Designing a Modular Strut for Union's Tensegrity Robot

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Abstract

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A tensegrity is a structure composed of a series of rigid members, called struts, and tensile elements, usually springs, connecting the struts. Vibrating a tensegrity at a specific frequency, using vibration motors attached to the struts, can induce interesting and potentially useful movement in the structure. Union has been using a tensegrity in computer science research for years, but it has reached its limit for a number of reasons: its motors were not especially strong and required wires to deliver power and signals when moving, inhibiting its motion. So, an improved tensegrity strut was designed, including features like on-board power, wireless Bluetooth communication, a more powerful motor, and an accelerometer for data gathering. The new strut will be used over the coming years as a starting point for new tensegrities made by students in the mechanical engineering, computer science, and electrical and computer engineering departments.

Acknowledgements

Thank you to my advisors, Professor Rieffel and Professor Hedrick, and my student collaborators, James Boggs and Alex Chu. Couldn't have done it without you.

Also thanks to Amanda Ervin and Frankie Chiarulli for help with the laser-cutter and dealing with lots of questions and prototypes.

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Introduction

1.1 What is a Tensegrity?

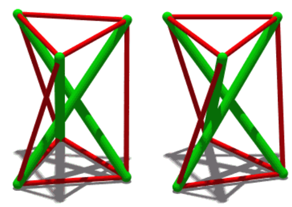

FIGURE 1.1: A Three-Bar Tensegrity in Simulation (via Wikimedia Commons)

Tensegrities are a relatively new yet interesting addition to the field of robotics. Originally coined by the architect Buckminster Fuller, "tensegrity" is a portmandeau of the words "tensational integrity" (Swanson, 2013).

> A tensegrity is composed of a series of isolated rigid members, called struts, and tensile elements, often springs, connecting the struts to form a structure under continuous tension.

Because tensile members comprise the defined shape of the robot, and therefore are not entirely rigid, tensegrities belong to a field of robotics called “soft robotics.” They are interesting due to their unique methods of movement, partially because they are useful models of some elements in biology, but also because they might theoretically be better at moving through certain environments.

Union College and its Computer Science Department have used tensegrities to study the differences in the simulation and implementation of complex systems. This project has been done under Associate Professor of Computer Science John Rieffel with a tensegrity called VALTR. This project will act as an update to VALTR, adding new features and capabilities to allow the research on tensegrities to expand.

1.2 A Robot Named VALTR

Rieffel has been researching morphological communication and soft robotics using tensegrities at Union College since 2010 and before his time at Union (Rieffel, Valeo-Cuevas, and Lipson, 2010). Union’s tensegrity, VALTR, has been in use for nearly four years. VALTR, an acronym for Vibrational Active Limbless Tensegrity Robot, is a six-bar tensegrity, meaning it is composed of six struts. It was developed in Union's CROCHET Lab to study morphological communication and the movement of soft robots. This particular robot is at its limit of usefulness to Professor Rieffel due to its simplicity and fragility.

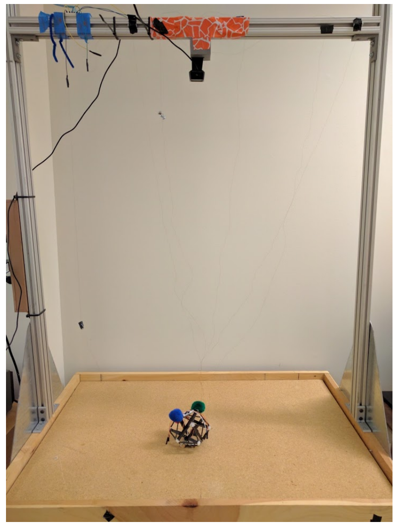

FIGURE 1.2: VALTR in its Test Bed in the CROCHET Lab

VALTR is merely composed of its struts, springs, and three hot-glued motors powered and controlled by repurposed magnet wire. The computer's only data used in controlling VALTR is indirect, originating not from the robot itself but from an overhead camera as pictured in the above image. These shortcomings, to be discussed more in depth in Chapter 2, were first addressed by Steve Stangle '14, an electrical engineering student who first attempted to make a wireless tensegrity for his senior thesis.

1.3 Stangle's Attempt to Update VALTR

Stangle researched components and designed a prototype of a wireless tensegrity system on a protoboard (Stangle, 2014). He used an Arduino Micro microcontroller, a Bluetooth unit for the Arduino, a standard DC motor and motor controller, a gyroscope/accelerometer, and a 1000 mAh, 7.4 volt Lithium-Polymer battery. These components, though somewhat small, are still far too large for use on an actual strut in a tensegrity. The battery in particular is a problem, with his choice for this prototype weighing in at 100 grams, far too big for a small tensegrity strut. Though, he did acknowledge that any future attempts at creating a wireless tensegrity would require a significantly smaller battery. Combining all of his components on an actual strut, as opposed to on a protoboard, would create an unreasonably large strut. While these components were considered for this project, and in some cases did help inform my decisions on components, ultimately no item Stangle used could be recycled for a small tensegrity strut.

Stangle also worked with the spiking neural network that is used to control the tensegrity. This algorithm is currently implemented for a Linux machine, and its use with the motors in VALTR is restricted to communication through the aforementioned magnet wire.

Stangle attempted to convert it to Arduino for use in a wireless tensegrity. His choice in microcontroller was affected by this need to run this algorithm, and he eventually was able to run the entire system wirelessly with his prototype strut components. This research is applicable to this current project because this new, modular strut will also have to run a similar genetic algorithm on a comparable Arduino microcontroller. Stangle's research, while useful in creating a starting point for this project, is only truly relevant in that regard.

Chapter 2

Design Requirements

2.1 The Problems With VALTR

As mentioned in the previous section, the tensegrity currently in use at Union, named VALTR, has reached a limit in its usefullness to Professor Rieffel. This is due to some significant problems with the design of the robot, pictured below.

