.

Despite these desirable properties, tensegrity robots have remained mostly a novelty for many years due to difficult control properties that make them hard to control with traditional control algorithms such as:

1. **Complex oscillatory motions**: Tensegrity robots tend to have oscillatory motions influenced by their interactions with their environment.

2. **Elastic Nonlinear distributed interactions**: A force generated on one part of the tensegrity propagates in a nonlinear way through the entire tensegrity, causing shape changes, which further change force propagations.

Fortunately the combinatorial optimization capabilities of evolutionary algorithms combined with the distributed properties of multiagent systems are a natural match to these problems. Evolutionary algorithms can learn complex control policies that maximize a performance criterion without needing to handle the oscillatory motions and distributed interactions explicitly. In addition, increased performance can be achieved by assigning evolving agents to different control points throughout the tensegrity. Then as a multiagent system, the agents can co-evolve to create a unified control policy.

### 6.3 Compact Storage and Deployment

The six bar icosahedron tensegrity structure used as a basis for the tensegrity probe is capable of collapsing down to a base shape of an isosceles triangle with side lengths equal to the length of the struts and a height of about three times the diameter of the struts. Simulation has shown that the structure can collapse itself to this configuration by manipulating all 24 of its tension members with half of the tension members fully shortened and the other half fully lengthened (figure 10).
Figure 10: Deployment The six bar tensegrity probe can be packed into a flat triangle and then deployed to full functional configuration by changing the string lengths with the same actuators which will be used later for mobility.

6.4 Application to EDL

Tensegrity based probes have the potential to drastically lower the EDL system mass as well as reduce the system complexity by utilizing the benefits of the probe’s tensegrity structure in the EDL process. For this paper, the tensegrity probe’s structure will serve a dual purpose of protecting the structure on impact with the planetary body as well as provide mobility for the probe. Traditionally, the systems which enables the descent and landing are separate systems with most of the EDL cost and mass being attributed to these systems. In the case of NASA’s Pathfinder rover, an EDL system weighing approximately 580 kg was utilized deploying a parachute, a rocket assisted descent, an airbag, and a protective shell which housed the rover. This was all needed to safely land the 185 kg Pathfinder rover on Mars within a 3000 square kilometer area. Our proposed probe design will be able to land a 100 kg probe on a planetary surface using only a heat shield and not requiring the use of other external EDL systems such as parachutes, rocket assisted descents, or airbags. This is possible due to the benefits listed in the previous section of a tensegrity system; the most critical being the tensegrity structure’s impact tolerance and compliance. The distributed nature of how forces propagate through the structure prevents large bending moments on the solid members of the structure and allows the tension elements to dissipate the energy forced into the structure from an impact scenario. Lowering the overall EDL mass will also enable the use of smaller and less massive heat shields, decreasing the overall EDL mass even more.
6.5  Titan Mission Narrative w/ Surface Ops

An ambitious tensegrity based probe mission to Titan would seek to answer many of the primary questions regarding the moon’s surface chemistry, geology and meteorological properties through the delivery of the latest in-situ instruments to the surface. The innovative use of tensegrity structures to surround and shield the science payload during EDL advances this goal of delivering instruments to scientifically significant environments. Such a mission if launched in January, 2018 would arrive at the Saturn system within 10 years via Jupiter fly-by. The spacecraft, a Titan orbiter, will arrive at Titan traveling approximately 6.5 km/s. A tensegrity probe entry vehicle consisting of a heat shield, back shell, and a single light weight tensegrity probe stored in a space saving cruise configuration, will then be deployed from the orbiter and will enter the Titan atmosphere at 100,000 km above the surface. The entry vehicle will jettison of the heat shield at 200 km above the surface. Based on simulations using the Titan atmospheric data collected by the Huygens probe in 2005, each spherical tensegrity probe of .863 diameter with a drag coefficient of 0.5 is expected to be traveling at a terminal velocity of 11.4 m/s before impact.

![Figure 11: Mission to Titan. Once landed, the robot can move around, take ground or visual sensor readings. Most sensors can be suspended on the interior of the tensegrity to reduce impact stress.](image)

As the probe begins free descent, it will actuate its cable elements, increasing tension throughout the tensegrity structure causing it to expand from its flat triangular stored shape into its fully deployed and pre-tensioned spherical shape. The probe then commands each actuation element to engage brakes so that landing impact shocks do not reflect into the motors. The pre-tension state of the structure permits the full kinetic energy of the falling probe to be distributed through the structure. The cables, which have some elasticity, allow the structure to slightly deform from the
impact stress, while the center slung payload safely decelerates to a full stop without impacting the surface. Following the probe’s rebound off the surface and the eventual settling of the probe into a state of zero kinetic energy, the brakes can be released enabling the structure to move and reorient itself.

Tensegrity probe surface operations will rely heavily on the tensegrity structure for payload positioning and vehicle mobility. A mobile tensegrity probe on the surface of Titan will have the opportunity to seek out interesting sites to gather data and perform in situ investigations of the mineralogical content, organics, atmospheric and meteorological systems present on the icy moon. Whole segments of the surface operations will be devoted to acquiring samples, making measurements, and capturing images which will increase our knowledge and understanding of these scientific topics. Many particularly interesting geologic sites are also high risk sites due to limited reconnaissance and unknown soil properties, such as steep sand dunes or cliff faces. One of the advantages of a Tensegrity probe is that can withstand a fall at Titan’s terminal velocity, so it can survive falling off a cliff, or intentionally leaping into a cave or other scientifically interesting location. Unlike the Mars rovers, which discarded their airbags after landing, the probe’s basic mobility system is also its landing system, available to protect it at any moment. This will enable mission operators to explore areas that are of high scientific interest, but which would be far too risky for a traditional rover.

6.6 Target Tensegrity Platform

The structure of the tensegrity used in this paper is shown in Figure 12. Rods do not connect directly with other rods, instead, rods are indirectly connected through cables, resulting in a continuous tension network as the primary load transfer system of the structure. In the orientation shown in Figure 12 (left) one pair of the rods are parallel to x-axis, another pair is parallel to y axis and the last pair is parallel to z-axis. Each end of a rod is connected to the ends of other non parallel rods via 4 different cables. When the structure is in balance, it is symmetrical and convenient for a rolling motion. On the other hand, when an external force is applied, it easily deforms and distributes the force to every component of the structure.

In addition to the base tensegrity, we attached a ball shaped payload to the center of the tensegrity via an additional 8 payload cables. The payload represents the essential parts of the robot, such as computing, sensors, batteries, or other instruments. Just like the 24 outer cables, these 8 payload cables may be actively controlled depending on the control law being implemented. (Figures 12,17). The mass and volume of this ball shaped payload was determined via a notional operational payload designed by referencing the volume and mass parameters of instrument, communications, avionics and power distribution subsystems from other planetary exploration missions. This notional operational payload, designed to meet basic science requirements for a tensegrity probe mission to Titan, contains three science packages: the atmospheric and meteorology package, the analytical chemistry package, and the imaging package. The mass and volume of this operational science payload is used to determine engineering aspects of the tensegrity structure parameters, mission design, and mission operational scenarios, such as actuator strength and material properties. The notional operational payload is estimated to be 70 kg, including science instruments and support avionics and power. Given the operational payload mass, the tensegrity support structure and its actuators which weigh approximately 30 kg combined, the entire vehicle is estimated be
Figure 12: Tensegrity Structure. Tensegrities are composed of pure tension and pure compression elements (e.g. cables and rods) as seen in this picture of a tensegrity robot from our physics based tensegrity simulator. They are light-weight, energy-efficient and robust to failures.
Table 1: Notional mass properties of a tensegrity probe, with references to papers providing mass numbers.

<table>
<thead>
<tr>
<th>Probe Subsystem</th>
<th>Mass (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensegrity structure and actuation hardware</td>
<td>30.0</td>
</tr>
<tr>
<td>Avionics [13]</td>
<td>23.1</td>
</tr>
<tr>
<td>Communications [13]</td>
<td>6.0</td>
</tr>
<tr>
<td>Electrical Power Subsystem and Batteries</td>
<td>36.0</td>
</tr>
<tr>
<td>Imagery Package [38, 24]</td>
<td>0.7</td>
</tr>
<tr>
<td>Meterology Package [21]</td>
<td>1.4</td>
</tr>
<tr>
<td>Analytical Chemistry Package [15]</td>
<td>2.8</td>
</tr>
</tbody>
</table>

100 kg, as shown in 1.

6.7 Tensegrity Probes in Comparison to Other Flown Missions

For more than 20 years NASA’s Discovery program has funded low cost, highly focused missions demonstrating new technology and seeking out the answers to fundamental questions regarding solar system formation, potentially habitable environments, and potential locations within the solar system where life could begin and evolve. The program has many successes, amongst them, the Mars Pathfinder mission which deployed a Mars rover called Sojourner, NASA’s first rover on Mars [20]. A tensegrity based probe mission to Titan can be compared to other Discovery program missions due to it’s demonstration of new EDL technology, focused science objectives. A primary goal of the mission is the demonstration and validation of the tensegrity structure as capable EDL equipment and primary mobility equipment. Using a tensegrity structure in this way enables the tensegrity probe to comprise a larger percentage of the entry mass than other missions such as Pathfinder, the Mars Exploration Rover missions, or the Mars Science Laboratory mission. When compared with the Mars Exploration Rovers which had an entry mass of 830 kg, of which 146 kg of equipment directly supported instrumentation and scientific study, the tensegrity probe represents the entirety of the planned landed mass and will not have to discard any hardware before initiating surface operations, other than a heat shield for initial entry. Based on titan heat shield studies which show that it would be reasonable to assume 35-41% TPS/probe mass using Pica, Tufroc, or heritage SLA, we assume 40kg of heat shields required for the 100kq probe. After slowing to terminal velocity and discarding the heat shield, a tensegrity probe is capable of landing and carrying a center slung payload weighing as much as 70 kg as it travels across the surface of Titan. This payload will contain all science instruments and payload support equipment. Thus, as can be seen in Table 2, the tensegrity probe enables a mission to dedicate 50% of the entry mass to productive science equipment whereas Pathfinder delivered 1% science payload, MER’s was 18%, and MSL provided 22% of its entry mass as productive payload. Since mass is a driving aspect of mission cost – driving everything from launch vehicle to the interplanetary vehicle and fuel
Table 2: Planetary Exploration Missions by Mass

<table>
<thead>
<tr>
<th>Mass</th>
<th>Pathfinder</th>
<th>MER</th>
<th>MSL</th>
<th>Tensegrity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry</td>
<td>587</td>
<td>831</td>
<td>3301</td>
<td>140</td>
</tr>
<tr>
<td>Landed</td>
<td>372</td>
<td>540</td>
<td>943</td>
<td>100</td>
</tr>
<tr>
<td>Mobility</td>
<td>11</td>
<td>175</td>
<td>943</td>
<td>0</td>
</tr>
<tr>
<td>Payload</td>
<td>8</td>
<td>146</td>
<td>723</td>
<td>70</td>
</tr>
<tr>
<td>Science H/W</td>
<td>Mass %</td>
<td>1%</td>
<td>18%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td></td>
<td></td>
<td>50%</td>
</tr>
</tbody>
</table>

References: Pathfinder [46], MER [46], MSL [34]

requirements, we believe that enabling better science payload to entry system mass will help drive down future missions costs.
7 Evolutionary Controls

In this section we explore the use of Evolutionary algorithms to develop controllers for surface mobility of the tensegrity probe once on Titan. Evolutionary algorithms, genetic algorithms and reinforcement learning are all part of the broad field of machine learning that can be applied to sophisticated control problems. What makes these algorithms unique is that the control solution is not created in a top-down manner, but is instead “evolved” or “learned.” These methods of controls are ideally suited for difficult control problems that exhibit complex and non-linear characteristics making it difficult to apply traditional control algorithms. In this report, we describe how we successfully applied “evolutionary” algorithms to the task of controlling a tensegrity robot. The evolutionary aspect comes from our use of a population of control policies that is then slowly evolved to create populations of higher and higher performance. Note that this work does not exclude the possibility of using reinforcement learning for this problem, which would involve the tensegrity robot exploring the environment and learning to improve its control policy through negative and positive rewards.

