Continuum Robotic Quadruped (CRoQ)

A Major Qualifying Project
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree of Bachelor of Science
in
Robotics Engineering
By

Theodore Belmont

Date: 04/27/2023

Completed under the advisement and approval of

Onal, Cagdas D., Advisor, and

Chaing, Shou Shan, Co-Advisor

Abstract

Soft robots show promise in exploring dangerous and complex environments due to their adaptability. However, common soft and continuum robotic manipulators use flexible or corrugated materials to form actuators. These approaches can create an obstacle to their practical implementation, because they are often unable to carry the weight of their power and control systems. This paper describes the development of a novel continuum manipulator and its implementation into a robotic quadruped. The manipulator, known as the Serial Underactuated Sphere Actuator (SUSA) is a novel, modular, 2DoF, underactuated, cable-driven actuator with discrete rigid segments that allow for strength and compliance, while also exhibiting a slight Fin Ray Effect. The SUSA is implemented into the novel Continuum Robotic Quadruped (CRoQ) platform. This design allows for an untethered platform with adaptable movement over complex terrain without the need for a complex control system. The latest version of the robot encountered difficulty in traversing obstacles due to insufficient motor power. In future work on the CRoQ, stronger motors can be used to improve rough terrain operation, and multiple stages can be added to give the robot better maneuverability. Future work regarding the SUSA is endless, with possibilities including exploring complex, dangerous environments, enhancing existing rigid and soft robots, and developing robots for use in medical and geriatric facilities.

Executive Summary

Robotic systems exist on a spectrum of rigidity. A majority of robots today are on extreme ends of the spectrum. Simply put, existing robots tend to be either fully rigid or fully soft. These approaches each have their own merit. Rigid robots are ideal for high precision and accuracy, as well as exerting large forces, but tend to need complex control systems to operate in real-world environments. On the other hand, soft robots are ideal for complex environments with basic control, because they are able to conform to the environment, making them more forgiving. Soft robots are severely disadvantaged in force application, however, due to their soft nature. This disadvantage is especially apparent in untethered systems, as fully soft systems often cannot support the weight of their power and control systems, necessitating a tether. Therefore, in order to reap the benefits of both systems for an untethered system, an ideal robotic system will have rigid members, but still exhibit soft behaviors.

This is the niche filled by the Serial Underactuated Sphere Actuator (SUSA). The SUSA uses a series of spherical vertebrae that are connected flexibly via their actuation cables. This means that while the SUSA can exert appreciable forces on its environment, its underactuation allows it to adapt to said environment. This is the inspiration for the novel Continuum Robotic Quadruped (CRoQ). The goal of the CRoQ is to create an untethered legged robotic platform that is able to traverse complex terrain without the need for complex control systems by leveraging the strength and compliance of the SUSA.

The SUSA was developed over four major prototypes, the last of which is the functional module. The SUSA module has multiple interface points, making it very modular for future development. Possible applications for the SUSA are endless, ranging from exploring complex, dangerous environments, including extraterrestrial and aquatic environments, to enhancing existing rigid and soft robots, to developing full robotic systems for use in medical and geriatric facilities.

The final implementation of the SUSA into the CRoQ creates a compact, fully untethered system with a body footprint of 144 x 144 x 73.5mm (not including legs). This version of the CRoQ is reserved to dragging itself due to the limited power of the actuators. The dragging gait does show promise for locomotion in environments with limited clearance or those that require a limited profile. Additionally, using the dragging gait, the CRoQ shows little to no loss of mobility upon the removal of one of the four modules. This suggests that the SUSA enables robust walking, even in situations where all feet do not contact the ground or under unconventional walking arrangements.

Introduction

Soft robots show promise in exploring dangerous and complex environments due to their conformability, allowing them to grip obstacles better [1]. Existing continuum robotic actuators tend to use either corrugated or flexible backbones with cables for actuation [2][3], or pneumatic bladders that can be pressurized to cause differential expansion for actuation [4]. These methods of using fully flexible structures often have a variety of problems. For example, robots with corrugated backbones can lose tension and consequently lose control when under compression. Further, robots with fully flexible members tend to require tethering to power and control systems, reducing their usefulness. Overall, there tend to be problems with rigidity and control.