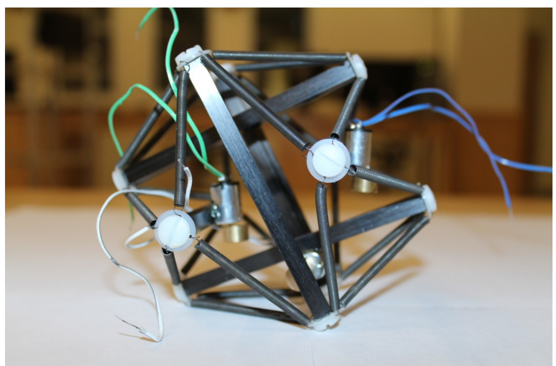

FIGURE 2.1: The Six-Bar Tensegrity VALTR

This project is intended in part to serve as a much-needed update to the current robot to aid Professor Rieffel in his research. Therefore, the design requirements of the strut being created for this project are significantly influenced by the issues with VALTR.

Component	**In VALTR**
Strut	Repurposed Carbon-Fiber Kite Spar
Motor	*Precision Microdrives* 12mm Vibration Motor – 15mm Type
Power	DC Power Supply, Delivered through Magnet Wire
Data Transmission	External Camera, Delivered through Magnet Wire

TABLE 2.1: A Breakdown of the Current List of Components in VALTR

2.1.1 Wiring

One major update needed for a new tensegrity involves the wiring needed to power and control the on-board motors. Wiring is a significant problem for tensegrities because restriction on a strut's motion will have a substantial influence on the overall movement of the tensegrity. Since the research on this particular robot is based on its movement through strut vibration, any appendage on the structure is going to affect results. To minimize this effect, an extremely thin, lightweight wire is used to supply power and signal to the motors (Stangle, 2013). While the weight of this wire is desirable to minimize its effect on the robot's vibration, it is extremely brittle and is a major source of frustration in using the robot due to its tendency to break. The best solution is simply to remove the wiring, install batteries on the strut to supply power, and make all communication wireless.

2.1.2 Motor

There are two primary problems with the motor, separate from wiring: its attachment and its strength.

Currently, the motor is hot-glued to a carbon-fiber strut. However, just as the vibration of the robot can lead to wire breakage, it can also cause the motors to detach from the structure. Again, this creates a hindrance in using the tensegrity. Glue is insufficient for the amount of vibration being applied to the strut and motor attachment.

This is especially true when considering that a new strut should have more power than the current model. VALTR's vibration is produced by a 12mm, DC vibration motor with a maximum amplitude of 14.3G. While this has served VALTR well, a new strut should have more power to allow greater freedom in the use of the robot. Additionally, if more components are added to the strut, it will need more power simply to create similar movement to VALTR due to the weight added to the strut.

2.1.3 Other Components

VALTR has one more significant limit: it lacks data collection. Right now, all data collected on the tensegrity's movement is through an overhead camera. This allows the overall movement of the robot to be tracked, but little information is gained on the actual vibration of the struts. This information could be useful in creating more reliable motion for the robot.

2.2 Necessary Design Considerations

Since this project is intended to be an update to the current robot, the new strut design must address the shortcomings in the design of VALTR. With these issues in mind, the following requirements apply to the design of the new modular strut:

Component	Planned Design
Strut	Modular, sturdy, with attachments
Size	Length of 4 to 6 inches, to compare to VALTR's 4 inch struts
Motor	Increased motor amplitude, over 20G
Power	Containing its own battery
Microcontroller	Embedded in the strut to give a signal to the motor
Data Transmission	Wireless communication with a computer for data transfer
Telemetry	Inclusion of a sensor for vibration sensor or acceleration
Cost	Under $100 per strut

TABLE 2.2: A Breakdown of the Planned Design

Each of these attributes is important to the overall function of the robot and will aid in the research being done by Professor Rieffel. The strut must follow each of those requirements while maintaining simplicity for easy assembly and repair. In addition, the strut is expected to be modular, meaning it should be usable in other tensegrity robots. VALTR is a six-bar tensegrity, meaning it is composed of six struts, but other sizes exist, including a 15-bar tensegrity currently in the design process with Professor Rieffel and another senior project. The design of this modular strut should accommodate other tensegrity designs by way of simplicity and a small size.

Chapter 3

Design Alternatives

3.1 Considered Design Options

With a tensegrity already in use at Union, and this project intended to create a similar tensegrity, some aspects of the design were already determined. For example, to perform similar to VALTR, the new tensegrity should not have struts more than 4 to 6 inches in length. However other aspects of the robot needed to be considered, like the material, battery, microcontroller, and sensors.

3.1.1 Strut Material and Fabrication

The strut should be made so that it is sturdy, with a specific, replicable shape and embedded components. These requirements make laser-cutting the ideal method of strut fabrication. This leaves two primary material options: wood and acrylic. Wood is cheap and lightweight, easy to use on a laser-cutter, and readily available for rapid prototyping. Acrylic will be more expensive but should be just as easy to laser-cut as wood, with an advantage in strength. There is also a marginal increase in weight using acrylic over wood.

3.1.2 Battery Type

A battery contained on the strut must be durable and rechargeable with a large enough capacity to last for a day's worth of use. The batteries considered were all lithium-ion polymer batteries, commonly known as LiPos. There are multiple shapes and capacities of LiPos, with both attributes being major considerations for this strut. LiPos are easily rechargeable and easily usable with other selected components. LiPo batteries are either cylindrical, like a standard AA battery, or flatter and as small as the size of a postage stamp. Another consideration in batteries is that they supply sufficient voltage and current to operate the motor on the strut. Single LiPo and Li-Ion batteries usually have a voltage of 3.7 volts. However, the vibration motors in consideration need up to 7 to 8 volts to be used properly. To accommodate this higher voltage, two 3.7 volt batteries could be used in series or a voltage step-up regulator could raise the voltage of a single battery at a cost to efficiency and current.

