System Design and Locomotion of SUPERball, an Untethered Tensegrity Robot

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***Abstract*— The Spherical Underactuated Planetary Exploration Robot ball (SUPERball) is an ongoing project within NASA Ames Research Center's Intelligent Robotics Group and the Dynamic Tensegrity Robotics Lab (DTRL). The current SUPERball is the first full prototype of this tensegrity robot platform, eventually destined for space exploration missions. This work, building on prior published discussions of individual components, presents the fully-constructed robot. Various design improvements are discussed, as well as testing results of the sensors and actuators that illustrate system performance. Basic low-level motor position controls are implemented and validated against sensor data, which show SUPERball to be uniquely suited for highly dynamic state trajectory tracking. Finally, SUPERball is shown in a simple example of locomotion. This implementation of a basic motion primitive shows SUPERball in untethered control.**

I. Introduction

NASA Ames Research Center's Intelligent Robotics Group has been exploring tensegrity robotics for a variety of applications where other space exploration missions would be difficult or impossible. Common space robotics platforms have limitations in the terrain they can cover and their robustness to unknown environments. Additionally, these heavy and typically expensive robots make certain missions impractical. In contrast, robots based on the structural concept of tensegrity ("tensile-integrity") can potentially locomote over dangerous terrain, may have less weight than comparatively-equipped wheeled robots, and may not require external landing equipment [1], [2]. This high strength-to-weight ratio has prompted much research into the deployability of tensegrity structures, and their ability to fit into space-constrained launch fairings [2]. More importantly, system-level compliance and passive force redistribution make tensegrity robots more robust to unexpected environmental disturbances, particularly when in highly dynamic locomotion [3].

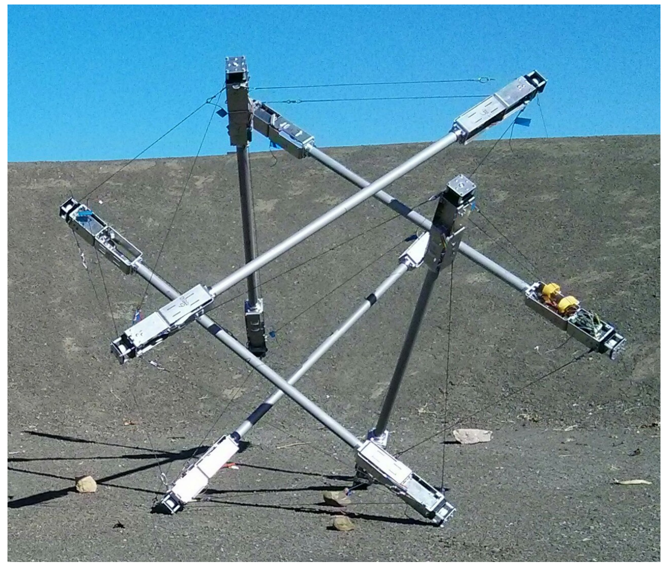

Fig. 1: SUPERball, fully assembled, in the NASA Ames Research Center Roverscape.

The SUPERball project is developing a spherical tensegrity robot for rolling locomotion. Preliminary prototypes of this robot have been focused on the 6-strut icosahedron geometric configuration, one of the simplest spherical morphologies. Movement is generated by actuating the structural cables of the robot: as its shape changes, SUPERball rolls forward. This approx. 1.7 m diameter robot weighs 21 kg, with a relatively high strength-to-weight ratio.

This work presents the completed, working platform of SUPERball in locomotion for the first time. Though the desired highly-dynamic locomotion is not demonstrated, SUPERball is shown to be uniquely suitable for the task. This is the first time that sufficient sensing for state estimation has been combined with a (limited) feedback controller on an untethered spherical tensegrity robot, and the first time that such a system has demonstrated simple locomotion.