7.1 Target Tensegrity Platform

Our experiments for evolutionary controls of a tensegrity robot involves our basic “6-bar” tensegrity used throughout most of this report. This platform has 6-rod and 24-cable tensegrity as shown in Figure 13.

Figure 13: Structure for Tensegrity Robot. This six-rod design is one of the simplest designs that can behave as a “ball.” It is capable of rolling, changing shapes, and can be robust against failures.

7.2 Tensegrity Actuation

The tensegrity is controlled by changing the lengths of the cables. Many hardware implementations do this by using a motor to wind the cable onto a spool that is either interior to the tensegrity or inside a rod. Other concepts involve using dynamic cable twisting or elastomers to change the
length of the cable. In this section we do not consider the hardware implementation, though we
do limit our abstract model of actuation to reasonable performance characteristics for velocity,
acceleration, and string elasticity.

The control of the robot is done via sinusoidal control of the lengths of the cables. The lengths of
the cables change over time according to a sinusoidal signal, and the parameters of the signal are
the output of the evolutionary algorithm. The length of each cable is calculated with the formula:

\[ y(t) = C + A \sin(\omega t + \phi) \]  

(1)

where,

- \( C \) represents the center position of the sine wave.
- \( A \), the amplitude, is the peak deviation of the function from its center position.
- \( \omega \), the angular frequency, is how many oscillations occur in a unit time interval
- \( \phi \), the phase, specifies where in its cycle the oscillation begins at \( t = 0 \).

By using 24 sinusoidal signals for 24 cables, overall control of the tensegrity is based on 96 \((24 \times 4)\) parameters.

### 7.3 Simulation

Our tensegrity simulator is built on top of the open-source Bullet Physics Engine [9]. Bullet was
chosen because of its built in support for soft-bodied physics, and has been used previously in
tendon-driven robotics simulators such as Wittmeier et al’s CALIPER software [77]. Due to lim-
itations of the physics engine at the time this analysis was performed, we had to scale everything
such that the simulated tensegrity structure has a size of 10 meters for each rod due to the fact that
the physics engine is more precise for objects approximately that size. Thus, distances and veloc-
ities reported in this section should be scaled by a factor of 10 to represent sizes and speeds more
appropriate of an actual mission. A better approach to scaling the simulated world was developed
for subsequent parts of this project and later sections of this report do not include this extra factor
of 10 in their results. Cables are represented as nodes with Hooke’s-law-like stiffness between
them. Therefore our “cables” are actually somewhat elastic and exert a force dependent on their
length. We keep our model of actuation abstract in order to explore the best control solutions and
then drive requirements back into real hardware design requirements. To enforce additional real-
ism, we prevent the cables being actuated when stretched more than 25\%, as an upper limit on the
hypothetical motor force. This approach allows us to find the types of control and requirements
that will be driven into actuation selection.

### 7.4 Evolutionary Algorithms

While the control parameters of our tensegrity platform are relatively straightforward, the rela-
tionship between these parameters is highly complex. In this section we explore how we can use
the simulation combined with a fitness evaluation to implement an evolutionary algorithm that can evolve a set of control parameters that leads to the desired behavior.

### 7.5 Evaluation Function

We measure the performance of a simulated tensegrity based on how far it can travel from a starting location within 60 seconds:

\[
f = d(C_1, A_1, \omega_1, \phi_1, \cdots, C_{24}, A_{24}, \omega_{24}, \phi_{24})
\]

where, \(d\) is the distance travelled, which is a function of the 96 parameters of the control policy. Note that the decomposition of the distance function \(d\) is not readily obtainable in closed form. Instead it must be computed from observing simulations or measured from a physical implementation. Also note that our evaluation does not explicitly take any behavior into account besides distance moved. Tensegrities can exhibit many different gaits, ranging from hopping to rolling, and many different paths, ranging from spirals to straight lines. However, tensegrities that maximize our fitness function tend to roll in fairly straight lines. Deviations from this pattern tend to hurt performance.

### 7.6 Centralized Evolutionary Algorithms

In this paper, we perform both centralized evolution and multiagent coevolution. In the centralized case, a single control policy is evolved for the entire tensegrity robot. This control policy sets the 96 parameters for the sinusoidal controllers. The algorithm is a simple evolutionary algorithm designed to maximize our fitness function. At the beginning of training, a population of \(n\) random policies is created and evaluated based on our fitness function \(f\). After each round of evolution, the worst \(k\) policies are removed, and are replaced by mutated versions of the best \(k\) policies. Mutation is uniformly random for each parameter. For experiments that use crossover, we use a simplest basic single point crossover. In single point crossover, new \(k\) policies get coupled, and each couple switch the second part of the parameters after a randomly selected parameter between 1 and 96. In both cases, as evolution progresses, the population tends to converge to higher performance policies.

### 7.7 Cooperative Coevolutionary Algorithms

While centralized approaches often produce good results, evolving a centralized controller can be slow due to the size of the search space. If the control parameters are tightly coupled, then the centralized approach may be the best we can hope for. However, control of a tensegrity robot is not necessarily tightly coupled. While changing the length of a cable will strongly affect neighboring components, it will have less of an effect on components on the opposite side of the tensegrity. Therefore decentralized control is possible and can greatly reduce the search space for each component in the decentralized controller.

In this paper, we introduce such a decentralized controller as a cooperative coevolutionary system, using principles derived from multiagent systems. In this paradigm each of the 24 cables is
controlled by an individual agent. The job of each agent $i$ is to control the four parameters of the sinusoid controlling its cable: $C_i$, $A_i$, $\omega_i$, and $\phi_i$. To do this, each agent $i$ will have its own population of control parameters, $p_i$, where each member of the population, $p_{i,j}$, specifies the four control parameters. Each agent then evolves its population to produce good values of control parameters in the context of the control choices of the other agents. The goal of these coevolutionary agents is still the same as the centralized evolutionary algorithm: Maximize the global fitness evaluation, $f$.

The advantage of this paradigm is that each agent now only has to search through four parameters. The difficulty is the value of each agent’s choice of control parameters now depends on the choices of the other agents. The exact same choice may be good or bad, depending on what other agents are doing. One way to address this is to evaluate every possible team existing at the current generation. In this paper, this is not possible due to the number of possible cooperators. We attempt to handle this issue by taking a fixed number of samples of the population at each generation of evolution. Between two generations, each agent’s population is sampled $s$ time and they are put together to form $s$ complete control policies. Each of these control policies is then evaluated with respect to our global fitness evaluation function, $f$, producing $s$ evaluations. Typically the number of samples $s$ will be many times larger than the size of the population, therefore each individual member of a population will typically be part of multiple control policies. The main issue now is how we evaluate a member of a population $p_{i,j}$ which has participated in multiple control policies, when each control policy has received a different global fitness evaluation $f$.

In this paper, we address this issue in the following three ways:

1. Generational Average - Assign the mean value of the global fitness evaluations for control policies in which the member participated during this generation.

2. Leniency - Assign the highest value of the global fitness evaluations for control policies in which the member participated in.

3. Historical Average - Assign the mean value of global fitness evaluations, averaging across all the generations that the member survived.

Taking average and Leniency are commonly used methods with cooperative coevolution [50]. To improve performance, we augment this approach by taking historical averaging. Historical averaging uses all the samples that the members had been part of, not only the current generation but also the ones with previous generations with previous teammates (Algorithm 1). Every surviving agent carries its history to the new generation and uses that information to calculate its average score.

### 7.8 Hand-Coded Solution

In addition to creating control policies through evolutionary algorithms, we explore how to hand-code a control solution using the same parameters available to the evolutionary system. The goal here is to explore the challenges of hand-coding a solution and to see how well our best effort compares to our learned solutions. It turns out that creating a control policy by hand using our 96 parameters is extremely difficult, so we created 8 control groups with 3 cables in each group. These 3 cables form a triangle that have the same length, making it easier to write a hand-coded controller. Even with this simpler approach, the best achieved solution barely moved. This problem will only
Algorithm 1: Cooperative coevolutionary Algorithm with Historical Average

**Data:** Population of $n$ elements for each agent

for $i=1..15$ do
    random team $\leftarrow \emptyset$
    forall the Populations do
        random team $\leftarrow$ random agent;
    end
    score = evaluate random team;
    forall the agents $\in$ random team do
        agent.history $\leftarrow$ agent.score;
    end
end
forall the Populations do
    forall the agents do
        agent.fitness $=$ average(agent.history);
    end
    order the population;
    eliminate last $k$;
    copy first $k$ to last $k$;
    set score of last $k$ to $MIN$;
    mutate last $k$;
    clear history for last $k$;
end
get more difficult as we scale the tensegrity robots to more complex versions with more elements. To improve performance, we reduced the parameter space by hand coding the amplitudes of each group and making the oscillation frequency the same for all groups. The results shown later in this paper are for this second, better-performing hand-coded solution.

7.9 Experimental Results

In this section, we present experiments evaluating the performance of our evolution-based methods to control tensegrity robots in the physics simulator described in Section 7.3. The goal of our experiments is to evaluate whether evolutionary systems can be successfully applied to tensegrity robots under nominal conditions, and how robust these solutions are to limitations in the range of actuation, to actuator noise and to a physical breakage in a cable of the tensegrity. For the nominal condition case we test the following methods of creating the controller:

- **Hand Coded** Control policy is developed by hand to try to achieve maximum performance.
- **Centralized Evolution** A single control policy is learned for the entire tensegrity robot.
- **Decentralized Evolution** Cooperative Coevolutionary Algorithms (CCEA) approach.

We then test different fitness methods for CCEAs: Average, Leniency, Historical Average. We test the robustness of our highest performance solution (historical average) in the following ways:

- **Actuation Noise** We add noise to how far cables are actually moved as compared to how far they are being requested to move.
- **Cable Failure** We test performance when a single cable in the robot breaks.
- **Obstacles** We randomly place half sphere obstacles into the environment.

All experiments start with a stationary tensegrity robot on the ground. For each experiment, the robots are created on a flat surface, and after 5 seconds of stabilization time, active control of the cables starts. The agents are given a fixed amount of time (60 seconds) to move the robot as far as possible. The evaluation function is the distance between the starting position and the position at the end of the given time period. The population size in the policy search is set to \( n = 10 \) and the selection parameter is set to \( k = 5 \). We perform 10 statistical runs for each type of experiment. Using a t-test we confirm that our conclusions are statistically significant.

7.9.1 Centralized, Decentralized and Hand-Coded

The first experiment compares three different control policies: Hand-coded, centralized evolution and multiagent evolution. Figure 14 shows that both evolution-based approaches can easily outperform the hand coded solution. The multiagent evolution approach provides the best performance by moving 100% more quickly than the single agent and 400% more than our hand coded agent. Both centralized and decentralized evolution are able to achieve smooth rolling motions as shown in Figure 17. Note that while our hand coded tensegrity is not able to achieve a rolling motion,
Figure 14: Performance of Control Algorithms. Multiagent coevolution performs significantly better than other methods since it is able to take advantage of distributed nature of tensegrity control.

we are not trying to imply that this problem is impossibly complex for non-evolving algorithms. In fact there have been several successful algorithms to do this [61, 33, 74, 11]. Instead we are illustrating that it is in fact quite difficult to create these controls, and that the centralized and multiagent evolutionary algorithms are creating complex, non-trivial control solutions. In addition a multiagent framework has the potential to be adapted to many different complex tensegrities with less effort than hand coding an algorithm for each new tensegrity.