This paper describes the development of a novel continuum actuator called the Serial Underactuated Sphere Actuator (SUSA), and its implementation into a novel quadruped platform, the Continuum Robotic Quadruped (CRoQ). The SUSA is a type of continuum actuator that consists of a series of spheres connected flexibly via actuation cables (Figure 1), allowing for smooth bending as a 2 degree of freedom (DoF) actuator. Connecting the spheres with the actuation cables serially allows the actuation to move between sphere gaps, resulting in underactuation.

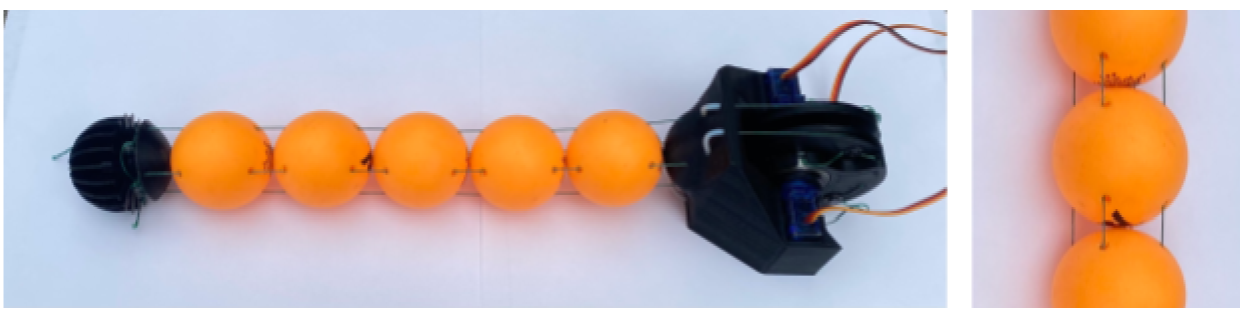


Figure 1: An image showing a SUSA module. On the right, a closeup of the actuation cables feeding through the actuator.

The SUSA is composed of a series of vertebrae, which are each spheres with holes, through which four control cables are fed. These cables are in a diamond pattern, allowing for antagonistic control in both the x and y directions (as one cable is pulled, the opposite cable is let out). These cables are then fixed on the final vertebra so that when a cable is pulled, it shortens the corresponding side of the SUSA, causing it to bend toward that direction. Each vertebra also has a hole in the middle of its top and bottom to allow another series of cables to be fed through, which can control a second stage (and third, fourth, etc. depending on the needs of the system).

The benefits of this system over conventional soft robots are that it has more rigidity than fully soft robots, allowing it to move its own weight. The benefits of this system over conventional discrete robots are that it has more flexibility and therefore more durability, because the actuator can bend instead of breaking, and it exhibits conformation behaviors, which can allow it to grip obstacles more effectively.

Development

The SUSA module was developed from a basic concept (described below). After basic proof of concept testing, the SUSA was developed with the CRoQ platform in mind. This includes creating mounting points on SUSA modules and keeping a vague module arrangement in mind for the final quadruped. The full development process will be discussed in the following sections. The objectives for developing the CRoQ are as follows:

a) Develop and iterate upon a novel cable-driven, continuum actuator from a concept
b) Implement the novel continuum actuator into a quadruped
c) Traverse rough terrain without the need for complex control systems
d) Maintain a budget of $100

These objectives were set with a focus on novelty and accessibility with the overall goal of facilitating widespread development and implementation of continuum robotic systems.

Mechanical Development

There were many iterations in bringing the SUSA up to a functional level from a basic concept. The SUSA was inspired by cable-driven finger joints [5]. When a single cable is pulled, the serial joints bend evenly across the length of the finger. However, these joints only have full actuation in one direction. To move in all directions, the hinge at each joint would need to bend in all directions, meaning that it would need to be infinitely thin. Therefore, to modify the joint, the SUSA uses spheres rolling against each other as the joint, with the same cable actuation scheme.