II. Background and Prior Work

A. Tensegrity Systems and Robotics

Tensegrities are mechanical structures based on a subtle interplay between compressive and tensile forces [8]. By combining compressive elements with a well structured tension

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TABLE I: SUPERball and Related Robots Design Overview.

	l_{strut}	Δl_{act}	$k_{passive}$	tethered?	control	f_{act}	#act.	mass	sensors	actuators	ref.
Pneumatic	0.57 m	-	-	Y	open loop	800 N	24	3.3 kg	none	McKibben	[4]
ReCTeR	1 m	0.3 m	$28.4\,\mathrm{N\,m^{-1}}$	N	closed loop	12 N	6	1.1 kg	F, L, IMU	DC	[5]
Rapid Proto Kit	0.69 m	5 mm	$1193\,\mathrm{N\,m^{-1}}$	N	open loop	<45 N	24	2.7 kg	none	linear DC	[6]
SUPERball 2014	1.5 m	0.2 m	$613\,\mathrm{N\,m^{-1}}$	N	closed loop	140 N	12	9 kg	F, L, τ, IMU	BLDC	[7]
SUPERball 2015	1.7 m	0.42 m	$998\,\mathrm{N\,m^{-1}}$	N	closed loop	250 N	12	21 kg	F, L, τ, IMU	BLDC	

The variable l_{strut} indicates the length of a strut, Δl_{act} is the nominal spring-cable retraction length in tension, $k_{passive}$ is the linear stiffness coefficient of a passive spring-cable (or active spring-cable if fully actuated), tethered indicates if the robot is powered externally or by internal systems, control indicates whether sensor feedback is used, f_{act} is the nominal actuated spring-cable tension and #act. is the number of actuators. In the sensors column, F represents a linear force sensor (for cables), L is cable length sensor (in the form of motor encoders), τ represents a torque sensor for motors, and IMU represents an accelerometer/gyroscope inertial motion sensing unit. Actuators are specified as DC motors or brushless DC (BLDC) motors. The SUPERball 2014 values are revised original design requirements based on NTRT simulations, and changed to the 2015 values after additional detail design.

network, one can build free-standing structures which make highly efficient use of materials. Tensegrities are pin-jointed structures and their elements are therefore in pure axial compression or tension. As a consequence, the compressive and tensile elements need not resist significant bending or shear forces. In this work, we will refer to compressive elements as *rods* or *struts* and tensile elements as *cables* or *spring-cable assemblies* (defined in Section III-A).

An important advantage of tensegrity structures with respect to general pin-jointed structures is their increased mass-efficiency due to a high fraction of tensile members. Tensile members are generally more mass-efficient as they need not resist buckling. A further advantage from a robotics perspective is that forces diffuse in a tensegrity. There are no lever arms and torques do not accumulate at the joints as in a classic serial manipulator. Forces distribute through multiple load paths, thus increasing robustness and tolerance to mechanical failure.

The static properties of tensegrities have been thoroughly studied and we will not review them here [8], [9]. On the other hand, few examples are known of truly dynamic motion of these structures. Early examples of kinematic motion include the work at EPFL's IMAC laboratory [10]. Skelton and Sultan introduced algorithms for the positioning of tensegrity based telescopes and the dynamic control of a tensegrity flight simulator platform [11]. Although there were some early efforts at MIT's CSAIL lab, it wasn't until the work of Paul and Lipson at Cornell University that the concept of *tensegrity robotics* became widespread [12]. Paul and Lipson were the first to study the properties of dynamic tensegrity structures in hardware and simulation. A few years later Fivat and Lipson designed the IcoTens, a small actuated tensegrity icosahedron robot, but did not publish results. In recent years, the BIER lab at the University of Virginia has been studying Central Pattern Generator based control for tensegrity based fish tails, which is closely related to the control architectures under consideration for SUPERball [5], [13]. Mirats-Tur has presented design and controls work on various other tensegrity morphologies that have been tethered or fixed to the ground [14], [15]. At Union College, Rieffel and colleagues are following an interesting line of work by considering vibration based actuation for small tensegrities [16]. Related work was presented by Böhm and Zimmermann, who demonstrated controlled locomotion of vibration driven tensegrity robots with a single actuator [17]. Finally, Shibata, Hirai and colleagues have developed pneumatically actuated rolling tensegrity structures [18].

Building upon these works, the SUPERball project seeks to push forward the tensegrity robotics field and develop truly untethered, highly dynamic and compliant robots exploiting the aforementioned advantages. In the next section, we briefly review our previous efforts towards this goal and lay out our vision of tensegrity robots for space exploration.