Figure 15: Evaluation Methods. Using a historical average reaches best score and it is consistent. Lenient learners have bigger error bars.

It can be seen that the tensegrity controlled by policies evolved from coevolution reaches a performance around 900 meters in 60 seconds. By observing the behavior, we confirmed that the movement is established by smooth rolling motion as illustrated in Figure 17. This rate corresponds to the tensegrity moving at approximately 28 revolutions per minute. This result is independent of the size of the tensegrity. Therefore we would expect a 1 meter diameter tensegrity to move at approximately 90 meters per minute.
7.9.2 Historical Average, Average and Leniency

The second experiment compares different fitness assignment methods for CCEAs. As it can be seen, using a historical average performs better than every other method. Moreover, the small error bars signifies that using the historical average consistently provides similar performance. Looking at the error bars of the lenient learners, it can be seen that standard deviation is high: It also reaches very good policies in some of the statistical runs, but the average success is lower.

![Figure 16: Sample Size. Taking more samples for each trial improves stability but takes more time reach better behavior](image)

To make sure that the sample size that we chose does not significantly affect the results, we tested the historical average method with different sample size between each generation (s). Figure 16 shows that the sample size affects performance when it is too low such as 10, on the other hand, a sample size as high as 1000 decreases the learning speed. Considering this result, we used 50 as the default value for the rest of the experiments.

7.9.3 Actuation Noise

To measure the robustness of our evolutionary algorithm against noise, we test the multiagent tensegrity robot in an environment with different levels of actuation noise. Actuation noise is applied at every time step to the sinewave that the evolutionary algorithm generate to control the cables. At every time step, noise is directly added to the value of the Equation 1. To test different levels of noise, we use different environments where the standard deviation of the noise is set to 1%, 2%, 5%, 10%, 25%, 50%, 100% of the amplitude of the sine wave for each cable.

In this experiment, we test two different policies in our noisy environment: 1) Policies from a multiagent system that had learned in an environment without noise, and 2) Policies that are learned in an environment with the same amount of noise they are tested in. Figure 18 shows that tensegrities trained both with and without noise can perform remarkably well when the level of noise is below 15%. This is an impressive result, as it shows that the solutions generated in a non-noisy environment are not highly specific to an exact model of a tensegrity and exact environmental conditions. Instead the solutions appear highly generalizable. Beyond this level of noise performance goes
Figure 17: **Tensegrity Dynamics.** Tensegrity is able to achieve smooth rolling motion. This rolling is accomplished solely by changing the length of the cables. Our learned control policies produce rolling that is also dynamical as the tensegrity does not stop to setup next roll action. This type of rolling can be fast and highly efficient.
Figure 18: Actuation Noise. The best policy can take up to 25% noise, evolving in a noisy environment scores better in higher noise environments.

down significantly. However, while performance is low, a tensegrity trained with a high level of noise can still perform at a base-line level while subjected to high levels of noise, which could be very useful in many situations.

Figure 19: Robustness Tests with Obstacles and Broken Link. Coevolutionary Algorithms can overcome both obstacles and broken link scenarios

7.9.4 Broken Cable and Obstacles

The fourth experiment tests the robustness of the structure and the controller. In our first experiment we remove one of the cables, which decreases controllability and also disrupts the balance of the structure. With the cable removed, the structure is no longer symmetrical and it can not keep its ball shape by default. In our second experiment we place the normal tensegrity in an environment containing randomly placed half sphere obstacles. When we test our best policy trained in a perfect environment in these two conditions, the performance drops to 50% with obstacles and it cannot roll with a broken link (Figure 19). On the other hand, if we perform evolution in these conditions,
the evolutionary algorithm can still find successful locomotion policies for a tensegrity with broken

cable, or in an environment with obstacles.

This result shows that under adverse conditions we can evolve a controller that takes advantage of

the large range of motion inherent in tensegrity robots to effectively maintain locomotion. Note

that this result does not show that the evolved control policy dynamically adapts to problems, since

in this experiment we retrain our policy after the breakage. However, it does show the flexibility of

the evolution process and the ability to pre-evolve controls associated with potential failure modes.
8 Dynamic and Central Pattern Generator Controls

The controls used by our evolutionary methods were a simple form of semi-distributed oscillatory control: All the actuations were controlled through sine waves synchronized through their relative phase shifts. These controls proved to be robust and sufficient for our goals of having our tensegrity platform roll smoothly. These controls also gave excellent examples and insight into what fundamental dynamics were required for fast smooth motion. On the other hand, a major limitation of these evolved controls is that they do not provide a means to direct or steer the motion of the tensegrity probe. Rather, a control law is learned which can be abstracted, but which does not allow reactive changes of direction. To develop steerable controls we took the insights gained from the evolved controllers and hand crafted reactive dynamical controllers that used a variety of simulated sensor feedbacks to enable steerable rolling. This approach was very successful and was shown to work on a variety of terrains, including moderate hills (Figure 24). But, this approach relied on significant amounts of sensor feedback which may be difficult to implement, so we wanted to find a hybrid approach that enabled steering while using a minimum amount of sensor feedback. Central Pattern Generators (CPG’s) are able to store complex gait cycles in their network dynamics allowing for a significant reduction of sensor feedback required. We explored a variety of ways to use this property and to combine it with aspects of the dynamical controls approach to enable steering. The best result found so far uses the hand-coded dynamical controller as a trainer to learn the parameters for a Hybrid CPG which combines Hopf oscillators and Inverse Kinematics.

8.1 Principle

By inspecting the fast rolling controllers learned in the prior section we observed that the most efficient controllers would locate the central payload inside the probe such that its mass would cause the probe to roll. This was accompanied by different approaches for controlling the size and location of the polygon of ground contact points. Thus, in our dynamical controller the tensegrity structure is controlled using the torque created by the displacement of the center of mass from the ground contact surface as illustrated on figure 20. This is achieved in 2 different ways: the heading is determined by the displacement of the central payload relative to its rest position in the center of the structure and speed is determined by the actuation of the outer shell strings.

The inner strings were actuated using three different approaches, a reactive approach, an inverse kinematics approach and a CPG approach (see sections 8.2, 8.3 and 8.5 respectively). The outer strings where controlled in a different way. The goal of their dynamics is to reduce the contact surface with the ground. This affects the motion in several ways. First, it allows the creation of greater torques with the same payload displacement. Second, it allows a smoother rolling behavior of the whole structure, preventing shocks of the rods with the ground. Playing with the reactivity of the lengths corrections can also affect the global angular speed of the tensegrity structure.

The height of each string relative to the ground is computed using IR-like distance sensors located at the end of each rods (see figure 21). The height assigned to each string is computed as the average of the two end points height. These measurements are performed continuously during the simulations and the height parameter is constantly updated. If the tensegrity needs to move on
uneven ground surfaces, it is important to know if the displacement occurs in the desired direction. Typically in the presence of a slope, the reduction of the ground contact surface can trigger the robot to roll down the slope without any control. In order to take this into account, we added a measure of the velocity. The velocity is computed using the global center of mass displacement between two consecutive time steps and the heading direction vector $v$:

$$\text{velocity} = v \cdot \frac{p^{(n)} - p^{(n-1)}}{dt}$$

(3)

where $p^{(n)}$ is the 3d position of the center of mass at time $t_n$ and $dt = t_n - t_{n-1}$ is the simulation time step. With this method, the velocity is a scalar number and has a sign depending on the heading of the tensegrity (positive if heading in the desired direction and negative otherwise). It can thus be used as a feedback to influence the strings command. The strings rest lengths are then computed using the following actuation rule:

$$\begin{cases}
\dot{\ell}_i = w (\ell_0 + \min(h_i^2, h_0) - \ell_i), & \text{velocity } \geq 0 \\
\dot{\ell}_i = w (\bar{\ell} - \ell_i), & \text{otherwise}
\end{cases}$$

(4)

where $\ell_i$ is the rest length of string $i$, $\ell_0$, $h_0$ and $\bar{\ell}$ are constant parameters and $w \in \mathbb{R}_+$ accounts for the time scale at which lengths corrections occur.

Motor commands adjusting the strings rest length are performed through impedance controllers. The use of impedance controllers allow a smooth actuation of the string lengths and avoid creation of too high tensions within the string network. The commands are computed using the following actuation rule:

$$T_i = T_0 + k(\ell_i - l) + \eta(V_i - V_0)$$

(5)

where $T_i$ is the target tension, $T_0$ is the offset tension, $k$ is the elastic coefficient, $\ell_i$ the current rest length, $l$ the current length, $\eta$ a viscosity coefficient and $V_i$ and $V_0$ the actual and target velocity of the motors, respectively. In our simulation, we kept $T_0, k, \eta$ and $V_0$ constant.
Figure 21: Schematic view of the IR-sensors firing to the ground. Distance sensors are located at each rod's end.

8.2 Reactive Method

Keep in mind that the only parameter that can be controlled is the rest length of each string. We denote by $\ell_i$ the rest length of the inner strings, $l_i$ their actual lengths. The global heading direction is defined by the unit vector $v$ and the orientation of each string is represented by the vector $v_i$. For each inner string we use the dot product $d_i = v \cdot v_i$ as feedback to control the position of the payload as follows:

$$\dot{\ell}_i = (\ell_0 + d_i \gamma - l_i)w$$
$$\ell_i(0) = \ell_0$$

where the weight $w$ determines the reactivity of the system and $\gamma < 0$ is a fixed parameter. Thus, without any external perturbation, the system has a stable equilibrium position at $\ell_0 + d_i \gamma$. With this implementation, the strings that have their orientation aligned with the global heading see their rest length reduced and the strings pointing in the opposite direction are elongated. The global result is a displacement of the payload in the direction of the heading vector. See figures 22 and 23 below for a graphical representation of the method.

Note that the heading direction $v$ can be chosen arbitrarily and can be adjusted dynamically. It can be chosen in an absolute frame of reference or relative to the tensegrity orientation.

With this implementation, we were able to obtain stable and smooth rolling gaits allowing the tensegrity to roll up to 60 meters in 60 seconds over flat terrain. The robot could also handle slopes up to 8°, bumpy terrain (Figure 24), obstacles and collisions.

Possible improvements:
The main disadvantage of the reactive method as presented here is the large amount of feedback required to actuate the motors. This can be a serious complication when it comes to designing...
the real tensegrity hardware. This justifies the research for simpler methods, based on the same physical principle but requiring less feedback information.

### 8.3 Inverse Kinematics Method

#### 8.3.1 First order IK

The inverse kinematic method presented here can be an alternative to the reactive method. The idea is to apply the classical transpose Jacobian algorithm used in traditional robotics to control the 3d position of the central payload. Because of the intrinsic compliance of the tensegrity, the geometry of the robot is changing over time and an important modification that we have to add to this method is the dynamical computation of the Jacobian matrix to account for these changes of configuration.