3.1.3 Microcontroller

The microcontroller must be able to run a lightweight genetic algorithm, control the motor, receive input from any sensors, and communicate wirelessly with a computer running a more sophisticated program to weigh the algorithm of all the struts. In addition, it must do this while using a minimal amount of power and not taking up much space or weight on the strut. Because Arduino is especially easy to use under these requirements, two Arduinos were considered: the Arduino Pro Mini from SparkFun Electronics and the RFduino RFD77201. The Arduino Pro Mini is more versatile, but is larger and doesn't include any built in wireless capabilities. The RFduino, however, is Bluetooth-enabled out of the box and is the size of a fingernail, ideal for a lightweight strut.

3.1.4 Telemetry

Sensing capabilities are also needed. The two most interesting sensing options, due to the nature of the tensegrity as a vibrating robot, are accelerometers and piezo vibration sensors. The piezo vibration sensor has an advantage in that it is designed for use with vibration, and therefore should be more suited to a tensegrity strut, though it only works in one axis. The accelerometer works in three axes and is smaller. Theoretically, an accelerometer with a sample rate at least twice the vibration frequency of the strut would be just as capable of detecting frequency as the vibration sensor. An accelerometer would also give the opportunity for an algorithm to attempt to find useful data beyond frequency, possibly including information about position or direction.

Chapter 4

Components

4.1 The Selected Components

Of the possible design alternatives, a new strut will be composed of the components that are smallest and most capable to fill the tasks set out by the project requirements. Since each component needs to fit on the strut, size is the most important feature and the real problem with the attempt by Stangle to design this strut. The components are laid out below.

4.2 Microcontroller

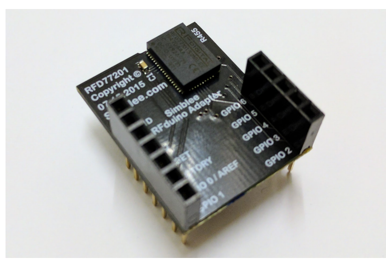

FIGURE 4.1: The RFduino RFD77201

This particular RFduino has three things going very well for it: tiny size, minimal operating power, and completely built-in wireless capabilities. The choice of microcontroller was therefore relatively simple, since WiFi-based wireless alternatives tend to have large antennae and few microcontrollers have built-in Bluetooth. This particular Arduino was the easiest solution.

4.3 Accelerometer

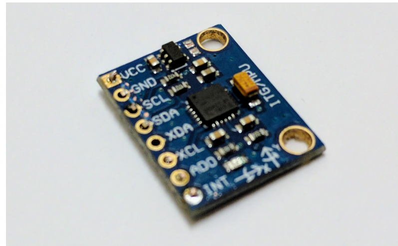

FIGURE 4.2: The MPU6050 Accelerometer

The accelerometer will be used for on-board telemetry as opposed to a piezo-electric vibration sensor. This is more because of the shortcomings of the vibration sensor, which was an awkward shape to fit on a strut, since it needs open space to vibrate. It also provided much less data, showing vibration in one axis, as opposed to a more comprehensive gyroscope and accelerometer that could contain much more information than merely vibration.

4.4 Battery Pack

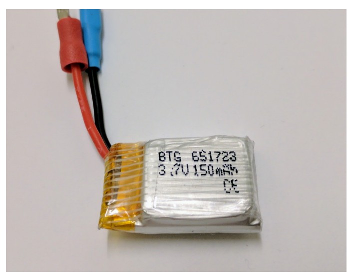

FIGURE 4.3: A 3.7 Volt, 150 mAh LiPo Battery

While considering the option between one battery or two batteries, a voltage step-up regulator was tested. However, the current was so low with one 3.7 volt battery and a 9V step-up regulator that the motor was inoperable. So, two batteries had to be used.

However, two batteries in series would force a minimum voltage of 7.4 volts, much too high for the microcontroller, even if it is right for the motor. At first, the plan was to simply grab the voltage from between the two batteries, which would lead to discharging at different rates but two distinct voltages. That trade-off was considered worth it, but even a single 3.7 volt battery had simply too high a voltage when fully charged for the microcontroller to handle. At one point we managed to completely overheat and ruin one RFduino from this heat.

So, the final decision was to use a two-battery pack and step the voltage *down* to accommodate the RFduino. While this isn't especially efficient, particularly with the specific part planned for use, it is the easiest way to reduce size and weight on the board when compared to adding a separate battery for the microcontroller.

4.5 Motor and ESC

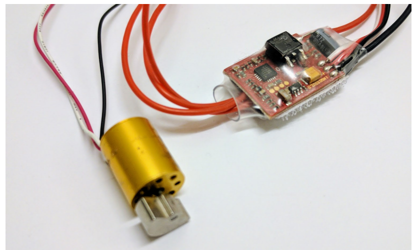

FIGURE 4.4: The Vibration Motor with ESC

The motor and ESC are unique in this section as they were actually selected by Alexander Chu, a mechanical engineering student currently also working on a tensegrity project with Professor Rieffel. His Capstone project reports in depth about his selection process from the perspective of mechanical engineering, but the basics are that this motor has the vibrational amplitude, frequency range, and size that make it optimal for a small tensegrity's strut (Chu, 2017).

4.6 Acrylic with Laser-Cutter

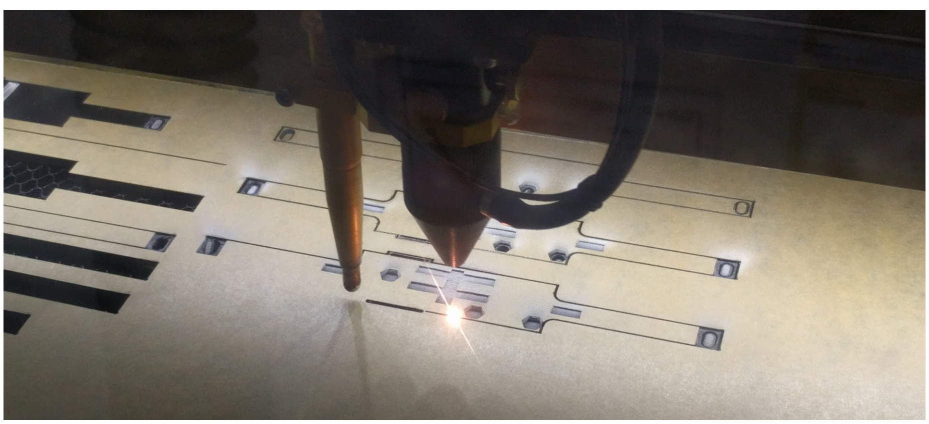

FIGURE 4.5: The Laser-Cutting Process

Union's new Fiegenbaum Center for Visual Arts provides an open-use laser cutter for students. Since the strut would need a specific design to incorporate many components, laser-cutting was an optimal way to manufacture struts.