B. Tensegrity Robotics for Space Exploration

The Dynamic Tensegrity Robotics Lab (DTRL) at NASA Ames Research Center has been studying multiple tensegrity morphologies and control strategies for space exploration. The primary mission concept envisions a tensegrity robot with a controllable tension network, which allows the robot to be tightly stowed for launch and then unpacked for landing [2]. During landing the robot will act much like an airbag and absorb impact forces by diffusing them through the tensile network, protecting a science payload. The robot will then transport the payload on the planetary body, with the added benefit that the payload remains protected. In short, a robot like SUPERball integrates Entry, Descent and Landing (EDL) with rover locomotion into a single device, hence decreasing mission cost and mass.

Since tensegrity robotics remains largely unexplored, the DTRL has developed a simulation package for designing and testing robots like SUPERball, the NASA Tensegrity Robotics Toolkit (NTRT) open source simulator[1] [5]. This software allows researchers to quickly develop and test control strategies and to study the physical properties of complex tensegrities. Concurrently with the development of NTRT itself, we have used this simulator to study various

[1]NTRT is available at `irg.arc.nasa.gov/tensegrity/NTRT`

control approaches, and for identifying SUPERball's engineering design requirements. While SUPERball is currently a terrestrial robot, the goal is to gradually incorporate more constraints leading to a space-qualified design. In this paper, we present the current state of this work.

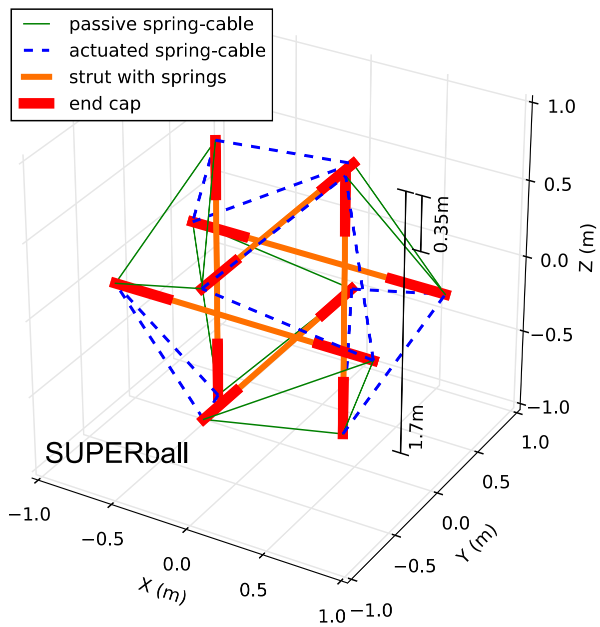

Fig. 2: SUPERball size and active cable hookup pattern, which currently actuates half of the equilateral triangular faces.

The DTRL and our collaborators have developed a variety of other prototypes which complement SUPERball's capabilities. ReCTeR is a small, lightweight, underactuated prototype that was used to initially explore the capabilities of these robots and to validate various aspects of NTRT [7], [5]. The TetraSpine robots study the properties of snake-like tensegrity configurations [19]. The DuCTT robots target duct climbing applications and flexible manipulators with many DOF [20]. Finally, the UC Berkeley Rapid Prototyping Tensegrity Kit enables low-cost experimentation with tensegrity design and control schemes, which pair with NTRT to create a flexible package for tensegrity robotics research [6].

C. SUPERball Design Requirements

Using NTRT, design requirements were developed from the learned locomotion controls. Prior work showed that a 6-strut robot with 1.5 kg rods, which could withstand average cable tensions of 75 N, peak cable tensions of 200 N, and 800 N compressive loads on the struts, would be able to execute learned control trajectories [21]. The actuators were also required to adjust cable lengths at $0.2\,\mathrm{m\,s^{-1}}$. As shown below, the current SUPERball version is heavier than intended, at 3.5 kg per strut including batteries. However, the capabilities of the robot exceed the other design requirements to compensate for this. Though SUPERball has successfully performed some motion primitives, discussed below, work is ongoing to learn more complicated locomotion trajectories with the increased mass with respect to our prior simulations.

D. Comparison with other Spherical Tensegrity Robots

The size, weight, and capabilities of SUPERball are unique in comparison with other tensegrity robots, including those made within DTRL. Table I compares this version of SUPERball to the previous iteration, and to other similar robots. A primary differentiator is SUPERball's autonomy and onboard power, making it entirely untethered, as opposed to such robots as Hirai's pneumatic tensegrities [4].

