Design and Evolution of a Modular Tensegrity Robot Platform

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***Abstract*— NASA Ames Research Center is developing a compliant modular tensegrity robotic platform for planetary exploration. In this paper we present the design and evolution of the platform's main hardware component, an untethered, robust tensegrity strut, with rich sensor feedback and cable actuation. Each strut is a complete robot, and multiple struts can be combined together to form a wide range of complex tensegrity robots. Our current goal for the tensegrity robotic platform is the development of SUPERball, a 6-strut icosahedron underactuated tensegrity robot aimed at dynamic locomotion for planetary exploration rovers and landers, but the aim is for the modular strut to enable a wide range of tensegrity morphologies.**

SUPERball is a second generation prototype, evolving from the tensegrity robot ReCTeR, which is also a modular, lightweight, highly compliant 6-strut tensegrity robot that was used to validate our physics based NASA Tensegrity Robot Toolkit (NTRT) simulator. Many hardware design parameters of the SUPERball were driven by locomotion results obtained in our validated simulator. These evolutionary explorations helped constrain motor torque and speed parameters, along with strut and string stress. As construction of the hardware has finalized, we have also used the same evolutionary framework to evolve controllers that respect the built hardware parameters.

I. INTRODUCTION

As part of our research for the NASA Innovative Advanced Concepts (NIAC) program, we are developing the SUPERball (Spherical Underactuated Planetary Exploration Robot), which is a compliant icosahedron tensegrity robot designed for planetary landing and exploration. Tensegrity robots are soft machines which are uniquely able to compliantly absorb forces and interact with unstructured environments. However, instead of engineering a single new robot, we have chosen to develop a fundamentally reusable component for tensegrity robots by creating a modular robotic tensegrity strut which contains an integrated system of power, sensing, actuation, and communications. The purpose is to enable the exploration of the wide range of possible tensegrity robotic morphologies by simply combining the robotic struts into new systems.

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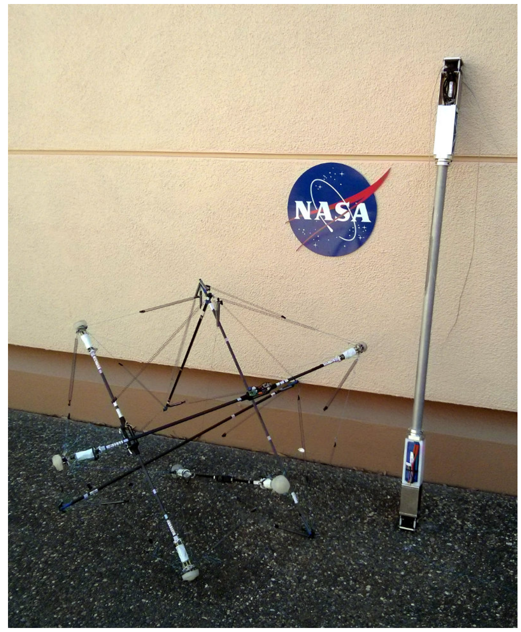

Fig. 1. The tensegrity prototypes studied in this paper. Left: ReCTeR, a lightweight ($1.1kg$), untethered tensegrity icosahedron with six DC motors and rich sensor integration. Right: current version of the strut design for our modular tensegrity platform. The end caps each house a powerful brushless motor and batteries, while the central aluminum tube contains compression springs and sensors to which external cables can be attached.

A. Tensegrity Structures

It is possible to design free-standing structures by arranging axially loaded compression elements in a well crafted network of tensional elements. Such an arrangement is called a tensegrity structure (tensile integrity). Each element of the structure experiences either pure axial compression or pure tension [1], [2]. The absence of bending or shear forces allows for highly efficient use of materials, resulting in lightweight, yet robust systems.

Because the struts are not directly connected, tensegrities have the unique property that externally applied forces distribute through the structure via multiple load paths. This creates a soft structure, for a soft robot, out of inherently rigid materials. Since there are no rigid connections within the structure, there are also no lever arms to magnify forces. The result is a global level of robustness and tolerance to forces applied from any direction.