The two main advantages of the laser-cutter, as opposed to another way of creating a strut, are rapid prototyping and quick mass production. Prototypes can be produced no more than a few minutes apart. If a design flaw is noticed in a freshly printed strut, a modification can be made and a new strut printed immediately. Prototyping helped not only design the strut, but choose the material as well. The first strut prototypes made of wood, with high-strength acrylic becoming the final choice for the strut. Prototyping helped not only design the strut, but choose the material as well.

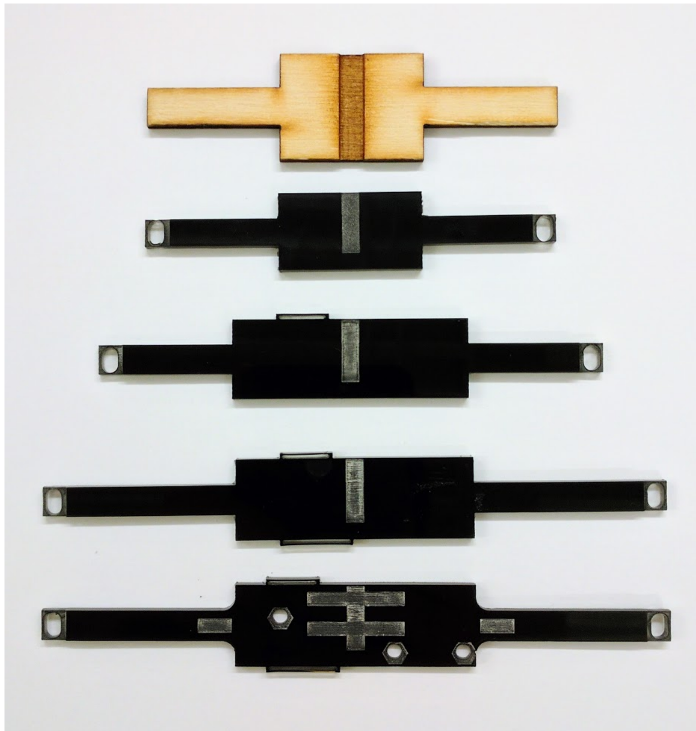

FIGURE 4.6: The Evolution of Strut Prototypes

Later, mounts for the batteries and motor were designed with acrylic. The motor is mounted by a circle hugging the motor, with the acrylic mount being glued to the strut. It is shockingly strong for such thin plastic, and can easily handle the force of the motor's vibration without breaking. Batteries are mounted by two arms, one for each battery. They are cut at a slight downward angle to press the battery into the body of the strut. Each of these mounts took multiple attempts to make useful, but they turned out to be excellent solutions to the problem of mounting components. The precision of the laser-cutter, and the ability to try designs over and over again, make the production replicable, cheap, and strong mounts extremely simple.

One a design is finalized, multiple copies of the strut can be printed in five or ten minutes. So, a new tensegrity can be built much more quickly than VALTR, despite the fact that VALTR was much simpler.

Chapter 5

How To Build A Strut

5.1 Introduction

This section will walk you through the necessary steps to build a strut like mine for use in a tensegrity of your choice. I expect the primary beneficiaries of this how-to guide to be future research students of John Rieffel, but I encourage anyone interested in exploring tensegrities to try it. However, I did have access to some resources, primarily the laser-cutter, that might not be available to those not affiliated with an institution like Union.

Acquire these materials and follow step-by-step to produce a strut for use in three or six-bar tensegrities, and feel free to experiment with other configurations. The exact parts and tools listed were what were available to me, or what I chose to use, but some could be substituted for comparable alternatives.

5.2 Lists of Parts and Tools

5.2.1 Specific Tools and Materials

The components in this table are produced by a specific model and manufacturer and reflect exactly what was used for this project. Some may be replaced with generic alternatives or other specific models, as reflected in Table 5.3.

Component	**Description**	**Manufacturer**
Acrylic	Transparent Grey Acrylic Sheet	Inventables
Motor	12mm Brushless Vibration, 15mm Type	Precision Microdrives
ESC	Plush 10A Brushless Speed Controller	Turnigy
Battery	3.7V, 150mAh LiPo	BTG
Microcontroller	RFD77201	RFduino
Telemetry	MPU6050 Six-Axis Gyro/Accelerometer	Longruner
Laser-Cutter	P-Series Pro 24X16+	Full Spectrum
Voltage Regulator	LM1117T, 3.3V	Nat'l Semiconductor

TABLE 5.1: A List of Specific Tools and Materials Used

5.2.2 Generic Materials

For many elements of the strut, it is irrelevant exactly what model or make is being used. Use this complete list to determine the materials that will be necessary, outside of the specific components in Table 5.1.

Material	Purpose
Plastic/Acrylic Superglue	Attaching Mounts to Strut
Stranded Wiring	Connecting All On-Board Components
90-degree Header Pins	For Connections to Components
Terminal Connectors	Deliver Battery Power, Disconnect for Charging
#4-40 Nylon Hex Nuts and Bolts	Attaching Components
Solder, Heatshink	Connecting Wires, Headers, Terminals

TABLE 5.2: List of Necessary Generic Materials

5.2.3 Alternative Tools and Materials

This table features items that could replace items in Tables 5.1 and 5.2. However, each would require a change at some point in the step-by-step directions.