From this basic concept, a hand-controlled proof of concept was made, in which the cable actuation was controlled by a marionette-style controller. This controller revealed one of the driving factors in the development of the SUSA module. Due to how spheres roll over each other, as the actuator bends, the length on the outside of the bend increases faster than the length on the inside of the bend. The relationship between bending angle and string length can be seen in Figure 2.

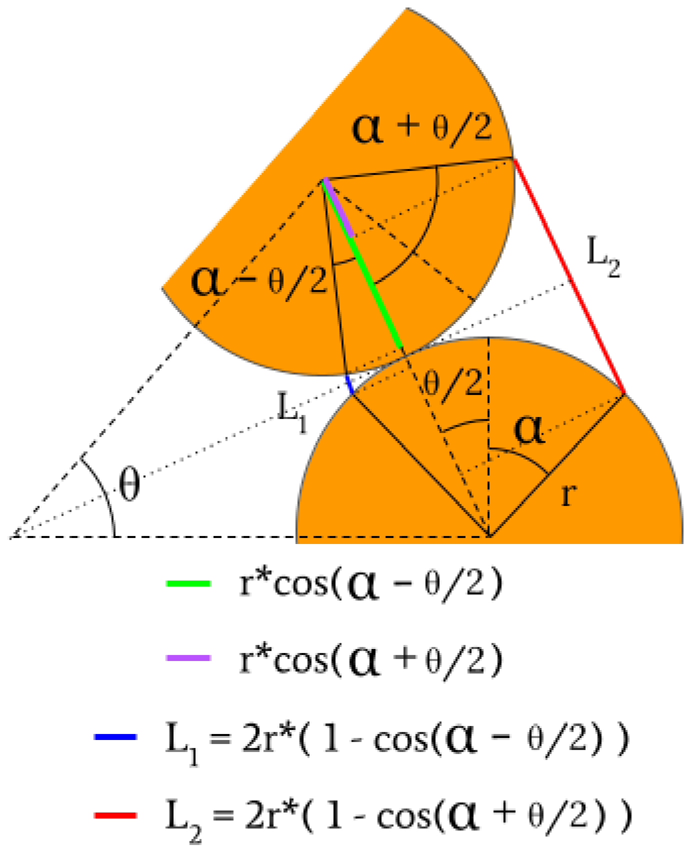


Figure 2: An illustration showing the string lengths on either side of the actuator, given a bending angle α.

Based on this relationship between bending angle and string lengths, a control system was needed to prevent tension loss. Tension loss could result in increased backlash, as well as reduced strength against an obstacle. For this project, a cam with a variable radius was chosen. This variable radius results in a variable circumference, and allows the amount of winding and unwinding string to be tailored to meet the requirements of the system.

From the above string length equations, we can determine the total string lengths for the SUSA by multiplying the length and dividing the angle by the number of sphere interactions (G), then converting from SUSA actuation angle to cam actuation angle. From there, to find the required radius, we can treat the cam as a cylinder, and integrate the radius with respect to the cam angle to get the circumference. We can then take the derivative of the circumference with respect to the cam angle to find the cam radius. This process for one side can be seen in Figure 3. The same process is followed by the other side, but θ (or λ) is made negative.

$$L_1 = 2r(1 - cos(\alpha - \frac{\theta}{2}))$$

$$L_1 = 2Gr(1 - cos(\alpha - \frac{\theta}{2G}))$$

$$L_1 = 2Gr(1 - cos(\alpha - \frac{\theta_{max}}{2G\lambda_{max}}\lambda))$$

When spooling around a cylinder, unspooled string length at a given cylinder angle λ is given by:

$$L_\lambda = L_0 - L_{spooled}$$

$$L_{spooled} = L_0 - L_\lambda$$

and

$$L_{spooled} = \int_0^\lambda R\, d\theta$$

$$\int_\lambda^0 R\, d\theta = L_0 - L_\lambda$$

$$R(\lambda) = \frac{d}{d\lambda}(\int_\lambda^0 R\, d\theta) = \frac{d}{d\theta}(L_0 - L_\lambda)$$