The idea of this method is to define the 3d position of the central payload $p = (p_1, p_2, p_3)$ as a function of the strings rest lengths $\ell = (\ell_1, \ldots, \ell_n)$. Mathematically, we can write $p = p(\ell)$. As a consequence, in first approximation, a small displacement $\delta p$ of the payload can be written as:

$$\delta p_i \approx p_i(\ell(0)) + \sum_{j=1}^{n} \frac{\partial p_i(\ell(0))}{\partial \ell_j} \delta \ell_j, \quad i = 1, 2, 3$$  \hspace{1cm} (6)

If we define now $J$ the Jacobian matrix as $J(p) = \left[ \frac{\partial p_i}{\partial \ell_j} \right]_{ij}$, we can rewrite the above as:

$$\delta p = p(0) + J(p(0)) \delta \ell$$  \hspace{1cm} (7)
This equation relates the payload displacement $p^{(0)} - \delta p$ to the change of rest lengths $\delta \ell$. We can therefore determine what should be the change of the rest lengths to have the payload move in a certain direction. This can be expressed as:

$$\delta \ell = J^{-1}(p^{(0)}) \left( p^{(0)} - \delta p \right)$$

(8)

However, computing the inverse of the Jacobian matrix is a very costly and complicated operation. Instead, we use the mathematical trick known as transpose Jacobian method where we replace the inverse of $J$ by its transpose to obtain:

$$\delta \ell = \alpha J^T(p^{(0)}) \Delta p$$

(9)

with $\alpha \in \mathbb{R}_+$ and $\Delta p = (p^{(0)} - \delta p)$. This relation allows us to compute the motor commands (i.e., the change of rest lengths) to move the payload in any direction we want. The main issue relies in the computation of the Jacobian matrix. In a static system made of bars and joints only, this matrix is constant and can be computed very precisely using appropriate mathematical tools. But in the case of a very compliant tensegrity structure, the coefficients of the Jacobian matrix are time dependent. The idea is thus to recompute the matrix coefficients dynamically using a finite difference method:

$$J(p) \approx \begin{bmatrix} \frac{p_i^{(n)} - p_i^{(n-1)}}{\ell_j^{(n)} - \ell_j^{(n-1)}} \\ \vdots \end{bmatrix}_{ij}$$

(10)

Using equation (10) and (9) we are now able to move the payload in any direction with a feedback only on the payload position in space and each string’s rest length.

The results obtained with these methods allow the tensegrity to roll up to 340 meters in 60 seconds on flat terrain. However, the rolling gait is much more chaotic than with the reactive method. Moreover, some sudden and large corrections can occur unexpectedly. These unstable features come from the non-linearities present in the tensegrity structure that cannot be captured by this too simple first order method.
8.3.2 Second order IK

Again, the main drawback of the previous method are numerical inaccuracies due to the first order approximation to compute the relation between $\delta p$ and $\delta \ell$. Since tensegrity structures are by definition very compliant and oscillatory, higher order terms should be added in order to account for these non-linear behaviors. A possible improvement consists of extending the Taylor expansion to higher order terms, yielding (here up to 2nd order terms):

$$\delta p_i \approx p_i(\ell(0)) + \sum_{j=1}^{n} \frac{\partial p_i(\ell(0))}{\partial \ell_j} \delta \ell_j + \frac{1}{2} \sum_{j=1}^{n} \sum_{k=1}^{n} \frac{\partial^2 p_i(\ell(0))}{\partial \ell_j \partial \ell_k} \delta \ell_j \delta \ell_k, \quad i = 1, 2, 3$$  \hspace{1cm} (11)

or

$$\delta p_i \approx p_i(\ell(0)) + \left( J(p(0)) \delta \ell \right)_i + \frac{1}{2} \delta \ell^T H \left( p_i(\ell(0)) \right) \delta \ell, \quad i = 1, 2, 3$$  \hspace{1cm} (12)

where $H(p_i) = \left[ \frac{\partial^2 p_i}{\partial \ell_j \partial \ell_k} \right]_{jk}$ is the Hessian matrix associated to $p_i$.

Considering (12), we define additionally $\Delta p = \delta p - p(\ell(0))$ and $f(\delta \ell; \Delta p)$ as

$$f_i(\delta \ell; \Delta p) = \left( J(p(0)) \delta \ell \right)_i + \frac{1}{2} \delta \ell^T H \left( p_i(\ell(0)) \right) \delta \ell - \Delta p_i, \quad i = 1, 2, 3$$  \hspace{1cm} (13)

The idea is, given a desired displacement of the payload in the 3d space $\Delta p$, to find the corresponding lengths change $\delta \ell$ that will lead to this displacement. This correspond to finding $\delta \ell$ such that $f = 0$. Note however that this system is overdetermined, non linear and might not possess a real solution. In order to bypass these difficulties, we can compute an approximation of the solution using a quasi-newtonian iterative method. The idea is to start with an arbitrary position, e.g. $\delta \ell_0 = 0$, and compute the next iteration as:

$$\delta \ell_{k+1} = \delta \ell_k - J_k^{-1} f(\delta \ell_k; \Delta p)$$  \hspace{1cm} (14)

until convergence is achieved. $J_k^{-1}$ denotes here the Moore-Penrose pseudo inverse of the Jacobian defined by $J = \left[ \frac{\partial f_i}{\partial (\delta \ell_j)} \right]_{ij}$. Note that this matrix is not the same as the one appearing in the Taylor expansion of $p(\ell)$. The pseudo inverse is computed using a singular value decomposition of the Jacobian matrix $J = U \Sigma V^*$ where $U$ is a unitary matrix, $\Sigma$ is a rectangular diagonal matrix containing the singular values of $J$, and $V^*$ (the conjugate transpose of V) is a second unitary matrix. Once the three matrices have been computed, the pseudo inverse can be found by a simple matrix multiplication $J^{-1} = V \Sigma^{-1} U^*$ with $\Sigma^{-1} = \text{diag}(1/\sigma_i, i = 1, \ldots, n)$.

**Possible improvements:**

Of course this system is then much more complicated than the first order approximation and requires therefore more complex and costly numerical techniques to be solved. Moreover, convergence cannot be guaranteed as solutions may not exist or numerical instabilities might drive the
system out of the convergence region. Note also that in real hardware these additional computations may lead to higher energy consumption and would require a greater computational power in order to solve these equations in real time. Another major drawback is the fact that the payload position depends only indirectly from the strings rest lengths. As a result, the inverse kinematics might be “mistaken” if two or more antagonist motor commands are executed at the same time. Indeed, in this particular case, a motor might reduce a given string’s rest length but still measure the payload moving away from the string’s anchor point due to the other motors actions. This effect leads to contradictory motor commands once the inverse kinematics algorithm is executed and, unfortunately, these errors cannot be solved by better numerical accuracy or even higher order methods.

A possible improvement that might address this issue would be to reduce the number of strings that can be actuated. This would reduce both the complexity of the problem and the mistakes happening when antagonist strings are actuated. However these errors would always remain present at a certain level as they are inherent to the tensegrity physical properties and to the control and feedback method we adopted.

8.4 Gyroscopic Method

An easy way to tackle the orientation issue is to use the physical properties of gyroscopes to create torques in any given direction and keep track of a given orientation. The idea of the method is
to construct a gyroscope inside the central payload and change its orientation in order to create a torque on the whole structure. The torque will tilt the payload, pulling on the inner strings of the structure and thus creating a force on the ground pulling the tensegrity forward. See figures 26 and 27 for a schematic explanation.

This method has the advantage of requiring no actuation of the inner muscles, all the forces resulting from the payload twisting motion. Furthermore, the heading of the tensegrity can be chosen quite easily as the gyroscope will try to keep its orientation if no external force is applied. The control of the motion is also simplified as we reduce the problem of actuating 12 strings to choosing the pitch, roll and yaw of the payload. A detailed physical analysis of this method can be done on the model of the torsion pendulum.

With this implementation and the current physical shape (no modifications to the payload size or inner strings tensions), we were able to achieve displacements of more than 53m over 60 seconds of simulation. Note however that irregular terrain configurations such as bumps and slopes cannot be handle as well as with the reactive method.

Figure 26: Stable rest situation, no torque is applied. The tensegrity is schematized by the circular shape, the central payload is connected by 4 inner muscles.

Figure 27: Once a torque is applied, the central payload is tilted and pull on the inner strings. This motion creates a force $F$ on the ground moving the tensegrity forward.

Possible improvements:
Of course, the major drawback of this method is the requirement for relatively heavy and voluminous gyroscopes that have to be inserted in the payload structure. Also this method is heavily dependent on the diameter of the payload, the bigger the diameter, the greater the torque we can apply to the structure. As a result, the size of the payload would have to be optimized to match both the motion and security requirements. Moreover, the tension of the inner strings can be tuned to adapt to the magnitude of the force created on the ground.
8.5 CPG and Adaptive Frequency Oscillators Method

Another approach is the storage of a stable gait obtained in simulation inside a central pattern generator (CPG). The idea is to use as much feedback as needed in order to get a smooth motion and then store the resulting periodic commands as a stable limit cycle of a CPG. Once this process is done, the tensegrity can be driven with the CPG output with much less feedback than before.

8.5.1 Arbitrary Waveform Oscillator

In order to be able to store and recreate different types of signals, we use a so-called arbitrary waveform oscillator (AWO). The dynamical system driving the CPG is presented below. As usual, we denote the muscle rest length by \( \ell_i \).

\[
\dot{\ell}_i = \gamma(g(\varphi_i) - \ell_i) + \frac{dg(\varphi_i)}{d\varphi_i} \dot{\varphi}_i \quad (15)
\]
\[
\dot{\varphi}_i = \omega_i + \sum_j \sin(\varphi_j - \varphi_i - \phi_{ij}) \quad (16)
\]

where the function \( g(\varphi) \) is a periodic and derivable function, \( \gamma \in \mathbb{R}_+ \) is a parameter accounting for the system's time scale, \( \omega_i \) is the pulsation of the periodic output and \( \phi_{i,j} \) is the desired shift between signal \( i \) and \( j \). Without any external perturbations, the system converges to \( \ell_{i,\infty} = g(\varphi_i) \) where \( \varphi_i = \omega t \) and \( \varphi_i - \varphi_j = \text{mod}(\phi_{ij}, 2\pi) \forall (i,j) \). In our case, for geometrical reasons and for simplicity we choose \( g(\varphi) = A \sin(\varphi), A \in \mathbb{R}^* \).

Furthermore, in order to synchronize to a periodic input signal \( f_i(t) \) of pulsation \( \omega_{in} \) and mean value \( \bar{f}_i \), we add the following equation driving the time evolution of \( \omega_i \) during the learning phase:

\[
\dot{\omega}_i = \epsilon(f_i(t) - \bar{f}_i)g(\varphi_i + \pi/2) \quad (17)
\]

where \( \epsilon \in \mathbb{R}_+ \) is a parameter accounting for the time scale. When the learning phase is completed, the value of \( \omega_i \) is held constant by setting \( \dot{\omega}_i = 0 \forall i \).

On figures 28 and 29, we can observe the convergence of the CPG pulsation \( \omega \) to the input signal pulsation \( \omega_{in} \) in an ideal case where the input signal is a simple sinusoidal function \( f(t) = \sin(2t) \).

On figures 30 and 31, we can see the synchronization of the CPG output (red) to the learning signal (blue) during the learning phase. The signal here correspond to the value of the dot product \( d_i \) when the tensegrity is driven using only the reactive method (see section 8.2). Each string possesses its own CPG that learns and creates its own output. The perturbations and irregularities appearing between 0 to 15 seconds are due to a chaotic motion where the tensegrity has not yet found a stable rolling pattern. After about 20 seconds, one can observe that the input signal becomes much more regular and periodic, this correspond to a stable rolling gait that can be well captured by the CPG as a sine function. Note that the mean of the signal \( \bar{f} \) is dynamically updated in order to account for signal that are constantly shifted above and below 0.
Once the learning phase is completed, the parameters of the CPG are kept constant and the CPG output \( g(\varphi_i) \) is then used to command the rest lengths \( \ell_i \). If the CPG is able to mimic perfectly the previous commands, we would expect to see the tensegrity rolling with the same gait as with the reactive method but without the need for any orientation feedbacks. Using the phase shift parameters \( \phi_{ij} \) (see equation (16)), we can also force a delay between two (or more) oscillators. In some cases, for instance for diametrically opposed strings, it is obvious that a phase shift of \( \pi \) would be appropriate (see figure 33 for a graphical representation of the whole oscillator network). The value of the coefficients \( \phi_{ij} \) can also be extracted by a careful analysis of the signals shift during the learning phase and then be assigned to the corresponding coefficients.