This makes tensegrity robots inherently compliant and extremely well suited for physical interactions with complex and poorly modeled natural environments. Active motion in tensegrity robots can be performed by changing cable lengths in parallel, enabling the use of many small actuators that work together, rather than individual heavy actuators which work in series. There are also many indications that tensegrity properties are prevalent throughout biological systems, and the morphology of the SUPERball that we are studying, especially when carrying a payload, ends up bearing a striking resemblance to the nucleated tensegrity model of cell structure [3][4].

B. Prior Work in Tensegrity Robotics Design

Because of the limited research into actuated tensegrity robotics, many design aspects have yet to be carefully studied. To date, the majority of constructed tensegrity robots have been simple prototypes using servo motors, limited sensing, and are often tethered for power and control [5]. Others have had fewer limbs than the SUPER ball, or have been secured to the ground as opposed to free-standing [6], [7]. Some related approaches utilize tensegrity as part of a larger, more complicated system, but not as the primary locomotion method [8]. Others have created designs that do not use direct cable actuation, as in the SUPER ball, but instead have more limited forms of locomotion through vibration [9], [**?**]. Finally, the most similar designs to the SUPER ball have not been engineered to specific design requirements nor have the advanced sensing framework needed for controls testing [10].

C. Tensegrity Robotics for Space Exploration

The high strength-to-weight ratio of tensegrity structures is very attractive due to the impact of mass on mission launch costs. Large tensegrity structures have been shown to be deployable from small compact configurations which enable them to fit into space constrained launch fairings. While the above qualities have inspired studies of deployable antennae and other large space structures [11], it is in the realm of planetary exploration that we see the most significant role for many of the unique force distribution qualities of tensegrity robots. A recent NIAC project [12] specifically studies landing and surface mobility of tensegrities, exploiting the controllable compliance and force distribution properties which make for reliable and robust environmental interactions.

The main goal is to develop tensegrity probes with an actively controllable tensile network to enable compact stowage for launch, followed by deployment in preparation for 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 the ability to safely absorb impact shocks that might occur during exploration. This combination of functions from a single structure enables compact and lightweight planetary exploration missions with the capabilities of traditional wheeled rovers, but with a mass and cost similar or less than a stationary probe.

Therefore, a large fraction of the overall weight (as measured at atmospheric entry) of a tensegrity mission can be used for the scientific payload due to the dual use of the structure as a lander and a rover. This allows for cheaper missions and enable new forms of surface exploration that utilize the natural tolerance to impacts of tensegrities [13].

D. Tensegrity Control

Buckminster Fuller [1] and the artist Kenneth Snelson [2] initially explored tensegrity structures in the 1960s. Until the mid-1990s the majority of tensegrity related research was concerned with form-finding [14] and design analysis of static structure [15], [16]. More recently, active control efforts for tensegrities began to emerge [17], as well as descriptions of the dynamics of tensegrity structures taking the connectivity pattern into account [16].

The tensegrity principle allows for compliance and multi-path load distribution, which is ideal for physical interaction with the environment. However, these aspects also present significant challenges to traditional control approaches. A recent review [18] shows that there are still many open problems in actively controlling tensegrities, especially when interacting with an environment during locomotion or manipulation tasks. Though work has been done to control a tensegrity to change into a specified shape [19], practical determination of the desired shape itself is an ongoing challenge. Recently, locomotion of icosahedral tensegrity robots through body deformation was demonstrated [20]. Other work as addressed collision between rigid tensegrity elements during control generation [21], [22].

The approach taken by the NASA Dynamic Tensegrity Robotics Lab builds on this by developing body deformation control algorithms based on central pattern generators [23][24], distributed learning, reservoir computing, and genetic algorithms [25], instead of traditional linear and nonlinear systems approaches. To date, our approach has shown promising results at productively harnessing the potential of complex, compliant, and nonlinear tensegrity structures.

E. A Modular Tensegrity Platform

Though there is much prior work in a variety of theoretical areas for tensegrities, engineering knowledge of constructing practical tensegrity robots is limited. Since a staggering variety of different tensegrity structures can be constructed from collections of simple sticks and strings (for example, see the TensegriToy modeling kit), we have made it a priority to develop self-contained robotic tensegrity struts which can be used to explore and build a wide range of tensegrity robots simply by combining them into novel structures. Our designs are driven by experimental results obtained from a previous prototype, ReCTeR (Reservoir Compliant Tensegrity Robot) in combination with simulation results of our validated tensegrity simulator NTRT (NASA Tensegrity Robotics Toolkit) [26], [27].