Notably, SUPERball only has 12 actuators for 24 spring-cable assemblies, due to the extra space required for the 100 W motors used in its end caps (see Section III). This is more than ReCTeR, with 6 actuators, and less than the UC Berkeley Rapid Prototyping Kit robot, with a full complement of 24 actuators (one per cable). However, SUPERball has significantly more capabilities than the prototyping kit: SUPERball's motors are many times faster than the kit's, and can retract fully. This advantage of range can be illustrated by the minimum number of actuated cables for a single punctuated roll: the prototyping kit requires 3 actuated cables to induce a roll, but SUPERball only requires one.

Figure 2 shows the size of SUPERball as well as an initial hookup pattern of the actuated cables (with motor) versus passive cables (unactuated). A symmetric pattern of "actuated triangles" was chosen for SUPERball, where four out of eight equilateral faces on the robot are fully actuated, and other faces are fully passive [7]. This conservatively guarantees basic motion primitives - when placed on an actuated face, SUPERball is sure to induce a roll - but the pattern may change in the future as more options are explored or more actuators are added [21]. Additionally, a future goal is to suspend a science payload, which could potentially be actuated, in the center of the robot [5].

III. System Design

SUPERball is composed of 12 fully independent, autonomous units, termed *end caps*, which slide into each end of hollow aluminum tubes to create the 6-strut robot. Each of these end caps has a single 100 W Maxon brushless DC motor for actuation (Maxon 386674), four custom PCBs which serve various purposes, batteries, wireless communication, and two internal springs as part of the spring-cable assemblies. Prior work has discussed the mechanical design of these end caps [5], [7], [22]. Figure 3 shows one end cap in detail. Novel mechanical and electronic elements of SUPERball's end caps are discussed below.

A. Spring-Cable System and Sensors

In SUPERball, the tensile elements are called *spring-cable assemblies* and consist of a combination of steel wire cable, Vectran cable, a compression spring, sensors and optionally an actuator. Figure 4 shows the conceptual model of such a system. Each of SUPERball's motors is attached to a 1.4 mm Vectran cable (Cortland 7012 Vectran HT, 2.2 kN breaking strength). The opposite end of that cable is looped onto the free end of a steel cable, close to the opposite rod, which then transfers force through the cable into a spring inside that other rod. This internal enclosure for

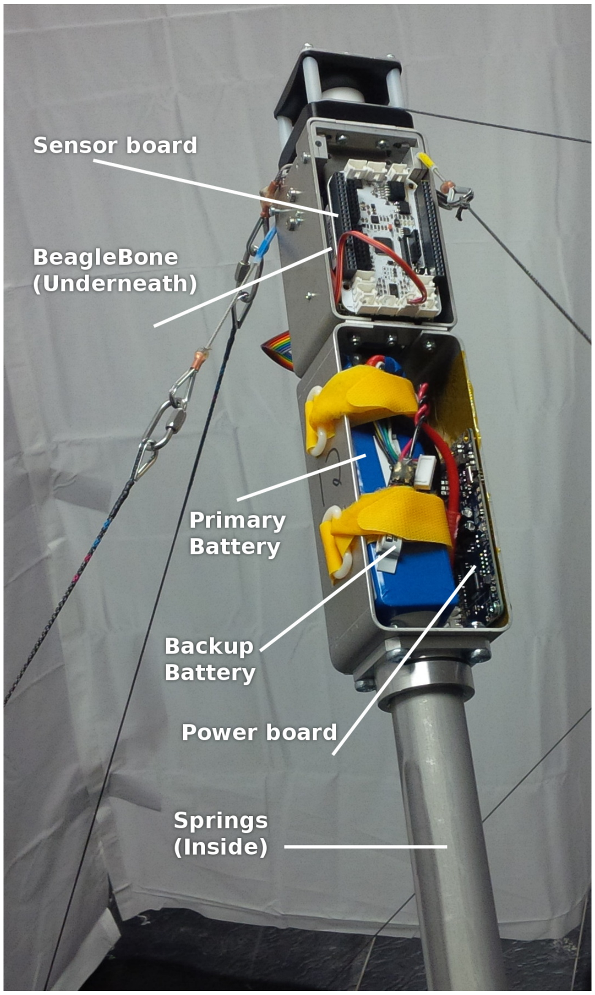

Fig. 3: One end cap of SUPERball. The springs of the spring-cable assemblies are inside the hollow aluminum tube. Steel wire cable transfers motion from the springs to the outer cables, and is routed through the end cap assembly using various PTFE tubes and pulley-bearing elements.

the springs is motivated by observations from past work where environmental snagging occurred on a similar robot's external springs [5]. Figure 5 shows the internals of the entrance point of this cable, which winds over a bearing then into a PTFE tube and then travels through the back of the end cap to the spring area. Unactuated (passive) cables are attached directly to one end cap and to a compression spring and sensor inside another end cap.