Material	Alternative
Acrylic	Generic
Laser-Cutter	Generic
ESC	Plush 6A Brushless Speed Controller, Turnigy
Battery	3.7V, Generic, Any Size
Microcontroller	Other RFduino Models
Telemetry	Piezo-Electric Vibration Sensor
Telemetry	MPU6050 Six-Axis Gyro/Accelerometer, Generic
Nuts, Bolts	Any Small Size
Step-Up, Step Down Regulator	Pololu 3.3V S7V8F3

TABLE 5.3: A List of Parts to Consider for Alternate Use

A change in acrylic or laser-cutter would make information below about the exact values for laser-cutting inaccurate. So, experiment with any different materials to attempt to achieve similar results.

Different telemetry could be useful, so feel free to buy different sensors. The exact accelerometer used in this project is actually a specific breakout of a more common chip, so many manufacturers sell their own breakouts that are virtually the same. These other brands could be substituted with little to no changes to any other aspect of the strut.

The ESC used is a Turnigy 10A, but the Turnigy 6A is smaller and should be able to handle the motor and batteries being used. It is probably worth ordering a smaller one and testing it, as the lighter size and weight could be much better for the movement of the strut. Different sized nuts and bolts could be used, but they would require a change to the Adobe Illustrator Drawings and strut manufacturing process. See Section 5.3.3.

Battery capacity is also not necessarily required to be 300mAh, as chosen for this project. These 3.7V LiPos can come even smaller than that, so perhaps smaller batteries could be useful. Seperately, some tensegrity experiments might require a larger capacity. Note that any change to the battery capacity, or, to a smaller extent, manufacturer will require a design change in the battery mounts.

A slightly different microcontroller may require a change to the program that creates that function. It also could force a change in the layout of the strut, which would simply be more inconvenient than anything.

Finally, a more efficient voltage regular could improve battery life. Additionally, the Pololu chip is a small, surface-mount component, which could be ideal if a better circuit is implemented as discussed in Section 7.3.

5.3 Laser-Cutting Pieces

This section will be described completely from the perspective I took when approaching laser-cutting: using the Full Spectrum P-Series Pro laser-cutter at Union College in accordance with Union's Makerspace protocol. If you're at another institution, look into using your laser-cutter (or another method of strut fabrication) and ignore Section 5.3.1. If you're a Union student, reach out to the Makerspace Coordinator and undergo laser-cutter training before proceeding.

5.3.1 Cutting from Union's Full Spectrum Laser-Cutter

The first step of using the laser-cutter is being trained, as stated above. Anything covered in that training, like how specifically to use the laser-cutting software or the machine itself, will not be covered here.

The next step is to download the Adobe Illustrator files that make up the shapes for the laser-cutter. They will be available for download, see A for details. There are six laser-cut related files, not all of which are directly used for printing.
Cutting the mounts is the simplest step. Load in *battery-mount-1.ai* and cut all lines at 100 percent power, two passes. Save the printed mounts for Section 5.3.2.

The strut itself is more complicated. First, take *strut-front-yellow.ai*. Use *Raster Only* mode to engrave the strut at 100 percent power, two passes. Then, **without moving the head of the laser or the acrylic**, switch to *strut-front-red.ai* and *Raster then Vector* mode to finish the strut, rastering one pass at 60 percent and vector cutting purple, blue, and green lines at 100 percent, two passes. It is very important that nothing inside the laser-cutter moves between rastering the yellow file and rastering the red file, as that would engrave the wrong parts of the strut or miss the strut completely.

FIGURE 5.1: Yellow Raster on Front of Strut

Additionally, if you're careful, the back side of the strut can be engraved. It currently isn't necessary, but if you have a component that requires engraving the back of the strut,

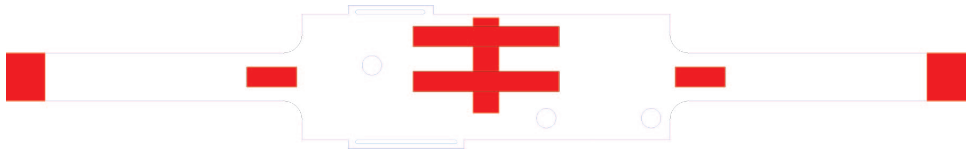

FIGURE 5.2: Red Raster and Vector on Front of Strut

follow the above steps, and then, **without moving the head of the laser or the acrylic sheet**, carefully pull the strut out of the leftover acrylic, flip it over, and place it back in the acrylic upside-down. If the acrylic sheet moves, and you therefore cannot place the strut back in the laser-cutter in the exact same spot, you've ruined this attempt and will have to start over. The laser-cutter is not designed to do double-side engraving, so we have to be very hack-y with that process. Raster the magenta at 100 percent power, one pass, in *Raster Only* mode.

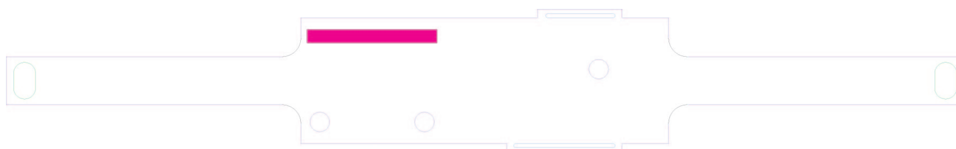

FIGURE 5.3: Magenta Raster on Back of Strut

The final step is one that was difficult to realize must be done and created a lot of frustration. After the strut has been laser-cut, you must scrape out all of the leftover dust from the engravings and break off hardened bits of this dust on the side of the engravings closest to the laser-cutter's fan. The fan pulls the dust onto the newly-cut, warm edge and melts it just enough to harden together and stick to the acrylic. Even after you think you've scraped it all off, you haven't. The motor will not fit into its slot and the mounts will appear to be the wrong size, but that is because of this problem with the dust. X-Acto knives are available in a cabinet across the room from the laser-cutter and are the best tool for breaking off the hardened dust.