F. Outline

This paper is organized as follows. We first present the detailed design of ReCTeR, a lightweight tensegrity prototype, in Section II. Section III discusses what we learned from experiments with ReCTeR and our tensegrity simulator and how this information defined the design goals for our modular tensegrity platform. Next, Section IV presents the design and construction of a modular tensegrity strut for use in SUPERball and related tensegrity configurations. The following Section V shows the performance of learned steerable control policies in our accurate tensegrity simulator. We end this paper with our conclusions and a future work outlook in Section VI.

II. ReCTeR

The common tensegrity icosahedron is advantageous for rolling locomotion, due to its symmetric spherical shape. Its relatively low number of compressive elements (6 struts), makes it rather practical to build [5]. Furthermore, tensegrity icosahedra can be folded into a flat star shape, which is interesting for future space exploration because of reduced mission payload costs [13].

ReCTeR (Reservoir Compliant Tensegrity Robot) was built to study compliant locomotion with tensegrity structures and to validate our simulation results [26], [27]. The robot is a lightweight, underactuated tensegrity prototype with rich sensor integration, based on off-the-shelf components (Fig. 2). In the following paragraphs, we detail the mechanical and sensor design of ReCTeR.

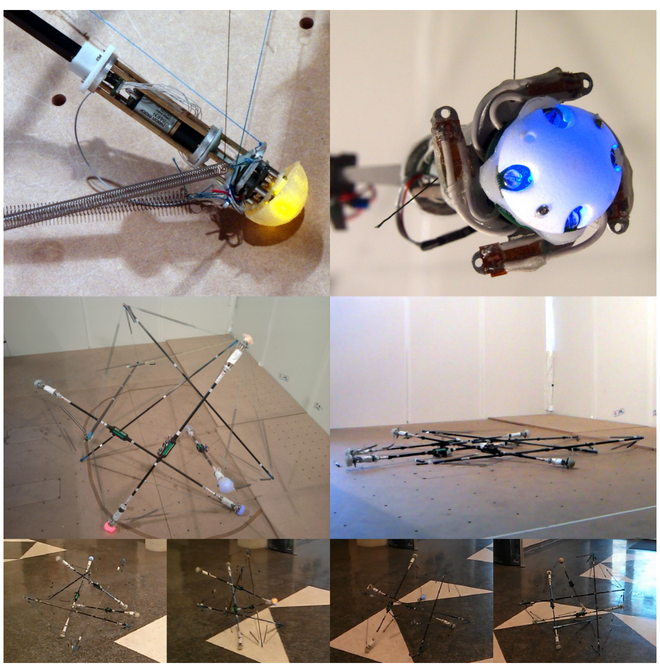

Fig. 2. ReCTeR compliant tensegrity robot. Top left: deployed open spindle end cap design with protective motor sleeve removed. Top right: close up end cap design without the protective silicone cap, showing the four force transducers per end. Center left: deployed robot with 3 active struts (6 4.5W DC motors). Center right: active folding. Bottom: ReCTeR rolling (from right to left).

A. Mechanical Design

The 24 shell tensile elements of ReCTeR are passive, the robot can move, fold and change shape by six actuated springs running through the assembly. ReCTeR has a total mass of $1.1kg$ (batteries included), which is achieved by using carbon fiber struts ($8mm$ outer diameter). The tensegrity principle allows to make effective use of the axial strength of the carbon fiber. Over the course of several months, we have performed drop tests up to $0.5m$ and various experiments without any of the struts splicing or breaking, clearly demonstrating how tensegrity structures use structural elements in pure compression or tension [27].

Three of ReCTeR's struts are actuated (two actuators each), while the other three are fully passive and sensorless (see Fig. 3). The total mass of the struts is $0.05kg$ and $0.270kg$ for the passive and active struts respectively.

The six actuated springs are selected such that each end cap has exactly one actuated spring attached to it. By further requiring the pattern to be symmetric and preventing parallel struts from being connected, we found exactly one pattern (up to a mirror symmetry). It can be seen that this connection pattern allows for large shape deformations, as the actuated springs have a large workspace compared shell actuation.