Each spring-cable assembly has minimum of two sensors. For direct motor torque measurements, the motor mount itself is designed as a torque sensor: a strain gauge attached to one of its legs measures torsional displacement. These sensors, previously discussed in [7], [22], were calibrated externally before assembly. Each of the springs, located at the bottom of the endcap for both active and passive cables, are paired with a linear force sensor in the form of a small aluminum mechanism with a strain gauge attached. Also, each sensor board is equipped with a 9-axis inertial measurement unit (IMU).

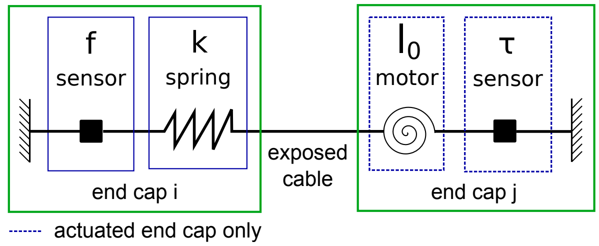

Fig. 4: Conceptual model of a SUPERball spring-cable assembly. Each spring-cable assembly contains a (compression) spring with linear stiffness k. The current spring force or cable tension f is measured by an in-line compressive force sensor. Only the cables are exposed to the environment as all sensors and actuators are embedded in the end caps. The dashed elements - motor & torque sensor - are available on actuated spring-cable assemblies. Such assemblies are effectively series elastic actuators (SEA) with a significant amount of passive compliance. The remote cable tension f on end cap i is only available to the motor controller on end cap j through a wireless link. Motor-side torque sensing τ allows for local tension control on end cap j, without introducing stringent requirements for the wireless link, which would reduce the flexibility of SUPERball's distributed design.

B. Sensing, Control, and Power Electronics

SUPERball employs four circuit boards per end cap. A custom sensor collection board, motor control board, and power distribution board are connected over a Controller Area Network (CAN) bus. A single Beaglebone Black is also housed on each endcap to directly implement high level code and facilitate WiFi communications. Each of these four PCBs has at least one microcontroller, with the three custom boards using Microchip's DSPIC33E series. SUPERball also has two types of wireless communication: WiFi on the Beaglebone, for data collection and high-level control, and a chip from Nordic Semiconductor on the power board that control the emergency kill switch.

Each sensor collection board takes in sensor data from strain gauges and processes the information for embedded controls on each end cap. For example, a 24-bit ADC reads sensor values from the motor mount torque sensor (discussed in detail in [7]). After processing and conversion into suitable inputs for the motor control, these data are sent over CAN to the motor control board. The sensor board thus calculates the primary closed-loop feedback controller currently on SUPERball. Future work will integrate higher level control on the BeagleBone's more powerful ARM microprocessor.

The power distribution board regulates the two independent lithium-polymer batteries on each end cap. Since calibration for SUPERball's cable lengths is expected to be a challenge, a backup battery is used to avoid recalibrating cable positions when changing out the primary cell. This board automatically switches between the larger 3 A h cell and the backup 160 mA h cell when the larger cell is disconnected.