This method has the advantage of requiring no (or almost no) feedback and thus only a very small amount of computations. It can therefore be implemented easily on real hardware. However, it is important to note that the dynamical system runs on a much larger time scale than the perturbations disturbing the system. A tensegrity driven only by a CPG would then only, in the best case, have a stable rolling gait on a flat, obstacle free terrain. This effect is even accentuated by the inherent non-linear response that tensegrity structures possess. As a result, it is necessary to include also a second control method that can work on this smaller time scale and give an appropriate response to these external perturbations.

Simulations were performed where the tensegrity was driven during 50 seconds using the reactive method. This first phase was used to synchronize the CPG output with the input signal given to the robot (figures 30 and 31). Then, the controls were shifted to be driven only by the CPG output and the learning phase was stopped. No further feedback was used to drive the robot’s motion.
Adaptive frequency oscillator learning from rolling signal

Figure 30: dynamic synchronization of CPG signal (string #3)

Results showed that the tensegrity could continue rolling for a few seconds but quickly rolled on the side changing completely the orientation and being therefore unable to move smoothly using the signal learned previously. After some time and random displacements, the robot can fall back in the right position and keep rolling for some more time but eventually falls back in an unwanted position. With this type of motion, only much small travel distances were achieved compared to the reactive and inverse kinematics method.

Possible improvements:
Since the tensegrity can easily be perturbed and roll on the side, and since the synchronization of all CPG signals is not always perfect, the tensegrity cannot keep rolling on a stable gait for more than a few seconds. Even on flat and obstacle free terrain, an open loop control is not sufficient to drive the robot smoothly. A good improvement would be to mix the CPG approach with one of the technique discussed above. As stated previously, the CPG could drive the global rolling motion, occurring on a large time scale, while the corrections, occurring on a much smaller time scales would be done through an inverse kinematics algorithm or a reactive control.

8.5.2 Hopf Oscillator

Due to the ball-like structure of the tensegrity, the signals we want to copy during the rolling phase can be assumed as sinusoids. Thus, instead of AWOs, we can consider using Hopf oscillators
defined by:

\[
\dot{x} = \gamma(\mu - (x^2 + y^2))x - \omega y + \epsilon f(t) \\
\dot{y} = \gamma(\mu - (x^2 + y^2))y + \omega x
\]

where \(\gamma\) is a time constant, \(\mu\) is the target frequency and \(\omega\) the target pulsation of the signal. This dynamical system can be adapted to synchronize to any periodic input signal \(f(t)\). The resulting adaptive frequency Hopf oscillator is defined by the following set of equations:

\[
\dot{x} = \gamma(\mu - (x^2 + y^2))x - \omega y + \epsilon f(t) \\
\dot{y} = \gamma(\mu - (x^2 + y^2))y + \omega x \\
\dot{\omega} = -\epsilon f(t) \frac{y}{x^2 + y^2}
\]

As with the AWO, we can now record the periodic signal during a learning phase and store it as a stable limit cycle of the Hopf oscillator. This signal can later be used to drive the tensegrity.

On figure ?? above, we can notice a coupling between the height signal (green), i.e. the height of the muscle connecting the payload with the learning signal (red). This coupling can be enforced by adding a new term to the dynamical system (18), (19). This coupling will allow the oscillator to synchronize with the real tensegrity motion and enable the system to deal with ground contact and unexpected perturbations that may occur during the rolling. We denote by \(h(t)\) the height signal.
Figure 32: 2D trajectory of the tensegrity (seen from above). The blue curve represents the trajectory while the robot is driven by the reactive control algorithm and the CPG is in the learning mode (50 seconds). The motion is very regular and the heading is maintained throughout the whole period. The red trajectory represent the path traveled once the CPG controller takes over (40 seconds). Due to the open loop implementation, the heading of the robot cannot be maintained and the tensegrity ends up rolling in random directions.

With feedback by the ID-sensors, the resulting dynamical system used for rolling is then given by:

\[
\begin{align*}
\dot{x} &= \gamma (\mu - (x^2 + y^2)) x - \omega y - kh(t) \\
\dot{y} &= \gamma (\mu - (x^2 + y^2)) y + \omega x
\end{align*}
\]

with \(k \in \mathbb{R}_+\) a coefficient. Adding the coupling term improves significantly the distance that the tensegrity can roll, see figures 34 and 35 for a numerical example.

Possible improvements:
Hopf oscillators can synchronize very accurately to periodic input signal and are therefore very well suited for learning motor commands for rolling tensegrities. Moreover, coupling can be added using feedback signals obtained from data measured by the robot sensors. This coupling enables the tensegrity to react to unexpected obstacles on the ground and adapts the output signal of the oscillator to the real robots position. This allows the tensegrity to roll faster and further.
Figure 33: Schematic view of the whole oscillators network. Nodes 0-11 represent the oscillators associated to the inner strings, nodes 12-35 represent the oscillators associated to the outer strings. The central node represent the payload, where the orientation and speed is computed and then shared to the other nodes through their common links (arrows). The arrows on the outer links represent a non zero phase shift $\phi_{ij}$. 
Figure 34: 2D trajectory of the tensegrity (seen from above). The blue curve represents the trajectory while the robot is driven by the reactive control algorithm and the CPG is in the learning mode (50 seconds). The motion is very regular and the heading is maintained throughout the whole period. The red trajectory represents the path traveled once the CPG controller takes over (40 seconds).

The CPG is here driven purely open-loop and the tensegrity travels a total distance of 56.8m.

However, while allowing longer rolling distances, this feedback does not control the robots heading. As we can see on figures 34 and 35, the red trajectory does not maintain a constant heading. As a consequence, additional parameters have to be added to the dynamical system or a hybrid method, such as a mix CPG - inverse kinematics can be used.
8.6 Hybrid CPG - Inverse Kinematics method

8.6.1 AWO and IK

The aim of this method is to close the loop of the AWO CPG in order to be able to control the motion of the tensegrity. For this purpose, we add two terms $\chi_i$ and $\xi_i$ to the original dynamical system equations (15) and (16):

$$\dot{\ell}_i = \gamma(g(\varphi_i) + \chi_i - \ell_i) + \frac{d g(\varphi_i)}{d \varphi_i} \varphi_i + \xi_i$$  \hspace{1cm} (25)

$$\varphi_i = \omega_i + \sum_j \sin(\varphi_j - \varphi_i - \phi_{ij})$$  \hspace{1cm} (26)

These feedback terms will account for unpredicted movements of the tensegrity and perturb the limit cycle of the dynamical system to let the robot come back on the desired trajectory. Since
these corrections have to be momentaneous, we impose a fading memory dynamic:

\[
\begin{align*}
\dot{\chi}_i &= -\lambda \chi_i \\
\dot{\xi}_i &= -\mu \xi_i
\end{align*}
\]

with \(\lambda, \mu \in \mathbb{R}_+\).

To compute the values of \(\chi\) and \(\xi\), we use the second order kinematics method as presented in section 8.3.2. \(\chi\) and \(\xi\) are updated if and only if the payload position lies on the opposite side of the robots center of mass. In this way, the corrections are made only if the tensegrity can potentially roll in a undesired direction. Note also that in order to use this method, we need to know the position of the payload and the center of mass.

8.6.2 Hopf oscillators and IK

We can apply the same method to the adaptive frequency oscillator as presented in section 8.5.2. We add the corrective term to the output of the oscillator. The resulting dynamical system reads:

\[
\begin{align*}
\dot{x} &= \gamma (\mu - (x^2 + y^2))x - \omega y - kh(t) \\
\dot{y} &= \gamma (\mu - (x^2 + y^2))y + \omega x \\
\text{out} &= x + \xi(t)
\end{align*}
\]

where \(\xi(t)\) decreases exponentially with time.

Possible improvements:

This method’s efficiency relies on the quality of the inverse kinematics algorithm used. As a consequence, if we want to improve the method, we need to look into more accurate inverse kinematics algorithms. For simple tensegrity structures such as the 6-struts icosahedron considered in this paper, closed form solutions for the inverse kinematics can also be worth investigating. Remember from the discussion of section 8.3 that the IK method has to be relatively cheap in terms of calculations and precise enough in order to deal with the dynamics of the tensegrity.
Figure 36: 2D trajectory of the tensegrity (seen from above). The blue curve represents the trajectory while the robot is driven by the reactive control algorithm and the CPG is in the learning mode (50 seconds). The motion is very regular and the heading is maintained throughout the whole period. The red trajectory represent the path traveled once the CPG controller takes over (40 seconds).

The CPG is now coupled to the height signal and receives inputs from the second order inverse kinematics algorithm in case it starts rolling in a wrong direction. The resulting trajectory is a long and relatively straight line extending well the reactive control.
9 Hardware Robot

In conjunction with our Phase I study we have been working collaboratively with the University of Idaho providing students with a capstone senior design project researching tensegrity structures for possible application in space exploration. This year project focused on investigating properties of spherical tensegrity including its load capabilities and mechanization of the packing and deployment methods. One common aspect of the projects was the use of the BULLET simulation program with this year's project specifically aiming to provide a more user friendly interface.

9.1 Project Goals

The three goals of this project were as follows: 1. Provide a structural design capable of withstanding a 30-foot test fall. 2. Mechanization of the collapse and standing method(s) of the structure. 3. Provide a user-friendly simulation tool for BULLET. The first goal was selected because the velocity achieved in a 30-foot drop here in earth's gravitational field is approximately equivalent to the terminal velocity reached in the gravitational field of Saturn's moon Titan. This means by withstanding a 30-foot drop here, the structure should be sufficiently strong to withstand the landing impact on Titan. In order to either increase the quantity or reduce the amount of space needed to send the structures to Titan, methods of collapsing and expanding were investigated. The structures would be sent in the collapsed state to conserve space, but upon deployment would expand to a standing position to brace for impact with the surface. The computer program Bullet was used to simulate this collapse, expansion, and impact. NASA's Intelligent Robotics Group (IRG) has been using Bullet for years, but had yet to develop a user-friendly interface for the program. Therefore, the final goal of the project was to create this interface so users with limited programming experience can use the program. This project could be divided into two components, the first structural, the second a control component.

9.2 Structural Component

9.2.1 Structure of Choice

In the beginning, the following three structures were considered: a six strut, 24-string Icosahedron; 12-strut, 36-string Cuboctahedron; and a 30 strut, 30-string Dodecahedron. These three structures are displayed below in Figure 37.

The 30 strut structure was quickly dismissed due to its lack of interior strength resulting from zero cross members in the design. The selection process was continued by a static load testing experiment. Since the structure needed the capability of withstanding a 30-foot test fall it was of interest to determine which configuration was inherently more rigid and thus most able to handle externally applied loads. To begin, three prototypes of both structures (for a total of six) were constructed out of standard SCH 40 1/2 inch PVC struts and 300lb test parachute cord. Static loading tests were conducted by placing each structure in its most stable orientation (most points of contact), placing a one foot square piece of plywood on top, and performing the following: 1. Measure standing height to bottom of plywood 2. Place weight on plywood 3. Measure height.
to bottom of plywood again (calculate deflection) 4. Remove weight 5. Measure again to check rebound and use for initial height of next load This was performed for a range of weights from 5 lbs to 25 lbs. Once all the data was collected a One Way ANOVA statistical analysis was used in search of trends describing and favoring one structure over the other. The analysis favored the six strut Icosahedrons load bearing capabilities indicating this as the more rigid of the two structures. Additionally, with time spent investigating the geometry of each structure two easily definable methods to collapse and expand the six strut Icosahedron were developed. These two methods will be further discussed later. Based on the ANOVA analysis and methods of collapse, the decision was made to continue the study with a focus on the six strut Icosahedron.