After everything is done, you'll have every piece you need to build the strut.

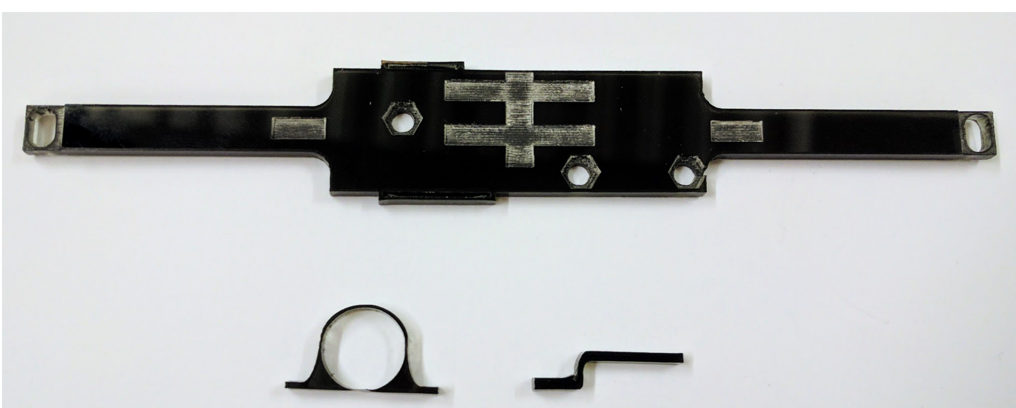

FIGURE 5.4: A Laser-Cut Strut with One of Each Mount

5.3.2 Attaching Mounts

After everything is cut, it's time to attach the mounts. While the battery mounts are easier to attach than the motor mount, the easiest order to do the attachments is motor first, batteries after.

First, without the mounts in place, attempt to fit the motor into its slot on the front of the strut. **It may not fit.** If it doesn't, it's almost certainly because of the dust problem mentioned above. After all of the dust is clear and the motor fits, repeat with the motor and battery mounts.

At this point, with all of the hardened dust removed, take two copies of the motor mount and slide them onto the motor. Then, place the entire structure onto the strut to orient the right distance between the mounts. Then, with the strut on the table, the motor and mounts in one hand, and superglue for plastics and acrylics in the other, lift the motor about one inch above the strut, trying your best to keep the mounts in the same place on the motor. Place a **very** small drop of glue at either end of each opening for the mount, avoiding the center part that fits the motor. Set down the glue, and with two hands press the mounts into the glue. Follow the instructions on the glue for the amount of time to hold them in place and for curing time.

The battery mounts are simpler. Place two small drops of glue in one mount opening, at either end of the opening. Then, place the mount and hold until the glue is ready. Repeat on the other side. Placing glue on the end of the mount toward the motor makes them significantly stronger than without, a lesson I learned after dealing with insecure mounts the first few attempts.

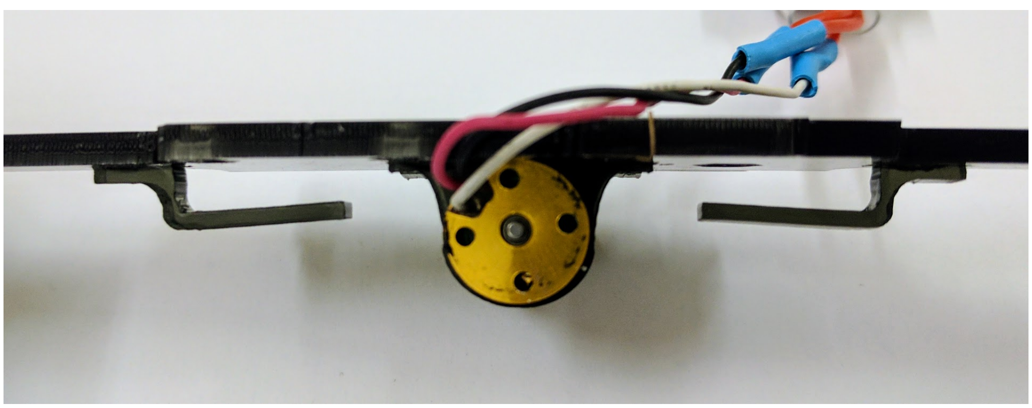

FIGURE 5.5: Strut with Attached Motor and Battery Mounts

5.3.3 Altering the Adobe Illustrator Files for Laser-Cutting

This will not serve as a tutorial in Adobe Illustrator, but rather how the files are set up so that each can be edited. Since the laser-cutting software treats all colors the same when engraving, engraving at different depths is a hassle. That is why there are two *strut-front* files, one with each color. However, it isn't easy to edit the shape of the strut in one and then do the same thing in the other. The best approach is to use the *strut-full.ai* file as a master file, recreating the others later.

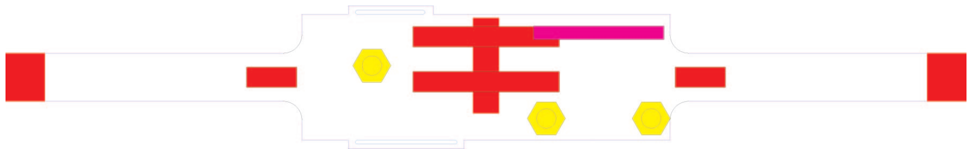

FIGURE 5.6: All Vectors and Rasters On Strut

First, edit *strut-full.ai*. Make it the correct size, reposition all the engravings, etc. Make it look like you want the strut to look, albeit with the front and back engravings on the same side. The front engravings are red and yellow, the back engraving is magenta.

Save copies of this file for the front-red, front-yellow, and back of the strut. In the new copy called *strut-front-red.ai*, delete the yellow and magenta rasters. In *strut-front-yellow*, delete the red and magenta ones. No lines should be deleted, since they are needed to ensure the laser cuts in the same place each time.