Where:

- r is radius of each sphere (mm)
- α is angle between the central axis of the sphere
- θ is the angle of a single interaction of the actuator
- λ is the angle of the cam
- θ_{max} is the maximum angle of the full actuator
- λ_{max} is the maximum angle of the cam
- G is the number of sphere interactions over the full actuator
- L_λ is the length of unspooled string at a given angle λ
- L_0 is the length of unspooled string at angle 0
- $L_{spooled}$ is the length of spooled string at a given angle λ
- R is the radius of the cam at a given angle λ

$$R(\lambda) = \frac{d}{d\lambda}((2Gr(1 - cos(\alpha))) - (2Gr(1 - cos(\alpha - \frac{\theta_{max}}{2G\lambda_{max}}\lambda))))$$

$$R(\lambda) = \frac{d}{d\lambda}(2Gr - 2Gr\, cos(\alpha)) - 2Gr + 2Gr\, cos(\alpha - \frac{\theta_{max}}{2G\lambda_{max}}\lambda))$$

$$R(\lambda) = 2Gr * \frac{d}{d\lambda}(- cos(\alpha) + cos(\alpha - \frac{\theta_{max}}{2G\lambda_{max}}\lambda))$$

$$R(\lambda) = 2Gr * (- \frac{-\theta_{max}}{2G\lambda_{max}} sin(\alpha - \frac{\theta_{max}}{2G\lambda_{max}}\lambda))$$

$$R(\lambda) = \frac{r\theta_{max}}{\lambda_{max}} sin(\alpha - \frac{\theta_{max}}{2G\lambda_{max}}\lambda))$$

Figure 3: Equations showing the derivation of the cam radius with respect to cam angle equation.

Based on this principle, the first versions of the control system used helical spools that completed multiple revolutions (maximum angle of ±270°), with cable guides to keep the cable on track with the changing radius. An example of this can be seen in Figure 4. The goal of these helical spools was to decrease the total radius needed by increasing the maximum spool angle (λ_{max}).

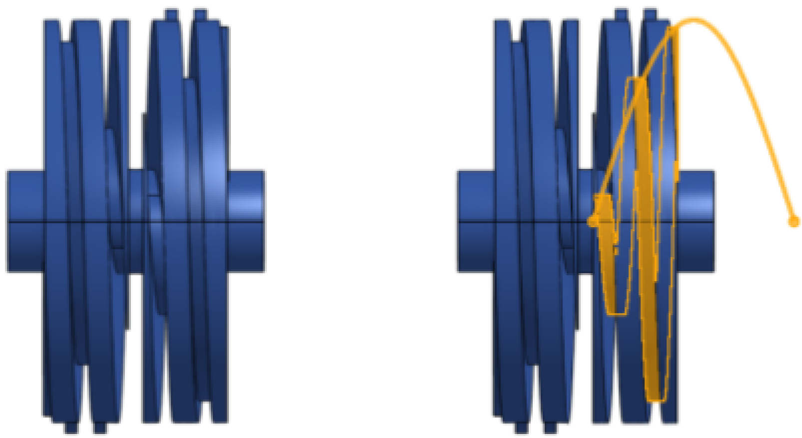


Figure 4: A side view of the initial version of the spool of varying radius. On the right, the spooling surface and sinusoidal curve is highlighted. As the cable is wound, it is pushed across the width of the spool by the cable guides.

The first version had problems with travel, because as the cable was wound, the spooling location would change by up to 8mm, which would change the tension on the actuator. Additionally, the chosen actuator for this design would need a range of ±270°. As will be discussed in the Control and Power Systems section, the actuators chosen for this project were 9g positional servos. Due to this design choice, the spool would need a range of ±90°. Therefore, the next version maintained the helical design, but modified the range to be only ±90°. This resulted in a helical spool. To amend the travel issue, the feeding point of the spool was placed to align with the pitch of the helix at the midpoint. Figure 5 shows a diagram comparing the spooling and feeding points of the first and second version. As can be seen in Figure 5, the range of spooling locations is more aligned with the initial cable position. The goal of this change was to allow the spooling location to displace minimally across the width through the motion. Additionally, the initial cable location (line from spooling point to feeding point) is tangential to the pitch of the spool at the initial position.