9.2.2 Structural Construction

Construction of the final prototype began by cutting a ten-foot piece of 1-3/8 OD, 1/8 wall thickness aluminum into 20 inch long pieces for use as each strut. Aluminum was selected as it is relatively inexpensive and has a sufficiently high strength to weight ratio. Instead of using the same material for all the tension members, it was decided to use both elastic and non-elastic members. By using the elastic members, the structure would be capable of deforming slightly on impact without breaking while the non-elastic members are necessary for creating actuated faces. For the 18 elastic members, extension springs with a spring constant (k) equal to 1.5 lbs/in were selected. Many other springs rates (ie 0.7 lbs/in and 0.5 lbs/in) were tried, but this was selected for the final structure due to the structural stiffness they provided. These springs also provided the amount of deflection necessary to reach full collapsibility. For the six non-elastic members on the actuated faces 200 lb test Dacron string was implemented. All connections were held in place by threading 5/32-28 holes on both ends of each strut and fitting them with steel spring anchors.

9.2.3 Motor Implementation

To mechanize the movement of the structure from standing to a collapsed position and back to a standing position six DC motors were internally mounted. Three in the ends of each strut that form one of the equilateral triangular faces with three more motors in the opposite side of the structure again forming an equilateral triangular face. Each motorized end assembly has the motor fitted in an aluminum sleeve with diameter a couple hundredths less than that of the aluminum pipe for a tight fit. 10-32 set screws were joined into the rod and pressed down onto the sleeve to hold the
motor in place. On the top shaft of each motor a spool was placed and locked in place with a 4-40 set screw. Figure 38 shows an exploded view of this motorized end assembly.

![Figure 38: Assembly of actuators into the Rods of the prototype lander](image)

**9.2.4 Methods of Collapse**

As previously mentioned, there are two methods of collapsing and expanding the structure which were desirable for this study. These two methods will be referred to as the Star Elongation and Linearly Extended methods and will be further discussed now.

1. **Star Elongation**: This method requires an orientation where the actuated faces are the top and bottom of the structure. By rotating the motors such that the sting faces are allowed to elongate, the structure will collapse into a relatively flat star shape. The final height of this method depends greatly on the springs implemented. In the final prototype, the diameter of the springs prevented it from collapsing as far as earlier models. This is because in earlier models, the springs were able to bend allowing a greater range of collapse while the diameter of the final springs used was too large to allow this. With regards to storage this method preferable as the configuration allows for the most effective use of allowable storage space. However, if a centrally located payload was attached, this method of collapse will provide no protection. Figure 39 shows the starting and final states of this structure. Note the bent springs in Figure 39 (right).

2. **Linearly Extended**: This method requires an orientation where the string actuated faces are the right and left faces of the structure. Through spooling the string in and collapsing these faces the structure collapses approximately linearly. This method does not provide effective use of storage capacity but does provide protection for a centrally located payload if one is desired to be attached. The method of collapse is displayed in Figure 40.
9.2.5 Abaqus FEA Simulation

In order to make informed design parameters and quickly and cheaply test designs without risking breakage, it was important to be able to simulate the structure falling in a computer simulation. It was necessary that the software package used be robust enough to handle the indeterminate nature of a complex tensegrity structure, while providing the engineering precision necessary to inform design decisions.

The finite element analysis software Abaqus fit the criteria above. It modeled the fall of a six strut tensegrity structure from 10 meters. The structure was modeled to approximate the structure our team constructed. All values were considered to be metric units to maintain consistency, even though Abaqus does not in fact have any defined units system. The struts were defined as beams with a pipe cross section that were 0.508 long and had an inner diameter of 0.0274 and an outer diameter of 0.0318. The struts were rotated and translated in the assembly to form a tensegrity icosahedron. The springs were attached at the appropriate endpoints and given various elastic moduli according to the requirements for each simulation. A discrete rigid plane was defined with a reference point at its center to be the floor that the spherical tensegrity impacted.

For the initial conditions, the reference point on the floor was ENCASTRE to fix the floor. The structure was given a negative velocity of 14 towards the floor as that corresponded to the velocity at which an object would hit earth from 10 meters high neglecting air resistance. The model was translated to small distance above the floor since it was already at its final velocity. It was also rotated to various configurations in the assembly to create various drop conditions. The model was given a tangential friction property of All with Self and the friction factor was defined to be 0.3.

The simulation was run as a dynamic explicit model to obtain convergence. In addition to obtaining the Mises stress in the field output, history output was specifically requested for each spring to record a force at small time steps in each spring during impact. Overall, it was found that imple-
menting springs with lower elasticity led to lower overall forces, but this had to be balanced with maintaining structure shape during impact. A recommendation based on these models is made for implementing springs with a spring rate around 25 lb/in and a maximum force of about 100 lbs. The simulation showed that stress in the struts should be below the yield strength for the 6000 series aluminum used on the structure.

Some issues with the model that may require further investigation affected the springs. Unlike the standard model, the explicit model supports only tension and compression springs. This led to oscillations in the spring force that would not occur in a real tensegrity model with tension only members. One solution to this problem may be to use tension only members connected between struts instead of springs. Furthermore, it was assumed that the springs had no length limit, so the elasticity in some of the models may not be achievable with the actual hardware.

9.3 Simulation and Electrical Aspects of the Spherical Tensegrity

9.3.1 DC Gear Motors

The Pololu 172:1 metal DC gearmotors are arguably the most important electrical aspects of this project. They are integrated into the tensegrity structure and must withstand the 30 foot drop and are also responsible for controlling the string length to expand and collapse the tensegrity for transport. They control the string length of the triangular faces of the 6 strut tensegrity by means of the spindle system described in earlier sections of the report.

In order to determine how the motors would perform in the structure, it was necessary to conduct an experiment to assess how much torque and current the motors could withstand without stalling. The motors were tested by using a with a 6 V AC C-Clamp to fix a motor to a workbench. A spindle and string were then fixed to the motor shaft. In order to apply a force, increasing amounts
of weight were attached to the string until the motor stalled. We attached a spindle and string to the motor shaft and a weight to the end of the string. We also powered the motor using a 6 V AC adaptor.

During the experiment, the motors stalled when a load of 29lbs was applied and ran with an average current of approximately 1.9A. When power was removed from the motor, the shaft of the motors would rotate and unspool at approximately 8.2 pounds of applied force.

9.3.2 Control Systems

The functioning prototype at the conclusion of this stage of the project used an Arduino Uno Microcontroller and three Arduino Motor Shields connected via a breadboard. This configuration does not allow independent control over each of the motors. The motor shields had two functions: to route current directly from the power source to the 6 DC motors and to act as an H-bridge allowing the motors to run in two directions for the collapse and expansion of the structure. Figure 41 shows the electrical system. Please note that the AC adapters see in this figure were not used in the final construction. Instead, only one AC adapter was used (to power the Arduino) and a 75W power supply. The power supply operated at 7V, and was capable of supplying 10A of current though this was higher than the required amount.

This final functioning schematic did not implement the motors encoders. Instead, a time based scheme was used to control collapse and expansion of the tensegrity structure. The code is linked to the team website. The code operated in a series of for loops with different time constraints for star-shaped collapse and elongated collapse.

Because the force necessary for each of the motors to overcome was not the same in each motor, the motors rotated at different rates. Meaning, the final lengths of each of the strings was no longer the same. For a few iterations, the difference in string lengths was not overly damaging to the design of the structure, but over time, this could cause many potential problems. Therefore, it was desirable to use the encoders to control the number of rotations of the motor shaft. Although the control scheme for this proved to be too complex for the time allotted in this phase of the project, an attempt was made to implement it.

A single channel, one-wire positional control scheme using an Arduino Mega 2560 was intended for the final prototype. The Mega 2560 has six different external interrupts and enough digital data pins to map encoder outputs. A single channel was envisioned originally to reduce complexity and resources used on the single Arduino control board but implementation showed that two-wire, two-channel encoder information was both possible using the single control board and necessary to obtain direction information.

Channel B input from the quadrature encoders could be mapped to any of the remaining digital pins on the Arduino Mega 2560, as only channel A is needed to invoke an interrupt. The previous values of channel A and B would be appended to the current high/low (0/1) values of channel A and B to obtain a 4-bit number to use in a lookup table to obtain direction information. This scheme helps debounce the encoder input as only four of the 16 possible values represent valid motor motion and invalid transitions can be ignored. Speed was controlled via the duty cycle of the PWM output pins. Full speed (100% duty cycle) was utilized unless the position was within approx. 5% of its target, in which case the slowest usable speed (20% duty cycle, or 50/255) was
utilized to prevent significantly overshooting the target position.

Due to time constraints, only the original single-encoder-channel scheme was tested on two unattached motors. Directions were assumed to be in the direction of motor motion unless the motor was off, in which case direction was assumed to be positive, lengthening the robots actuated tendons (and shortening the springs toward their rest lengths). Implementation and testing revealed that using both channels would most likely be preferable (less complex and substantially more accurate).

9.4 Conclusion of Hardware Prototype

This segment of the project ended with the completion of a 30 ft drop test, which, as previously mentioned, was one of the project goals. The after effects of this drop included minor unspooling of the motors and plastic deformation in a couple of the springs. In an earlier drop (approximately 20 ft) one of the wires powering a motor became trapped between two struts and the connection severed. This problem may be eliminated by better protecting the wires. However, the structure itself remained intact and the motors inside all still functioned (once power was restored).

The next stages of this project are primarily electronic in nature. Some minor conflicts to be
resolved include how to better protect the wires and how the control system may be mounted onto the structure. The most important issue to resolve will be how to use the encoders to control the motors such that all the motors release and take in the same amount string thus eliminating the current problem with the string lengths not remaining equal. Additionally, independent control over the motors is highly desirable in order to allow the structure to actually move across a surface.

In this project, a six-strut Icosahedron tensegrity structure was fabricated and studied. The structure was comprised of Aluminum compression members and both elastic (springs) and non-elastic (strings) tension members. Regarding the original project goals, the structure was found to have easily attainable methods of collapse and expansion, and strong enough to withstand a 30 ft drop. Additionally, a user friendly Bullet interface was developed allowing users with limited programming experience to interact with the program. All three of the original project goals were satisfied indicating this project is ready to move to its next phase of testing.
10 Landing Structure Analysis

One of our biggest questions upon starting our Phase I study was how suitable a tensegrity structure would be as a landing platform for a NASA mission. More specifically we wanted to answer the following questions:

1. Can a tensegrity structure survive the impact of a hard landing impact of 15 m/s.
2. Can an actuated tensegrity structure still move after a landing impact of 15 m/s.
3. Can a tensegrity structure protect a delicate payload after a landing impact of 15 m/s.

To answer these questions we performed the following:

1. Performed extensive landing simulations using both a physics engine and an Euler-Lagrange Solver.
2. Dropped an actuated tensegrity from a height of 30 ft (9.1 meters).
3. Dropped a tensegrity structure carrying an egg from over 30 ft (9.1 meters).

We are glad to report that the tensegrity platform was successful at all three of our tasks.