For the *strut-back.ai* file, delete the yellow and red rasters. Then, highlighting every line and raster in the file, reflect vertically. Since the strut will be upside-down for this engraving, the directions are switched. It is still important not to delete any lines, simply use *Raster Only* mode.

5.4 Building the Circuit

The circuit should be slightly more self-explanatory than the laser-cutter information.

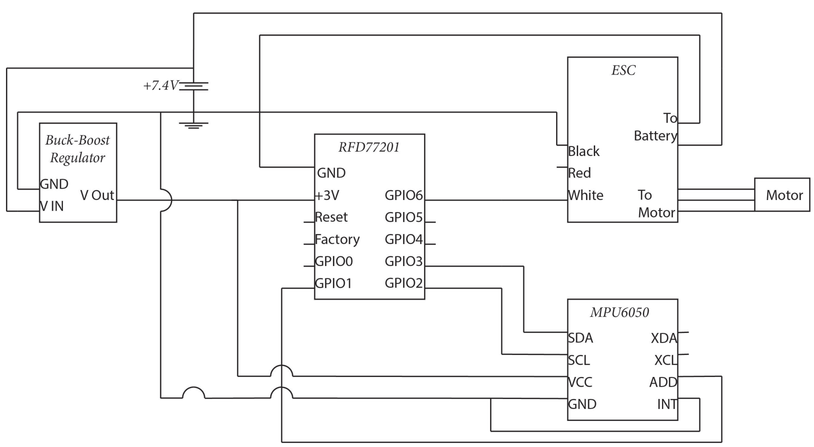

FIGURE 5.7: Full Circuit Diagram

The advice I have for wiring, however, is nothing at all like the laser-cutting. I truly did not figure out a good way to wire this system. While every component "works" when connected as in Figure 5.7, the wires protruding from the strut would be a major hindrance to the movement of a hypothetical tensegrity.

So, my advice to the next builder is to find a new way to wire the strut. The biggest issues right now are connecting the accelerometer to the microcontroller, securing the ESC, and creating enough connections to ground to satisfy the need from multiple components.

The voltage regular also will need careful attention the first time building this circuit, as it was never used with the batteries. It is included in the design regardless because it became clear, through the tragic destruction of an RFduino chip, that stepping down the voltage to a safe 3.3 volts is necessary. If the current listed chip is not a good fit, try the one described in Table 5.3.

5.5 Handling Bluetooth

Handling Bluetooth is most neatly described in the GitHub repository found in Appendix A. That is the best resource for learning how to use the RFduino in this project, and how the data transfers work. The system is actually quite robust, with little to no delay after a command is sent from the computer.

Chapter 6

Results

6.1 Comparison of Strut to Planned Design

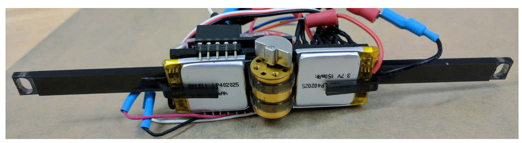

FIGURE 6.1: The Final Strut with Components

First, let's have another look at Table 2.2.

Component	Planned Design
Strut	Modular, sturdy, with attachments
Size	Length of 4 to 6 inches, to compare to VALTR's 4 inch struts
Motor	Increased motor amplitude, over 20G
Power	Containing its own battery
Microcontroller	Embedded in the strut to give a signal to the motor
Data Transmission	Wireless communication with a computer for data transfer
Telemetry	Inclusion of a sensor for vibration sensor or acceleration
Cost	Under $100 per strut

TABLE 6.1: A Breakdown of the Planned Design (Recreated from Table 2.2)

For some attributes, it's easy to determine whether or not the finished strut fits the requirements. For others, not so much.

6.1.1 Strut

The strut absolutely fits the strength requirements forced by the vibration of the strut. However, I'm slightly disappointed in the fact that I managed to accidentally break two struts. Each was along the neck where the arms meet the main rectangle, and the corners have been curved to compensate. Since the addition of the curved corners there has been no breakage.

The strength of the mounts, however, wildly exceeded my expectations. The motor simply cannot break its mount, and that's a great attribute for such a cheap and easy mount.

6.1.2 Size

Due to the fact that the struts themselves can be of any size, the 4 to 6 inch requirement was met. In fact, the printed test struts were usually of a 6 inch length, and should easily make a VALTR-type six-bar tensegrity in their current form. The only concern is a separate size factor: the mess of wires making the whole thing work. While there are no more wires running from the strut to a computer, the wires on the strut itself are a nuisance.

6.1.3 Motor

The motor is one of the best parts about the strut. The fact that is a double the increase in power from the motor on VALTR is significant. However, the ESC's presence diminishes the fact that the motor itself is still no bigger than the last. The strength of the motor still outweighs the costs, and a new, smaller ESC should be towards the top of the docket for improvements to this strut.

6.1.4 Power

On-board power was a necessity for this project, and was a serious hassle for much of the project. Different failures eventually led to the current two-battery configuration. Depending on the duration of sustained power by these batteries in actual use, the 150mAh cells could be even smaller, down at 100mAh.

6.1.5 Microcontroller

The microcontroller aspects of the RFduino, excluding the wireless features, are perfectly adequate. Arduino will be a suitable system for recreating Professor Rieffel's genetic algorithm, as shown by Steven Stangle and the specifications on the hardware exceed the minimums needed by Rieffel. Though, the RFduino's true highlight is the built-in wireless functionality.

6.1.6 Data Transmission

Two-way, wireless, low-energy data transmission was the biggest goal of this project and it is done well with the RFduino. Start commands can be sent to the motor and data can be gathered live from the accelerometer. While this was the most difficult aspect of the project by far, the system works well and will be useful in the creation of new tensegrities for years.

6.1.7 Telemetry

The data from the accelerometer can be gathered and should be useful, but that's for future research students to determine. The accelerometer is great in that it is small and unobtrusive, providing a lot of data for its size. The genetic algorithm being installed on the strut should be able to make use of this data and help inform the movement of future tensegrities.