Both of these versions used a derivation for the changing radius that differed from the one shown. The derivation for these spools used the pitch of the spool to relate the angle displacement to a linear displacement, and the radius was found with respect to the linear distance from the initial spooling position. This allowed the actual length of the spooling surface to be accounted for, as it would include the radial and axial components of spooling surface travel.

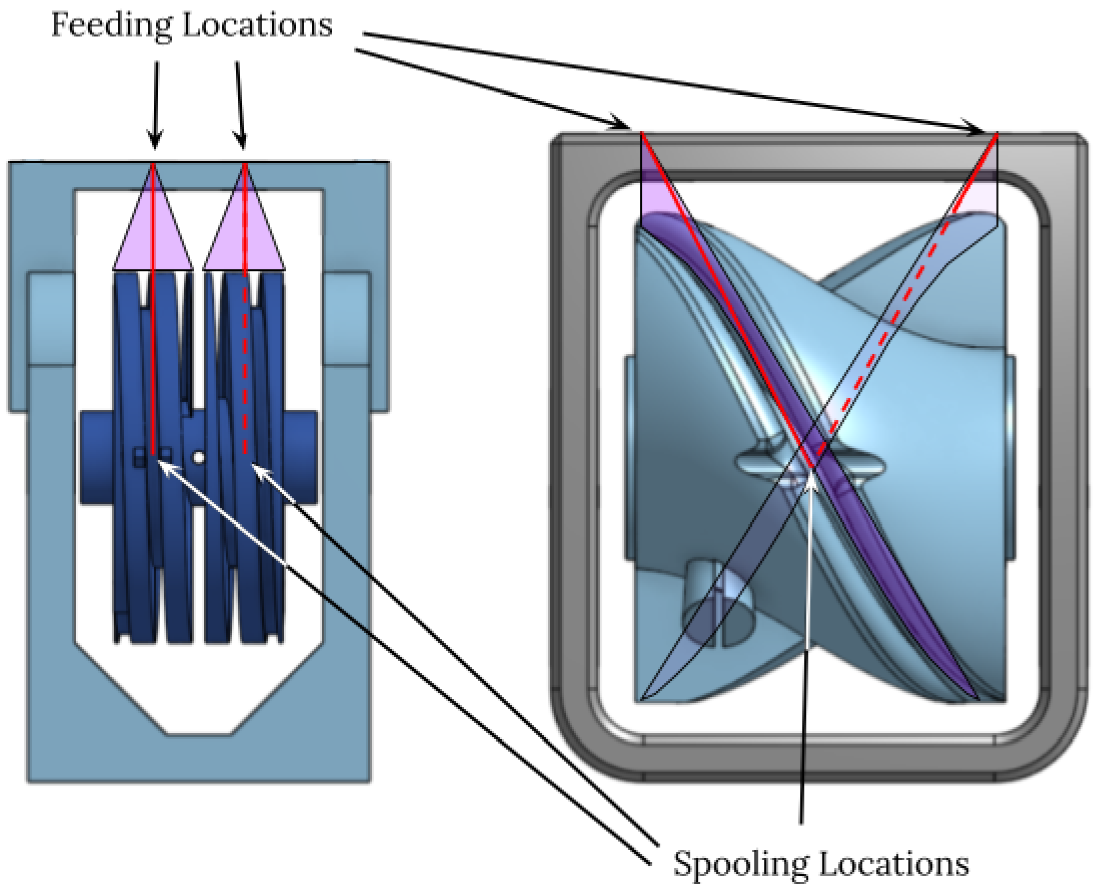


Figure 5: Feeding and spooling location of the first (left) and second (right) versions. Initial cable location is marked in red, with the range in spooling points highlighted in purple. Feeding location is defined as the point to which the cable feeds from the spool to the actuator. Spooling location is defined as the point at which the cable interfaces with the spool surface.