10.1 Simulation of Landing

10.1.1 Landing Simulation using Bullet Simulator

To simulate landing and locomotion, we utilize a tensegrity simulator based on the Bullet physics engine. Bullet is an open source physics engine that does 3D collision detection, rigid and soft body dynamics in discrete time, though our simulator does not use the soft body dynamics. For the tensegrity simulation, we use the rigid body collisions provided by Bullet for compressional elements (rods of the structure), and we added simulation of tensional elements (strings) using basic physics for elastic strings. To be able to simulate both rigid bodies and tensional elements together, at each time step, all the forces applied by the strings to the rods are calculated manually. These are then provided to the Bullet physics engine, and Bullet calculates the positions, orientations and velocities of all the rigid bodies considering previous states, tensional forces that we add, and possible collisions.

To simulate tensional forces, we use the rest length ($L_R$) and elasticity coefficient ($c_e$) of the strings that are defined as part of the material property. During the simulations, at each time step, the actual length ($L_A$) is extracted from Bullet, and if the string is stretched ($L_A > L_R$), the tensional force for each string is calculated using the elasticity formula $|F| = c_e \times (L_A - L_R)$. On the other hand, if the string is slack ($L_A > L_R$) the force is accepted as zero (no compressional force caused by strings).

The resulting graphical illustration of the process is given at the Figure 43. As it can be seen on the left, before the moment of impact, all the strings are equally stretched. On the other hand, after the impact, the payload moves down further stretching some of the strings and temporarily deforming the structure.
10.1.2 Landing Simulation using Euler-Lagrange (E-L) Solver

In order to verify the simulation results produced by our Bullet based simulator, we decided to compare the Bullet simulator to a published analytic model for tensegrity systems. We choose to use Skelton’s dynamic equations found in his *Tensegrity Systems* book [63] which is based on his work in [?]. In order to easily solve the dynamic equations with interactions with the environment, an Euler-Lagrange approach is used as well as Skelton’s constrained class 1 structure. The lagrange equation for a constrained rod is given by

\[ L = T - V - c \]  

(30)

where

\[ b = l^{-1}(n_j - n_i) \]  

(31)

\[ c = \frac{J_\xi}{2}(b^Tb - 1) \]  

(32)

Equation (31) is the normalized vector of a rod with \( n_{i,j} \) the nodal positions in \( \mathbb{R}^3 \), and equation (32) contains the lagrange multiplier \( \xi \) to keep (31) constrained. \( J \) is also defined as the inertia...
matrix for a 1 dimensional rod in 3 dimensional space. In order to define the system of \( k \) rods we need to define a combined Lagrangian as

\[
L = \sum_{i=1}^{k} L_i
\]  

(33)

where \( L_i \) is the Lagrange function for each rod. Using the approach outlined in Skelton’s book for deriving the equations of motion, we can then derive the configuration matrix

\[
Q = [R \quad B]
\]  

(34)

where \( R \) and \( B \) are matrices containing the translational and rotational vectors, respectively. They have the form

\[
R = [r_1 \quad \cdots \quad r_k]
\]  

(35)

\[
B = [b_1 \quad \cdots \quad b_k]
\]  

(36)

Also using the procedure to derive generalized forces within Skelton’s book, the system’s generalized force equations are computed as

\[
F_Q = [F_R \quad F_B]
\]  

(37)

with

\[
F_R = [f_{r_1} \quad \cdots \quad f_{r_k}]
\]  

(38)

\[
F_B = [f_{b_1} \quad \cdots \quad f_{b_k}]
\]  

(39)
Finally, we can define the resulting equations of motion in a compact form as

\[
(\ddot{Q} + Q\Xi)M = F_Q
\]

(40)

where

\[
\Xi = \text{diag} \left[ 0, \cdots, 0, \xi_1, \cdots, \xi_k \right]
\]

(41)

\[
M = \text{diag} \left[ m_1, \cdots, m_k, J_1, \cdots, J_k \right]
\]

(42)

This approach was then implemented in Python utilizing a 4th order Runge-Kutta formula for solving the system of ordinary differential equations. In order to implement a gravitational field, a force distribution function is applied along the length of each rod and calculated as a nodal force depending on the given density of the rod. This external force is then applied to the nodes during each time step, simulating a gravitational field.

### 10.1.3 Detailed Impact Simulations Using 2 Simulators

We used these two simulators because they both have strengths and weaknesses. The Bullet simulator is the most general purpose, allowing us to explore control algorithms and complex environmental interactions, but it is an iterative discrete solver that we were concerned might not be providing accurate answers. The E-L solver, on the other hand, has a much stronger analytical basis and should provide very accurate answers, but is limited because some of the nodes (i.e. rod ends) must be constrained and locked into place. This is unrealistic for the deformation caused during landing, and makes it an inappropriate choice for mobility and controls research.

![Figure 44: Bullet vs EL: Vertical Position](image)

In this section, we compare the bullet simulator and E-L solver at the moment of impact with the ground. The simulations are compared at the moment of impact with the ground because our implementation of the analytic E-L solver requires select nodes to be constrained. We setup the structure so that it is barely in contact with the ground and is in balance at time equal to 0. In both
simulations, we add an initial velocity equal to the terminal velocity of Titan, and compared each vertical trajectory, vertical velocity, and vertical acceleration of the payload. Since the structures horizontal speed is zero at the beginning and the structure is symmetrical, the payload’s horizontal components of position, velocity and acceleration are zero. As it can be seen in the Figures 44 and 45, both simulators closely match and generate the same results for position and velocity with the error margin close to zero. Comparing the accelerations generated by two simulators, it can be seen that there is a bigger difference. The reason behind this difference is the fact that bullet is a discrete time simulator and accelerations are calculated using two point estimations from velocities at the timestep before.

![Figure 45: Bullet vs EL Vertical Velocity](image1)

![Figure 46: Bullet vs EL Vertical Acceleration](image2)
10.1.4 Drop Tests

To test the structure against the given impact speed, we drop the tensegrity from 50 meters, using Titan’s gravity. We set two criteria to determine a successful drop test:

- The payload can not exceed the maximum $G$ force (earth) of $25G$ for our scientific equipment
- The payload must not contact a rod member of the outer tensegrity structure

Utilizing the specifications from section 6.6 and our initial calculations for the design of our structure, a 4.5$m$ structure with spring constants of $44kN/m$ for the springs not attached to the payload and $10kN/m$ for the other springs will give a successful drop test in any orientation. As it can be seen in Figure 47, the structure reaches the velocity of $11.4m/s$ when it reaches the ground. On impact, the pre-tensioned structure distributes the impact force through the tensegrity structure including the forces needed to keep the payload from hitting the ground. During this process, the acceleration (or deceleration) of the payload reaches $180m/s^2 (18.3G)$, maximum tension experienced by any given member in the structure reaches $4800N$ and the average tension reaches $2500N$.

![Figure 47: Position, Velocity, Accelerations and Tensions during landing simulation.](image)

Since we wanted to evaluate smaller tensegrity based probes of this type of structure, we tried all possible orientations to determine when the payload no longer meets one of our success criteria.
Figure 48 shows these orientations. To further analyze a safe zone in this graph in details, we chose a safe orientation of 35 degrees around x axis and 45 degrees around z axis. Figure 49 shows the maximum acceleration of this safe orientation with the x and z axis having error margins of $(\pm 10)$ and $(\pm 15)$, respectively. As it can be seen, in this area, the worst case is an acceleration of 175 $m/s^2$ and the best case is 140 $m/s^2$.

![Heat map of the maximum acceleration that the payload encounters for all possible landing orientations. Black areas are safe, colored areas are where the payload does not meet one or both success criteria.](image)

In addition to different orientations, we tested adding horizontal speeds during landing. Figure 50 shows the horizontal velocities above which the payload hits the rods that surrounds it. In this experiment, the orientation used is the same configuration as the previous landing experiment (45 degrees and 35 degrees). As it can be seen, the structure can handle additional horizontal speeds up to 50 $m/s$. Depending on the direction of the speed, the structure can handle even more speeds.

![Maximum acceleration that the payload encounters for the safe orientation.](image)
Max Deceleration for the payload for different horizontal landing speeds

Figure 50: Heat map of the maximum acceleration that the payload encounters for additional horizontal velocity, in addition to vertical terminal velocity. Black areas are safe, colored areas are where the payload does not meet a success criteria.

10.2 Drop Test of Actuated Hardware Tensegrity

10.3 Prototype Drop Tests

Once the prototype was built and deployment demonstrated, a series of drop tests were performed from successively greater heights until 10m (30’) was reached, at which point the prototype was landing at around 11 m/s, which is comparable to the terminal landing speed expected on Titan. After landing, the test was shown to be successful by demonstrating that the lander still functioned and could be collapsed to its packed state and once more deployed. In Figure 51 we show a sequence from the 7.5m drop test. During this landing, the probe rebounded and rolled sideways a distance about twice its diameter.

Most significantly, the probe survived the 10m (30’) drop test and was still functional afterwards, giving us confidence that this approach is viable, and that our simulation results are accurate enough to proceed to further analysis. One useful insight from this test is that the motors unspooled (i.e. were back driven) by a few centimeters during the landing. Thus, it is recommended that brakes be integrated to the motors, so they can be mechanically locked in place during landing.
10.4 Drop Test of Hardware Tensegrity with Payload

10.4.1 Tensegrity Configuration

Initially, the Tensegritoy kit was assembled into the icosahedron tensegrity structure with pentagonal nodes. The testing payload, an egg, was inserted into the chamber made from cardboard tubing, and then suspended within the tensegrity structure using six of the Tensegritoy kits tension members (See Figure 53).

Starting the payload from an initial height of two feet, the tensegrity structure (as seen in Figures 53 and 55) was allowed to freely fall onto a flat surface. The results were recorded. In the case the
payload was sufficiently protected and did not fail, the tensegrity structure would be dropped again from one foot higher than the previous drop. This was repeated until the failure of the payload, at which the data would be recorded.

Figure 54: 3D Solidworks model of Tensegrity Structure. Highlighted is the pentagonal node with side length L.

We tested two parameters. The first parameter involved tension in the payload suspension cables, which were measured in the number of coils utilized in setting up the structure. The next parameter was the rigidity of the structure. This was configured through the size of the pentagonal nodes of the structure, which was measured in terms of the length of the pentagons side; a smaller pentagonal node resulted in a more rigid structure.

Figure 55: Tensegrity structures with payloads (egg) suspended for testing. Left: pentagonal nodes configured to have 3 inch sides and suspension cable tensions calibrated to 3 coils. Right: pentagonal nodes configured to have 1.5 inch sides and suspension cable tensions calibrated to 3 coils.

Two sets of tests were run. The first set was run by maintaining suspension cable tension constant
while changing pentagon size. Each experiment was run three times to account for noise as seen in Table 3.

The next set of experiments was run holding pentagon size constant while changing suspension cable tension. Each experiment was run three times to account for noise as seen in Table 4.