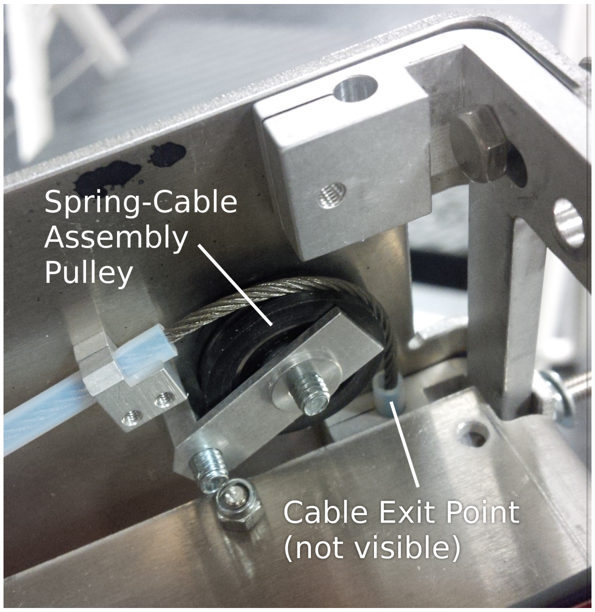

Fig. 5: Internal view of the pulley and exit point of the steel cable, which connects to springs inside the strut tube on one end and to the external vectran cables on the other.

C. Motor and Actuation Electronics

The motor control board implements the lowest level of control. Cable-length position control and speed estimation are achieved through the integration of hardware quadrature encoders on a dsPIC33E. Thus, the motor control board uses its own lowest-level controller with just the motor encoder positions as feedback, and then acts as part of a mid-level controller in coordination with the sensor board over CAN. Commutation is performed through space vector modulation, and the motor board's position controller uses a system ID'd model and a tuned proportional control. To assure temporal accuracy and synchronization during data acquisition and motor control, dedicated hardware peripherals of the dsPIC33E are leveraged to reduce the amount of operations which are otherwise costly and frequently non-reentrant computationally in an embedded environment. Figure 6 shows a motor control PCB on an end cap[2].

IV. Control Schemes

Prior work has discussed the locomotion goals of SUPERball [7], [5]. Since SUPERball has the capability to sense tensions on all cables, and includes inertial motion sensors for optional sensor fusion capabilities, full state estimation is possible. However, high-level trajectory-tracking control requires robust low-level feedback controllers for the brushless DC motor. In order to show that SUPERball is capable of complex movement, a linear-quadratic-Gaussian (LQG) position controller on the motor board was tested while sensor data was collected from multiple motor mount torque sensors.

[2]Schematics and code available at `github.com/fraubluher/PMSM`

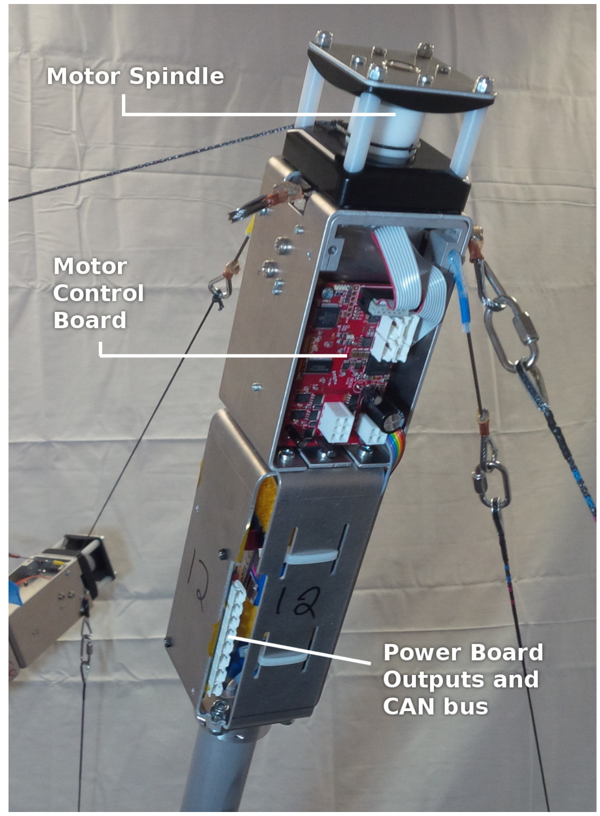

Fig. 6: Reverse view of SUPERball's end cap. This view shows the motor control PCB, the back side of the power management board, and the motor spindle.

For the results discussed below in all tests, a time series of inputs (a trajectory) was commanded using feedback from the motor encoder. This emulates future control schemes that will be based on state trajectory following, and shows the capabilities of SUPERball to perform such control.

V. Results

A. Position Feedback Control and Sensor Validation for Trajectory Tracking

For all the sensor readings below, tensions were calculated from torque values using an a-priori calibration curve.