From the helical spool, prototype frames were developed. The prototypes using the helical spools can be seen in Figure 6 (Spool Testing V1 and Spool Testing V2). The second frame was an adaptation of the first to provide more rigidity, as well as better spool support. Further differences between milestone versions (those pictured in Figure 6) will be discussed later.

These frames are designed with the same cable feeding scheme as shown in Figure 5, which then feed to the final actuator. These versions had a problem of cables interfering with each other as they completed a movement. This is because the conical ranges of cable locations intersected for adjacent spools, meaning that some actuator positions would require cables to move into each others' ranges.

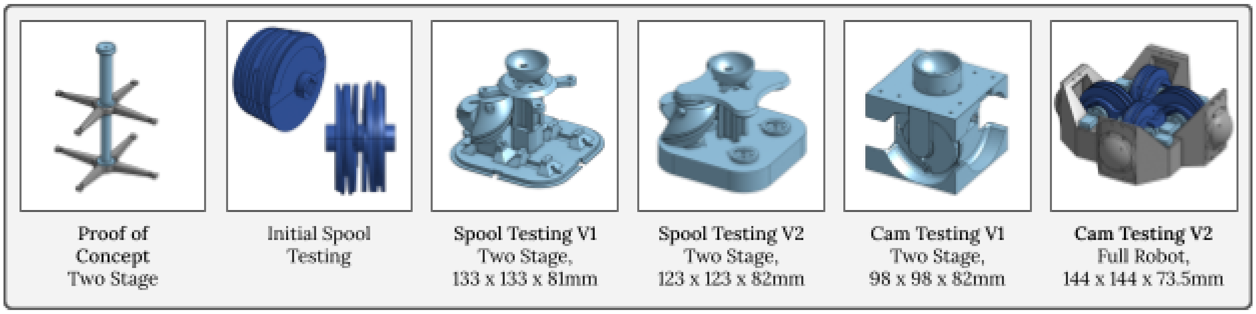


Figure 6: A diagram of each milestone version of the SUSA actuator. The differences between each version are discussed in the Mechanical Development section.

These designs also had a problem with friction, not only from the routing between the feeding point and the actuator, but also against the cable guide as the spool would rotate. This is because as the spool rotated, the guide walls became deeper (the guide radius remained constant, while the spooling radius decreased, increasing the relative depth). The deeper walls caused the cable to be pulled away from the intended spooling surface, increasing the tension in the system. To avoid this tension and resultant friction, another version of the spools was designed with a modified spool guide to follow the spooling surface more closely. The goal with this modification was to reduce the tension against the cable guide as the spool rotated. This modification can be seen in Figure 7.

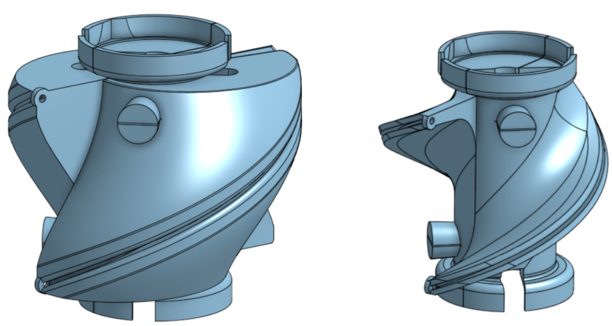


Figure 7: A comparison between the helical spool with the original cable guide and modified cable guide. The modified cable guide follows the spooling surface at a constant offset of 3.5mm, whereas the original guide had an offset of up to 18mm.

The modified cable guide did reduce cable tension as the spool rotated, but caused derailment. Despite the alignment change discussed previously (Figure 5), the movement of spooling location was too great with the reduced spool guide, causing the cable to move out of the guide, instead of following it through the full movement. Based on this problem, cams were adopted.