Fig. 3 also shows a different representation of the connection pattern. More precisely, it connects the centers of each equilateral triangle in the tensegrity icosahedron[1] with its adjacent equilateral triangular faces. It can easily be seen that the centers of the equilateral triangles form a cube. The edges of the cube correspond to the end over which the robot has to roll to move to an adjacent equilateral triangle.

In this representation it is easy to see that the actuated pattern is a dual to the strut connectivity pattern and is therefore an effective way to deform the structure with low power actuators.

The passive and active cables have inline springs with low spring constants at 28.4N/m and 81N/m, respectively. As a result, the natural frequencies of oscillatory modes for the structure are on the order of a few Hz. While it is not necessary to add springs to the actuated cables, we found that removing the stiffer springs of these cables results in a significant reduction in compliance of the structure, which can be problematic during impact.

ReCTeR is equipped with low power DC motors (4.5W brushed DC, Maxon 216000) with a single stage plastic gearbox (4.4:1, Maxon 112862). It is crucial to prevent the tensile forces on the actuated springs from exerting an excessive radial load on the motor axis. Therefore, two miniature ball bearings secure the motor axis (one is mounted inside the bottom of the spindle, one is mounted at the end of the spindle). The current design can shorten the actuated cables at a rate of $0.3m/s$ and we observed active unwinding speeds of over $0.6m/s$. The estimated effective (gears and bearings) nominal motor output is $3.5W$.

[1] The tensegrity icosahedron is not an exact icosahedron, as the parallel struts are $l/2$ spaced apart, where l is the length of a strut.

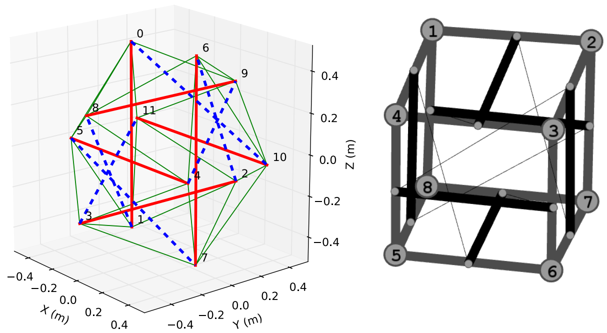

Fig. 3. ReCTeR connection pattern. Left: The thin green lines are passive springs (outer shell), the thick full red lines are struts and the dashed blue lines are actuated springs. Right: A different representation of the connectivity, showing how the actuated springs are dual to the struts. The large circles are equilateral triangular faces (cf. [5, Fig. 5b]) connected by edges representing the end caps (small circles) over which the robot has to roll to reach an adjacent face. The thick black lines represent the struts and the thin lines are the actuated springs, which form the same spatial structure as the struts in the representation on the left.

We used $20kg$ UHMWPE wires for the passive outer shell cables. The actuated cables are $7kg$ UHMWPE wires ($0.13mm$ diameter). We opted for an open node design to prevent wires getting caught. To this end, a PTFE cap fits tightly around the top and bottom of the spindle, separating the ball bearing and axis from the cable and providing a low friction surface for the wires when the robot is highly deformed.

Each strut is self-contained and fully wireless by utilizing a central module with battery power and wireless communication (Nordic nRF24L01+). The battery (Panasonic NCR18650A) is mounted in the center of the strut to minimize the moment of inertia around its longitudinal axis. ReCTeR has a battery runtime of about $1h$ with all systems active. The wireless link achieves a robust controller frequency of up to $100Hz$, but we currently control the robot from an external computer at $40Hz$ as faster control is not needed due to the inherent compliance of the structure.

B. Sensors

ReCTeR is outfitted with various sensors. First of all 24 tension sensors (four per actuated end cap, see Fig. 2) provide feedback about the deformation of the robot. The ADC (24bit Analog AD7192) is located on a PCB mounted above the motor spindle. To measure the motor position, a magnetic encoder (AMS AS5050) is located on the bottom of the circuit board that houses the ADC. Each actuated end cap also features ground reaction force sensors based on a common force sensitive resistor integrated into the end cap. Furthermore, a 6-DOF inertial measurement unit is located on each central module.

III. Evolved Design Goals

A. Lessons Learned from ReCTeR

While ReCTeR exceeds its design goals - sensor feedback, locomotion and folding - it has a number of limitations, which prevents it from being used as a general modular tensegrity robot platform.