6.1.8 Cost

The cost, as outlined in Appendix B, just exceeded the goal amount as set by Professor Rieffel. Including shipping costs and the difference becomes significant. This is mostly due to the motor and microcontroller, which are unfortunately the two most important components and the two most significant upgrades over VALTR. It's unlikely the cost can be brought down without removing important features.

6.2 How-To Guide

The How-To guide, outlined as Chapter 5, will be useful to future research students in Union's CROCHET lab but also to any others who hope to build a wireless tensegrity. All code is available for download, with instructions on where to find it in Appendix A.

This is perhaps more the product of this project than the strut itself, as this the paper and outline for building a strut will allow for continued development on a strut, hopefully culminating in one of the topics discussed in Chapter 7. An even more highly-developed strut could create new opportunities in tensegrity research both at and away from Union.

I attempted to make the guide as specific as possible, airing on the side of too specific, to hopefully answer any questions that may come up in the process. If you have more questions, contact me with the addresses in Appendix A.

Chapter 7

Future Work

7.1 Creating a Tensegrity

This project was intended to produce a strut modular enough so that it could be included in full tensegrity robots, especially of the six-bar variety like VALTR. The first application of this project is likely to be exactly that: using this strut to build a VALTR-like robot. A research assistant to Professor Rieffel will soon be able to purchase components for up to six struts, assemble the struts as outlined in Chapter 5, and build a tensegrity. However, two more steps must be done, which were not a part of this project, to synthesize this strut into a tensegrity.

The first is to build a connection on either end of the strut to connect springs between struts. While laser-cutting a whole is simple, a single hole for all springs being connected would lead to asymmetrical connections, lessening the integrity of the robot. So, Some sort of washer needs to be attached at the end to create a location for this connection. I would recommend 3D printing this part, as is currently done for VALTR. The same glue used to mount the motor and batteries to the strut could be used to glue this attachment.

The second remaining step necessary for a useful tensegrity is implementation of the genetic algorithm for Arduino. This could be done in two ways, whether the algorithm itself goes on board of each independent strut or a protocol is devised to communicate between a computer containing the algorithm and the strut's microcontroller.

7.2 Combining with JULIET

Another student in the Union College Class of 2017 created a senior project involving tensegrities: Alexander Chu of the Mechanical Engineering Department. His project was to develop a much larger tensegrity than has been studied at Union, so he designed and built a prototype of a 15-bar tensegrity he called JULIET.

His robot also contains wireless struts with some similarities to the one outlined in this project, in part because I aided him with certain design components outside of the realm of engineering. So, the RFduino, motor, and ESC are shared between the two projects. Future work could involve furthering the reconciliation of the two projects, in using this strut to make larger robots, or by adding features from this project, like the accelerometer, to JULIET.

7.3 Using a Printed Circuitboard for a Strut

The biggest drawback of the strut developed over the course of this project is the large amount of wiring needed to connect all of the on-board components. Though all of the wires connecting the strut to power and a computer have been removed, they have been replaced with wires all around the exterior of the strut. These wires could end up being more inconvenient for the robot than the magnet wire previously was. This could be avoided by creating a printed circuit-board that contains all of the chips and wiring necessary for the strut to function. At that point, using the strut would be as simple as plugging in batteries and a motor. This could be a suitable senior thesis for another Electrical or Computer Engineering student.

Chapter 8

Conclusion

8.1 The Next Step for Building Tensegrities at Union

The new generation of tensegrities at Union will be stronger, more powerful, and smarter than any used before. While I'm unsure of what research will be done with the strut described here, or even if the first strut based off this project in an actual tensegrity will differ greatly, this strut is a big step in a new direction.

The best takeaway from the project is really about the material itself: the strut. What is useful in a wireless strut and what is not is more or less unknown right now. The research to come out of this project, and others like it, including JULIET, will only serve to make tensegrity research better. I only hope the strut being used a year from now is even better than this one.

Appendix A

Files Available for Download

A.1 Wesbite and Git Repo

A description of the project, including a video demonstrating a strut working on a wireless signal, can be found at https://muse.union.edu/2017capstone-konsellr/.

All related files have been made available in a GitHub Repository, *rkonsella/tensegrity-strut*, at https://github.com/rkonsella/tensegrity-strut. This includes all of the code to run the motor and Bluetooth interface, though the Accelerometer program will have to be implemented as needed.

If all else fails, contact the author at konsellr@union.edu or rwkonsella@gmail.com, or, as a last resort, Professor Rieffel of the Union Computer Science Department.

Appendix B

Parts Breakdown

B.1 Links to Purchased Parts

The links to all of the purchased parts can be found in the Git Repo, main directory, in *parts-links.txt*.

B.2 Cost of the Strut

Component	Purchase Price	Cost in One Strut
Acrylic	\$10.21	\$1.02
Motor	\$48.00	\$48.00
ESC	\$9.45	\$9.45
Battery	\$12.85	\$5.14
Microcontroller	\$35.50	\$35.50
Telemetry	\$6.99	\$6.99
Total	—-	\$106.10

TABLE B.1: A Breakdown of the Costs of Components

Bibliography

Chu, A. (2017). “Through Yonder Window Breaks: The Rise of JULIET”. In:

Rieffel, J., F.J. Valeo-Cuevas, and H. Lipson (2010). “Morphological communication: exploiting coupled dynamics in a complex mechanical structure to achieve locomotion”. In: *Journal of the Royal Society*.

Stangle, S. (2013). “How to Build a Tensegrity”. In: URL: https://muse.union.edu/crochetlab/2013/04/17/how-to-build-a-tensegrity.

— (2014). “Designing Wireless Tensegrity Robot”. In: URL: http://stevenstangle.com/seniorproject/thesis.pdf.

Swanson, R.L. (2013). “Biotensegrity: a unifying theory of biological architecture with applications to osteopathic practice, education, and research-a review and analysis”. In: *The Journal of the American Osteopathic Association* 113.1, pp. 34–52.