Cams were originally avoided because they would have an increased radius compared to the helical spools. However, due to the tension, friction, and derailment issues of the helical spools, cams were adopted. Cams have the advantage of being flat, meaning that their spooling and feeding locations will remain coplanar, eliminating changes in tension, friction, and derailing caused by the cable guides. For cam versions, cables feed to a flat face, and are then routed to the initial sphere using PTFE bowden tubes. This reduces feeding friction, because the cables are always coplanar with their feeding location, and past the feeding location, friction is minimized via the bowden tubes.

The cams designed for this project use the radius derivation outlined in Figure 3. For six interactions, used in the working version of the SUSA, the maximum spooling radius of the cam is 34.6mm. Including cable guide geometry, the major radius of the cam is 36.1mm. This is an increase from the 28.5mm major radius of the helical spools, but due to the flat shape of the cams, they can be patterned more tightly. The modified patterning eliminates cable interference between controllers (mentioned earlier) and reduces the total envelope size, seen in Figure 6, bringing the total size from 123 x 123 x 82mm for helical spools (Spool Testing V2) to 98 x 98 x 82mm for cam control (Cam Testing V1).

From the initial cam testing, a second, working, version of the SUSA was developed. This version uses only two spools to control a single stage of the actuator. Previous versions had the goal of controlling two serial actuators, granting 4 DoF. This approach was abandoned for the final version to reduce complexity and envelope. As can be seen in Figure 6, the cam module was 98 x 98 x 82mm for a single module. Comparatively, the current SUSA module is 87 x 82 x 63.6mm, making the full quadruped implementation 144 x 144 x 73.5mm. Using the cam module, the full quadruped would likely be 200 x 200 x 105mm. Additionally, the cam module lacks connection points, whereas the SUSA has two dedicated dovetail interfaces (a male and female) that allow it to connect to itself.

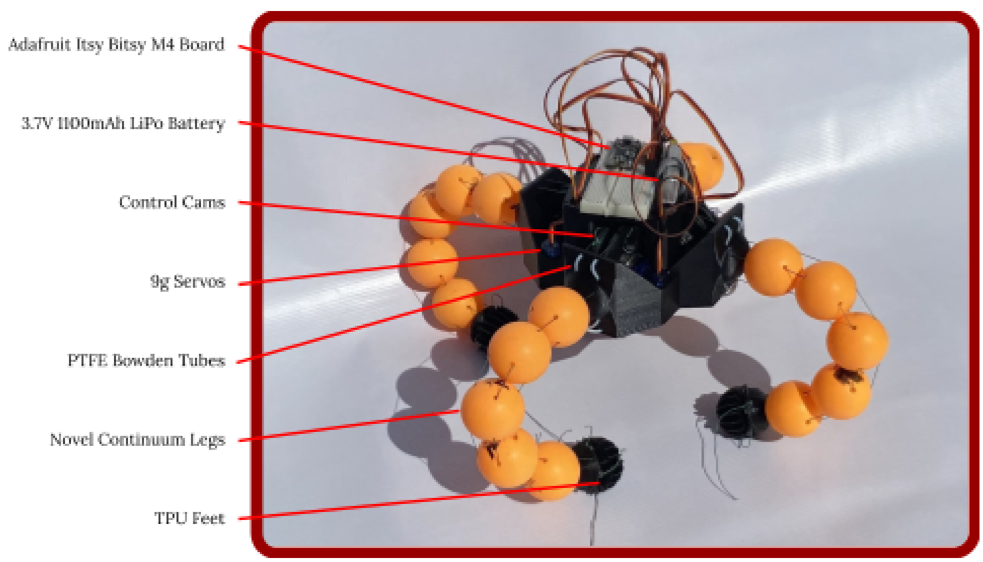


Figure 8: An image of the full SUSA CRoQ implementation. On the left, labels describing the components of the robot.