First, the lightweight design cannot transport any significant scientific payload, which is a major feature for any planetary exploration mission.

The exposed spring design of ReCTeR becomes a safety issue when increasing the robot's mass (and thus spring tension). It is also difficult to mechanically limit the maximum spring extension to prevent plastic deformation (e.g. in case of a heavy external load). SUPERball will therefore feature an encapsulated spring design, which overcomes both problems and simplifies assembly.

Robustness was not a primary design goal, but the prototype turned out to be more robust than expected. Extensive experiments (drop tests, rolling, reassembly and folding) have not resulted in any major mechanical or electrical failure. In future designs, we will aim for even more modularity and decentralization as a failure of a central module will now result in the failure of two actuators. We also aim to implement part of the control algorithms (e.g. CPG generation) locally, as to enable robust locomotion even in case of temporary communication failure.

ReCTeR is capable of dynamic locomotion, but has to achieve this by making use of the energy stored in the springs. As our calculations show that almost all parts of a tensegrity robot scale favorably in terms of specific strength, our goal is to obtain a final power-to-weight ratio about four times higher in SUPERball ($\pm 100W/kg$ vs. $25W/kg$ for ReCTeR). This permits locomotion and manipulation experiments in any situation and state (i.e. outside an energy efficient regime).

IV. SUPERball and the Modular Tensegrity Robot Platform

In order to develop SUPERball from ReCTeR's design limitations as well as our lab's need for rapid experimentation of various tensegrity configurations and morphologies, we came up with a modular tensegrity platform to research large scale robotic tasks; e.g. a tensegrity planetary probe to explore Saturn's moon Titan.

A. Design Requirements

Our lab obtained design requirements through an iterative approach involving NTRT and ReCTeR. As we recently validated our NTRT simulator by experimental validation with ReCTeR [27], we can now quickly evaluate various tensegrity configurations in simulation to find optimal mechanical design goals. Next to the NTRT solver, we also incorporated results obtained with our (open source) Euler Lagrange solver based on Skelton's work [16] and measurements on ReCTeR.

The design requirements obtained from the NTRT simulations are given in Table I. We are confident that a tensegrity

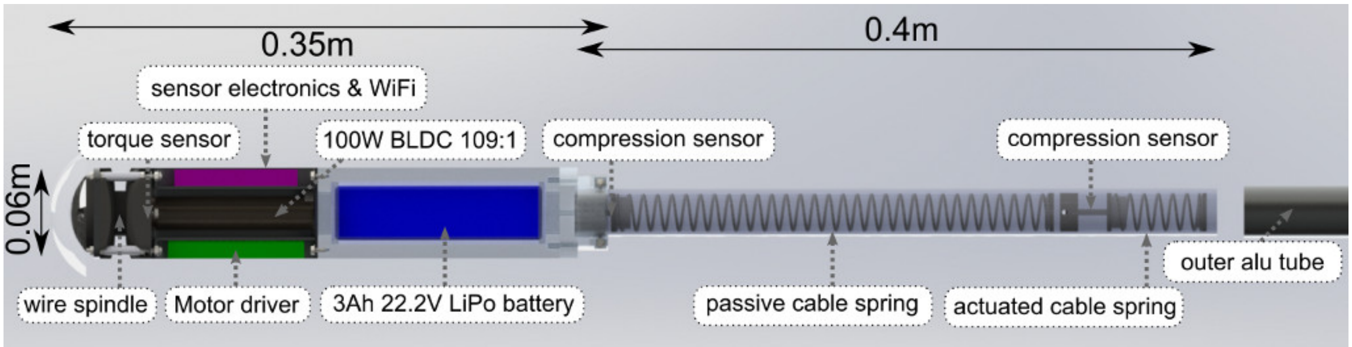

Fig. 4. Modular tensegrity platform strut design. To increase robustness and modularity, each end cap is fully independent and connects to other components, end caps or external controllers over WiFi or CAN. The compression spring design is safer than a mechanically more straightforward external extension spring design and also allows for spring tension sensing independent of the angle of cable with respect to the strut. The longer compression spring attaches to a cable that is not actuated, while the short, stiffer spring will attach to an actuated cable from another end cap. The complete spring assembly slides into an aluminum tube that connects both end caps.

robot achieving the following conditions will be capable of dynamic locomotion, as shown by our evaluation of control policies in Section V.