### 10.4.2 Results

Data gathered from experimentation is listed below in Tables 3 and 4:

Aside from the numbers, there were other observations worth noting throughout experimentation. One phenomenon was that the red rubber caps used to connect tension members to compression members often fell off during testing. It was observed that as the day went on, more caps tended to fall off. This was suspected to be resulting from the sunlight heating the caps and expanding them. Furthermore, there were significantly more caps that fell off during the 3 coil/1.5 inch tests than during the 3 coil/3 inch and 3 coil/4.5 inch tests. Unfortunately, these results were not

<table>
<thead>
<tr>
<th>Suspension Cable Tension (Number of Coils)</th>
<th>Pentagon Size (length of side)</th>
<th>Failure Height Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.5 in</td>
<td>22.33 ft</td>
</tr>
<tr>
<td>3</td>
<td>3 in</td>
<td>23 ft</td>
</tr>
<tr>
<td>3</td>
<td>4.5 in</td>
<td>24.67 ft</td>
</tr>
</tbody>
</table>

Table 3: Testing Matrix 1

<table>
<thead>
<tr>
<th>Suspension Cable Tension (Number of Coils)</th>
<th>Pentagon Size (length of side)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.5 in</td>
</tr>
<tr>
<td>3</td>
<td>1.5 in</td>
</tr>
<tr>
<td>3</td>
<td>4 in</td>
</tr>
</tbody>
</table>

Table 4: Testing Matrix 2

<table>
<thead>
<tr>
<th>Suspension Cable Tension (Number of Coils)</th>
<th>Pentagon Size (length of side)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3 in</td>
</tr>
<tr>
<td>3</td>
<td>3 in</td>
</tr>
<tr>
<td>4</td>
<td>3 in</td>
</tr>
</tbody>
</table>
Table 6: Results for Constant Pentagon Size

<table>
<thead>
<tr>
<th>Suspension Cable Tension (Number of Coils)</th>
<th>Pentagon Size (length of side)</th>
<th>Failure Height</th>
<th>Failure Height Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3 in</td>
<td>6/4/6 ft</td>
<td>5.33 ft</td>
</tr>
<tr>
<td>3</td>
<td>3 in</td>
<td>23/22/24 ft</td>
<td>23 ft</td>
</tr>
<tr>
<td>4</td>
<td>3 in</td>
<td>34/31/30 ft</td>
<td>31.67 ft</td>
</tr>
</tbody>
</table>

quantitatively recorded, as this was not a factor originally thought to be significant. During experimentation, support tension members would at times detach from payload (Refer to Figure 56).

Another phenomenon observed was that during certain tests, the suspension cables would detach from the payload.

10.4.3 Droptest Evaluation

It is important to keep in mind the goal of this experiment; it is an attempt to understand how various parameters of a tensegrity structure affect payload protection. An evaluation of these parameters is accompanied by a physical validation of the tensegrity structures reaction to impacts. This comes in the form of high frame rate video footage of tested impacts, allowing for visual inspection of the forces and deflections occurring within the structure to be compared to the simulated models currently employed by NASA. Both the parameter evaluation and video footage are tools to be used when considering the viability of tensegrity structures to protect payloads in high impact situations.
In order to understand the results of our measured parameters, it necessary to evaluate what constitutes payload protection. There are two main factors to consider: the maximal acceleration of the payload, and whether the payload collides with the structure itself. Both are determined by the vibrational mechanics of the payload, namely the natural oscillating frequency. If the oscillation frequency is too low, the payload will deflect more and collide with the structure. Inversely, if the oscillation frequency is too high, the payload will experience large accelerations that may break finely tuned instruments contained within. This phenomenon was analyzed previously in the Theory section.

Due to limitations in resources, the instrument used to measure protection in our experiment is an egg. The egg essentially measures the collision variable, as video footage shows most breaks occurred to collisions between the payload and structure. The evidence is not decisive though; it may be that high accelerations caused pressure points on the egg from the casing containing it. In any case, future experimentation should include an accelerometer that accurately depicts dynamics of the payload.

10.4.4 Parameter Analysis

Before analyzing the two parameters used—suspension cable pre-tensioning and structure configuration—there are other variables worth mentioning. Perhaps the most significant is that of the payload mass. The more mass the payload has, the more inertia it will have, which will result in greater forces needed to decelerate the payload upon impact. As seen in the Theory section, the mass of the payload also has an effect on the natural frequency of the tensegrity structure. In the investigation of said natural frequency through experimentation, it was concluded that with the resources at hand, the effective spring constant of the system would be easier to test than the mass.

Another variable not tested that could be potentially accounted for is permissible deflection, which is amount the payload can move within the structure. This is because the payload would potentially come in contact with the tensegrity structure itself, causing damage. This is determined by the volume of the structure, before and after deflection. Although our tests only used one size of tensegrity structure, it would be significant to analyze the opportune volume contained for a given natural frequency.

From our analysis in the Theory section, it is not readily apparent if larger or smaller values of natural frequency will protect the payload. However, if the two protection factors are kept in mind, the desirable natural frequency should be balanced between minimizing acceleration while maintaining allowable deflections. This natural frequency was examined through analyzing the effective spring constant of the system.

To account for this effective spring constant, a significant variable is the structural cable pre-tensioning. This regards the tension in the cables that are connected only to structural members, not the payload. This affects the effective spring constant of the system, as it both affects the deflection of the payload as well as affects the stiffness of the structure as a whole. With larger pre-tensioned structural cables, the payload is allowed to deflect less upon impact. Similarly, with larger pre-tensioned structural cable values, the structure resists compression more, making the effective spring constant of the system higher.

It is also worth noting however that the varying rigidity of the structure due to different nodal
configuration can also affect the effective spring constant. Changing this affects the total amount of deflection the structure can undergo with a given impulse. Less structural compression causes more wear on the structure, but maintains more room for the payload to deflect. Changing the pre-tensioning does not limit the total amount of deformation the structure can undergo. This propagates forces more easily, but at the cost of reduced internal volume.

Some variables to consider in the future are inherent in the design of the payload protection tensegrity structure, one of which is the payload casing shape. Our cylindrical casing allowed some protection to the egg for axial collisions, while radial collisions with the structure directly imparted forces on the egg. Furthermore, due to the shape of the casing, we were unable to attach suspension cables to the center of the payload. As a result, the distribution of cables was not perfectly symmetric around the egg, causing variant spring coefficients and thus natural frequencies about the egg. Both these factors imply that the orientation of the structure upon impact causes variable reactions of the payload.

The quantity and orientation of the suspension cables is another inherent design factor. Only a few nodes on the structure connected to the limited number of suspension cables. These nodes experienced unique forces due to both suspension cable pre-tensioning and payload oscillations. Additionally, the shape as a whole deforms due these forces applied at only specific nodes. Thus different allowable deflections occur along differing axis due to the deformed shape. Again, these factors implicate that the structure is not symmetric in its distribution of forces and allowable deflections, and thus subject to variable reactions dependent upon orientation.

Although we did not have the resources to experiment with these design variables, they can still be considered. The ideal configuration would most likely be a spherical payload casing with symmetric suspension cables connecting to each node on the structure. This would eliminate the aforementioned imbalances that cause orientation-specific reactions. Additionally, possible actuation significantly involves these suspension cables, although the implications of actuated tensegrity are not included in this analysis.

10.4.5 Measured Parameter Discussion

The structural rigidity parameter showed that there was a small correlation between rigidity and maximum height of drop before failure. It is difficult to draw significant conclusions from this data, as the result values are very similar. Conceptually, there are benefits and limitations to each side of the rigidity scale. A more rigid structure does not deform as much, and thus maintains more internal room for deflection. However, less rigid structures do not apply as much force onto the spring mass system, and thus minimize overall deflection. It is worth noting that the more rigid structure encountered much more stresses on the nodes, apparent by the amount of times node caps popped off during testing.

Pre-tensioning in the suspension cables demonstrated a much more significant effect on the results. The tensegrity structure could fall from a much higher height with more pre-tensioning, and thus a higher natural frequency. This makes sense conceptually; a larger natural frequency means less deflection. Since the egg broke due to too much deflection the egg colliding with the structure it makes sense that more tension would increase the max height before failure. This does not mean more tension is always better, however. Our instrument did not measure total acceleration of the
payload. It may be that the payload requires smaller accelerations, and thus less pre-tensioning. This would require that structure be larger for the increase in deflection.

10.4.6 Drop Test with Payload Conclusion

The experimentation described in this report showed promising application of tensegrity structures in the areas of impact absorption and payload deployment; an egg suspended within the structure was able to freely fall from heights over 30 feet during testing. In accordance to theoretical analysis, it was able to be concluded that increasing effective spring constant of the system, and thereby increasing natural frequency of the system, decreased the deflection the payload underwent. Unfortunately, the experimentation depicted within this report had limited resources, and only two parameters, suspension cable tension and structural rigidity, were examined. However, with future investment towards research in tensegrity structures, more thorough experimentation may be conducted, taking into account the effects of a multitude of other parameters. Some of these parameters include the material properties of compression members, material properties of the tension members, size of the structure, casing of the payload, and shape of the structure. Our team is honored to have helped pave the path towards understanding tensegrity structures and unlocking their potential.

10.5 Conclusions from Landing Structure Analysis

During an EDL phase of a mission, there are many events which can induce shock or large accelerations, and it is up to the ELD hardware to ensure the payload does not experience these shocks and large accelerations. As the EDL hardware increases capability and the reduces the kinetic energy at landing there is an increase in EDL equipment and mass. As shown section 6.7, a high percentage of the over all system mass is due to the EDL system. In this section, we proved that an EDL scenario utilizing a tensegrity based probe should be able to land on a planetary body with as little as a front and back shield. We then expanded on this idea by decreasing the size of the probe and determining in which landing scenario the probe would land successfully based on our two criteria. Within our scenarios in which the probe experienced a successful landing on Titan, the maximum acceleration applied to the payload was $180\text{m/s}^2 (18.3G)$ and the minimum acceleration was $140\text{m/s}^2 (14.3G)$. Comparing this to the Huygens probe’s landing acceleration of $32G$ [37], the tensegrity probe will have a 43% reduction in $G$ forces experienced by the scientific payload.
11 Future Work

While this NIAC study has validated many concepts related to the applicability of tensegrities as a planetary landing and mobility platform, we have just touched the surface of the research needed to have tensegrety robotics to reach its full potential. With respect to space missions, we focused on a Titan mission, since Titan is of high scientific interests and the atmosphere of Titan allows a unique mission profile where a tensegrity robot mission could be very low cost. However small asteroid mission are also of high interest to NASA, and tensegrities also could form a unique low-cost landing and mobility platform for such missions. A tensegrity robot could survive a moderate speed landing on an asteroid and could crawl or “hop” around the surface to perform scientific exploration. In addition the ability of a tensegrity structure to dynamically change its shape could make it amenable to an asteroid capture mission. Such a missions would require investigation into the low gravity landing and mobility properties of tensegrity robots.

In terms of control, we showed that we could control these non-linear and oscillatory structures using evolutionary algorithms, and get them to roll in a smooth manner. However, tensegrities lend themselves to a huge number of mobility options: We may want them to crawl up hills, reshape themselves to avoid getting stuck, dig into low traction surfaces, or change shape to position instruments directly attached to the structure. Control algorithms for all these movements will have to be investigated.

In terms of hardware, we showed that basic tensegrity movements could be made through cable / pulley actuation. Though in addition to this there are a huge number of possibilities to actuate a tensegrity robot, and each method of actuation has different costs and benefits. A thorough analysis of such actuation methods and tensegrity construction methods is needed.
12 Conclusions

Tensegrity robotics has the potential to dramatically change how many NASA robotic missions are performed. They can reduce costs, increase robustness, and decrease the overall complexity of robotic missions. Despite these numerous advantages, tensegrity robots have not been heavily studied until recently, partially due to the difficulty in controlling these oscillatory and non-linear structures. This Phase I study made significant progress in validating the use of tensegrity robotics as a landing and mobility platform and verifying that they can be controlled.

13 Acknowledgements

As part of our Phase I study, we directed and collaborated with numerous teams. The goals of our study were very broad and ambitious and we greatly appreciate the work done by these teams in helping bring this study together.

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  - Sarah Lynn - Mechanical Engineering, Physics
  - Karen Jolley - Computer Engineering, Physics
  - Joe Hepner - Mechanical Engineering
  - Kyle Morse - Mechanical Engineering
  - Nathan Clark - Electrical Engineering

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  - Sophie Milam - Mechanical Engineering

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– Grant Paulson - Mechanical Engineering
– Jon Saltz - Mechanical Engineering
– Anton Savinov - Mechanical Engineering

• Graduate Mentor

– Andrew Sabelhaus - Mechanical Engineering

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