DESIGN, BUILDING, AND TESTING OF SUPERball: A TENSEGRITY ROBOT FOR SPACE EXPOLRATION

Jonathan Bruce

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Chapter 1

Introduction

As part of our research for the NASA Innovative Advanced Concepts (NIAC) program, we are developing the SUPER- ball (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.

It is possible to design free-standing structures by arrang- ing 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 dis- tribute 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.

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 loco- motion 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][10]. 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 [11]

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 [12], 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 [13] specifically studies landing and surface mobility of tensegrities, ex- ploiting 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 mea- sured 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 [14].

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 [15] and design analysis of static structure [16][17]. More recently, active control efforts for tensegrities began to emerge [18], as well as descriptions of the dynamics of tensegrity structures taking the connectivity pattern into account [17]. 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 [19] shows that there are still many open problems in actively controlling tensegrities, especially when interacting with an environment during locomotion or ma- nipulation tasks. Though work has been done to control a tensegrity to change into a specified shape [20], practical determination of the desired shape itself is an ongoing challenge. Recently, locomotion of icosahedral tensegrity robots through body deformation was demonstrated [21]. Other work has addressed collision between rigid tensegrity elements during control generation [22][23]. The approach taken by the NASA Dynamic Tensegrity Robotics Lab builds on this by developing body defor- mation control algorithms based on central pattern generators [24][25], distributed learning, reservoir computing, and genetic algorithms [26], 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.

1.1 Motivation

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) [27][28]

1.2 Application

1.3 Goal

In order to develop SUPERball from ReCTeRs design limitations as well as our labs 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 Saturns 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 [28], we can now quickly evaluate various tensegrity configurations in simulation to find optimal me- chanical design goals. Next to the NTRT solver, we also incorporated results obtained with our (open source) Euler Lagrange solver based on Skeltons work [17] and measure- ments on ReCTeR. The design requirements obtained from the NTRT simula- tions are given in Table I. We are confident that a tensegrity robot achieving the following conditions will be capable of dynamic locomotion, as shown by our evaluation of control policies in Section V.

Chapter 2

Mechatronic Design

An ideal tensegrity system, either robotic or static, is a collection of rigid compressive elements suspended within a network of tensioned cables. For a robotic tensegrities without a payload, the actuation and supporting electronics would be logically designed into the compressive elements. Making each compressive element identical will also make the over all design and support of the entire tensegrity robot simplier. For SUPERball, each compressive element would be comprised of three parts: two identical end caps and a piece of tube stock. The end cap was designed

2.1 Mechanical

Write about the mechanical design of SUPERball. Make sure to give credit where credit is due.

B. Mechanical Design SUPERball is an icosahedron tensegrity structure com- prised of 12 motors at the end of the robots 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 ex- posed 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 613 N=m is attached to a passive cable element and a 2850 N=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.

2.2 Electrical

Write about the electronic board used on SUPERball.

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 com- munications. 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 SUPER- ball, 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.
- Untethered electronics -
To this end, we tried to develop electronics which where extensible for various communications Another driving parameter was the ability to drive the 100W BLDC Maxon motors chosen from the initial iterative design. These two main design criteria governed our prototype to implement four separate electronic boards per end cap. Three boards are custom designed PCBs and the fourth is an ARM based computer called Beagle Bone Black. Each custom PCB is designed for very different purposes: A board to condition sensor data and run real-time control loops, a board to condition and distribute a 5.5V electronic power rail and a 24V motor power rail, and a board to control the 100W BLDC motor. The boards are simply named by their main purpose, thus Sensor, Power, and Motor board, respectively.

Sensor Board

The sensor board was originally designed as the main processing unit on an end cap for SUPERbal. However, the design and building process has lead to the coupling of the sensor board with a Beagle Bone Black. These two versions are dubbed v1 and v2, respectively. I will first write about v1 of the sensor board, then follow up on how v2 was changed.

The main processing unit on each sensor board is Microchip's dsPIC33EP128GP506, a 16 bit microcomputer running at 140MHz. Besides the designer's familiarity with this family of microcomputers, the dsPIC33E chips feature multiple Universal Asynchronous Receiver/Transmitter (UART), Serial Peripheral Interface (SPI), and Inter-Integrated Circuit (I2C) communication modules. The dsPIC33E also features an ECAN modules with 2.0B support, a 12 bit Analog to Digital Converter, and four Direct Memory Access (DMA) channels. All these moudles coupled with almost complete pin to peripheral pin remapping made the microcomputer a solid choice for our sensor board.

2.3 Communication and Data Flow

Bibliography