TABLE I
SUPERBALL DESIGN REQUIREMENTS

	l_{strut}	Δl	$k_{passive}$	Ctrl. freq.	$\max \tau$
ReCTeR	1m	0.3m/s	28.4N/m	40Hz	0.03Nm
SUPERball	1.5m	0.26m/s	500N/m	100Hz	3Nm

In Table I, l_{strut} is the length of a strut, Δl the rate of of length change (the change in rest length of the inline spring) of an actuated cable and $\max \tau$ the maximum spindle output torque.

B. Mechanical Design

SUPERball is an icosahedron tensegrity structure comprised of 12 motors at the end of the robot's 6 rods. Each rod is comprised of three main elements, 2 modular end cap assemblies containing all the mechanical and electrical systems and a connecting aluminum tube as a support structure. The main structural elements of the end caps were kept simple and in sections to enable each end cap to be modular as well as self contained so that the end cap may be removed from the connecting rod as one whole unit. The end caps are held onto the connecting rods by a simple tube collar for easy removal. There are 5 sections to the modular end cap which are, a spring holder, battery holder, motor and electronics element, cable actuation section, and a ground contact section. These sections as they are designed for SUPERball are shown in Fig. 4. Each of these 5 sections can be removed from the rod as a full sub-assembly and replaced with a new component, increasing the versatility of each rod.

A lesson learned from ReCTeR was that externally exposed springs are not ideal for a robotic system. The exposed springs get caught on objects and the assumption of massless cables can no longer be applied. On the modular end cap for SUPERball, an enclosed compression spring system was developed to alleviate these issues. Compression springs were chosen so that during any unknown impact, the springs would not plastically deform. For SUPERball, a spring with a spring constant of $613N/m$ is attached to a passive cable element and a $2850N/m$ spring is attached to an actuated cable. The passive spring has a much higher compressive range to allow for pretension to be instated into the passive springs. A working prototype of our spring holder system can be seen in Fig. 5.

Fig. 5. Behavior of the inner tube compression spring design of an end cap. External cables attached to other end caps run into the tube and attach to one of two springs. Each spring is fitted with a custom compression sensor for spring tension sensing independent of the angle of the external cable. The whole assemble slides into an aluminum tube, allowing for various configurations and strut lengths.

C. Electrical and Sensor Design

SUPERball was developed with distributed controls in mind. Each rod end cap houses two control boards, one for motor driving and one for handling sensing and communications. Each board hosts a Microchip dsPIC33EP. The motor driver is a BLDC/PMSM driver board capable of block commutation and sensorless sinusoidal control. Each sensor board is equipped with an ADC *(24bit Analog AD7193)* and 9 DOF IMU data *(MPU6000 and MAG3110)*.

Two custom force sensors were developed for the SUPERball, a reaction torque sensor and a compression force sensor. Fig. 6 shows the reaction torque sensor. It is a symmetrical four arm cross design with the half bridge located in the center of each arm. This sensor, along with the compression sensors and current sensors allow us to implement high level control schemes such as impedance control in which the full state of the mechanical and electrical system must be known.

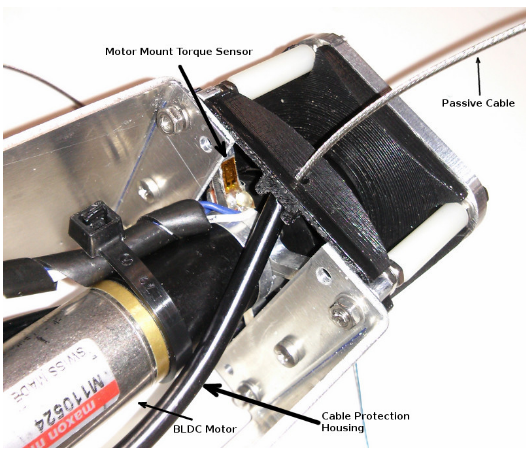

Fig. 6. Close-up of the motor assembly. A strain gauge based torque sensor senses the force on the actuated cable. The receiving strut can also locally sense this force by one of the spring compression sensors. The passive cables run into end cap below the spindle and are guided through the end cap to the compression springs.