1) Pseudo-static Kinematic Sensor Testing: Three tests were performed to validate the distribution of tension throughout the system, and to show that all sensors can work in conjunction simultaneously. Figure 7 shows tension readings from a different motor-mount torque sensor on the opposite side of SUPERball (*Cable 2*) from a cable which is being retracted (*Cable 1*.) *Cable 2* was not actively actuated during each test. For each plot in Figure 7, the actuated cable was retracted with various step inputs marked in the figure. Each data point in this figure (yellow) was collected by averaging data from the sensorboard for a total of 5 seconds at 1 kHz, after waiting 2 seconds after the step input actuation to avoid dynamic effects. These tests were done with different levels of pretension on the sensed cable: this pretension was adjusted by changing the length of the sensed cable. Though the lower-pretension tests show smaller changes in readings, the higher pretensions show monotonically-increasing readings which demonstrate the ability to sense forces throughout the tension network in pseudo-equilibrium states, as well as SUPERball's passive force redistribution properties.

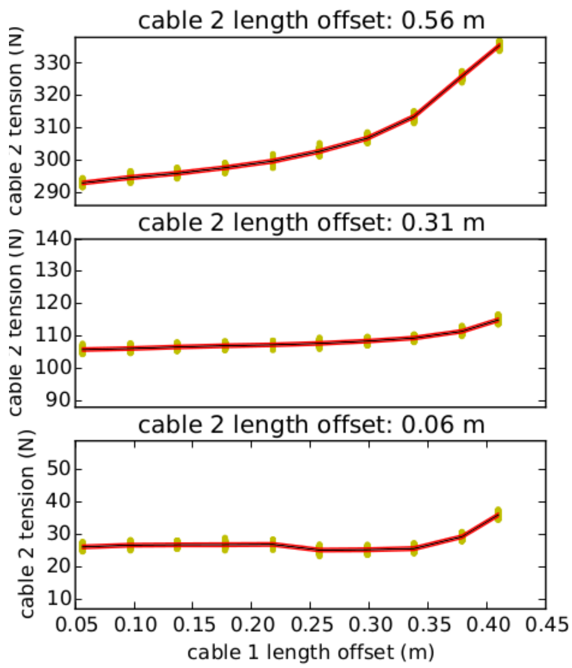

Fig. 7: Global force redistribution test. Yellow marks are the means of roughly 5,000 tension sensor measurements of *cable 2* opposite that which is actuated (*cable 1*.) The black line shows the linear interpolation between points, with the red boundary as standard deviation. The pretension in the sensed cable is adjusted in each test, showing measurement sequences at increasing pretensions.

2) Dynamic Sensor Testing: One additional test was performed to demonstrate the force sensors' ability to capture data under dynamic motion. Figure 8 shows a plot of sensor data from one end cap whose motor is commanded in a square-wave position trajectory. The position trajectory had a period of 13 s, and oscillated between 10 rad and 15 rad of the output shaft measured before the gearbox, by the encoder. The trajectory of sensor torque values reasonably tracks the position square wave: the commanded position trajectory starts at 10 seconds and ends at 62 seconds, as does the sensed tension square wave. The overshoot on the torque sensor measurements is due to the system inertia and spring dynamics.

These results show that SUPERball should be able to combine both closed-loop feedback with state estimation for trajectory following of multiple cables. Such tracking is crucial to future work, where system-level control will be employed for following a highly dynamic whole-robot rolling trajectory.

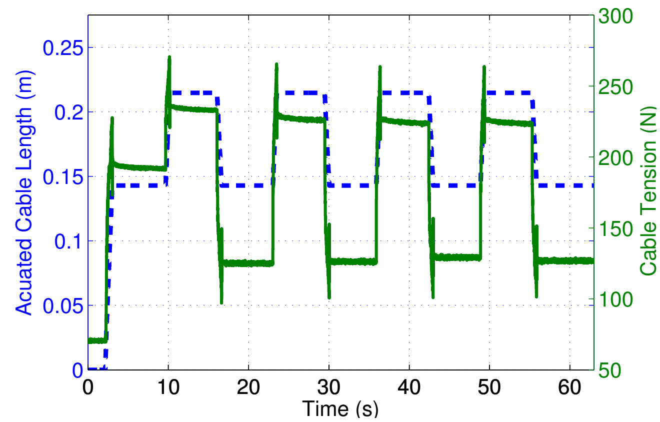

Fig. 8: Motor mount torque sensor data and motor position data recorded during a square wave input position trajectory for a single motor. This plot shows measured tension from the sensor and cable length from motor encoder measurements as a function of time for this dynamic movement.

B. Basic Locomotion

Using this step-input controller, SUPERball can perform simple motion primitives. Though more intricate and complex locomotion results are to come in future work, these motion primitives of punctuated rolling ("flopping") are performed under (currently limited) feedback control, a novel feat for this class of tensegrity robot.

Figure 9 shows still frames from an experiment where the motor position controller retracts a cable. The retraction distance required for movement was hand tuned, and will be validated against simulations in future work. In practice, one single face-change movement required retraction of roughly half of the starting length of one of SUPERball's cables.

In this case, the active cable being controlled is on the bottom triangle, and punctuated rolling is induced when the center-of-mass of the robot moves outside the shrinking triangle base. Similar to the UC Berkeley Rapid Prototyping tensegrity kit [6], this method represents one motion primitive for spherical tensegrity systems.

Shibata and Kim both describe the different possible face-change movements of icosahedral tensegrity structures [4], [6]; in Figure 9, SUPERball demonsrates motion from one equilateral triangle face onto another equilateral face. Though not discussed here, SUPERball is capable of performing punctuated rolls in the other two modes: from an equilateral to isosceles and vice-versa. Additionally, future work will include locomotion in which the dynamics and inertia of rods are used to propel the robot forward, as in [3], [23].

VI. Conclusion, Contribution, and Future Work

This work presents the first integrated results of the working platform of SUPERball in locomotion for the first time. It was shown that SUPERball includes sufficient sensing and actuation to test true highly dynamic rolling, the first time that such sensing and locomotion has been combined with a (limited) feedback controller on an untethered tensegrity spherical robot.

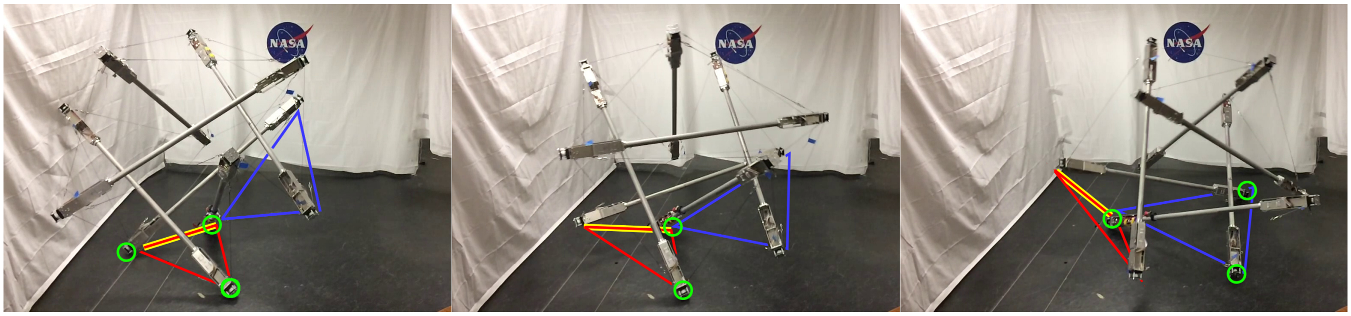

Fig. 9: SUPERball performing a single *punctuated roll* or face-change movement, from one equilateral triangular face to another. The robot begins with all endcaps of the red triangle touching the ground, indicated by the green circles. Note that one of these endcaps is also part of the blue triangle. Then, SUPERball retracts the yellow-highlighted cable on the red triangle, inducing movement. Frame 2 shows SUPERball halfway through the movement, in the midst of tipping over, with only two points of contact on the ground. Finally, frame 3 shows SUPERball at the end of this *puncutated roll*, with all 3 points of the blue triangle in ground contact.

However, more work must be done before such rolling can be performed. A state estimator must be written and coded on the robot's onboard computing systems, either in a distributed manner or centralized. More mechanical hardware tuning may be necessary for robust estimation and control; for example, minor redesigns may be required to reduce friction at the steel cables.

Once SUPERball can perform more purposeful locomotion, tests in different environments will occur, as will tests of goal-directed motion. Finally, future versions of SUPERball will include a central payload for science instruments, as per mission requirements of this planetary exploration robot.

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