V. LEARNING CONTROL POLICIES

The rolling locomotion for an icosahedron tensegrity robot is an ongoing research area [25][5]. The goal is to reach a smooth rolling behavior by changing the lengths of (some) of the cables that form the structure. In this section, the 6 strut SUPERball configuration and constraints were modeled in the NASA Tensegrity Robotics Toolkit (NTRT)[2]. We show the results of a new method for learning to roll by exploiting the symmetry of the structure, combined with coevolutionary algorithms.

The notion of rolling of an icosahedron tensegrity can be considered as consecutive *flops* made one after the other. For each specific flop, we study the movement of a static structure standing on a base equilateral triangle (i.e. one of the eight faces, as shown in Fig. 3) and rotating itself over one of the sides of this triangle. This method will enable the structure to move from one static position to another by destabilizing the system to *flop* along one side of the equilateral triangles.

Although rolling is now simplified to one flop, the control problem remains challenging. Coevolutionary algorithms are a natural fit to solve controlling this compliant, non linear system [28].

The fitness function used is the distance that the robot rolls over a fixed period of time. Using this experimental setup, the coevolutionary algorithms optimized the move of a flop to achieve smooth rolling when the policy is applied for a series of flops.

The advantage of a symmetric structure is that once we have learned a controller for rolling in a single direction, the learned policy can then be used for rolling in any direction. The robot can be controlled to go in a specific direction using a series of flops over the closest edge of the base triangle. Fig. 7 and 8 show the result of a controllable learned rolling motion with low tensions.

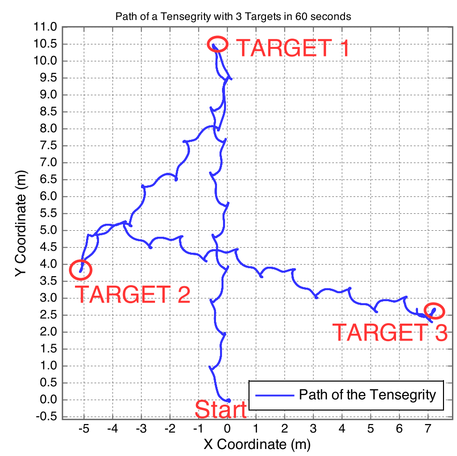

Fig. 7. Controllable rolling with a learned controller. After learning a control policy, the symmetry of the structure can be used to control the direction. The plot show the robot's center of mass. The zigzag is due to the robot rolling over a sequence of equilateral triangular faces.

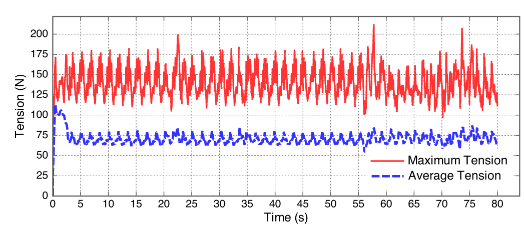

Fig. 8. Spring tensions for the trajectory in Fig. 7. A relatively low average tension of $75N$ keeps the structure in tension, with peak forces up to $200N$ due the actuators.

The main goal of this section was to verify if a tensegrity robot based on the proposed design parameters would be capable of dynamic locomotion. We omit the details of the locomotion algorithm and coevolutionary learning here, since the topic of this paper is the design of our modular robot platform.

[2]The NTRT simulator is open source software, available at http://ti.arc.nasa.gov/tech/asr/intelligent-robotics/tensegrity/

VI. CONCLUSION

Like other areas of soft-robotics, the field of tensegrity robotics is just starting to be explored now that the computational power and control theories exist to start the practical exploration of tensegrity robots interacting with the environment. Until now, the vast majority of realized hardware prototypes have been rudimentary proof-of-concepts systems, relying on servomotors, limited sensing, and/or being tethered in lab settings for power and data (or compressed air for pneumatic muscles). We are developing and validating some of the first purpose-engineered tensegrity component systems which are designed to robust engineering standards of self-contained power, actuation, sensing, and communications. Our goal is to enable the global community of tensegrity robotics researchers to be able to rapidly explore and develop new tensegrity robots, using a toolkit of modular components capable of meeting the unique needs of tensegrity robots. In this paper we have shared our approach, design methodology, engineering requirements, and early results from construction of our first components. We look forward to reporting locomotion results once we have assembled the complete system of tensegrity components.

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