Each SUSA module is self-interfacing, meaning that four modules can be attached without fasteners to form the full robot, with an additional table that attaches to the top to hold the power and control systems (which will be discussed further in the Control and Power Systems section). The full quadruped (CRoQ) can be seen in Figure 8. This modularity allows for extreme serviceability and adaptability. Initial testing showed that even with a leg missing from the CRoQ, it could maintain a similar level of control and movement (discussed further in the Results and Discussion section).

The final SUSA module uses two 9g servos to actuate in two directions antagonistically. The cable routes are perpendicular to each other, with a 45° offset from the base plane of the actuator. This was done to allow both servos to apply force when pushing off of the ground, improve symmetry, and reduce bowden tube routing length to minimize friction. The servos are coaxial, with a decoupler in between the cams. This means that each cam can rotate independently without interfering with the other's rotation. The servos, cams, bearings, and decoupler are assembled as a unit, then placed into the module frame (seen in Figure 9). The servos have a push fit into the module, improving serviceability and reducing complexity. The frame includes the initial sphere monolithically, whereas the previous versions required the initial sphere to be attached separately. This change reduces part count and improves durability. The frame also includes cable routing holes, bowden holes, and dovetail interface points monolithically. These features are based on lessons learned from the previous versions, making this module a sum of all previous versions. The full module can be seen in Figure 9, with labels highlighting important features.

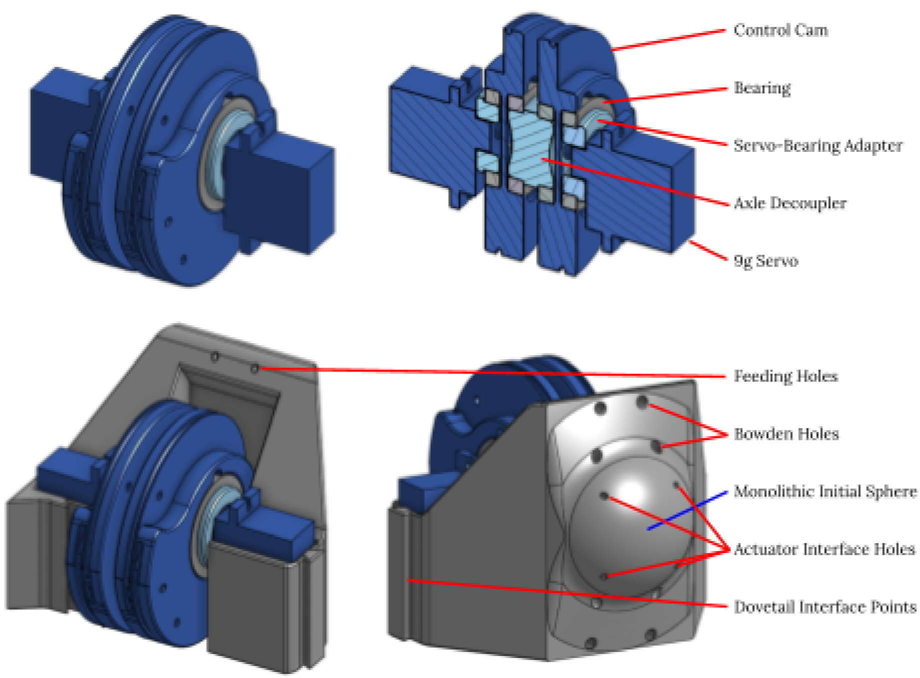


Figure 9: A diagram of the full SUSA module, omitting actuator spheres. Important, functional features are labeled. Top: Coaxial servo assembly, Bottom: Full module (omitting actuator spheres)

The SUSA module has a partial sphere on the end that fixes the cables on the end of the actuator (Figure 10). The partial sphere has cable holes, small machine screw holes, and a screw interface in the middle. The cables are fed through the partial sphere at the end of the actuator, where the machine screws are used to clamp down on the cables, allowing proper actuation with no slippage. The central screw face acts as a modular interface, allowing the user to attach an application-specific end effector. In the case of the CRoQ, a flexible, finned, TPU foot was printed (Figure 10). The flexible fins allow the end effector to deform around a complex terrain feature, improving the CRoQ's footing in rough terrain.

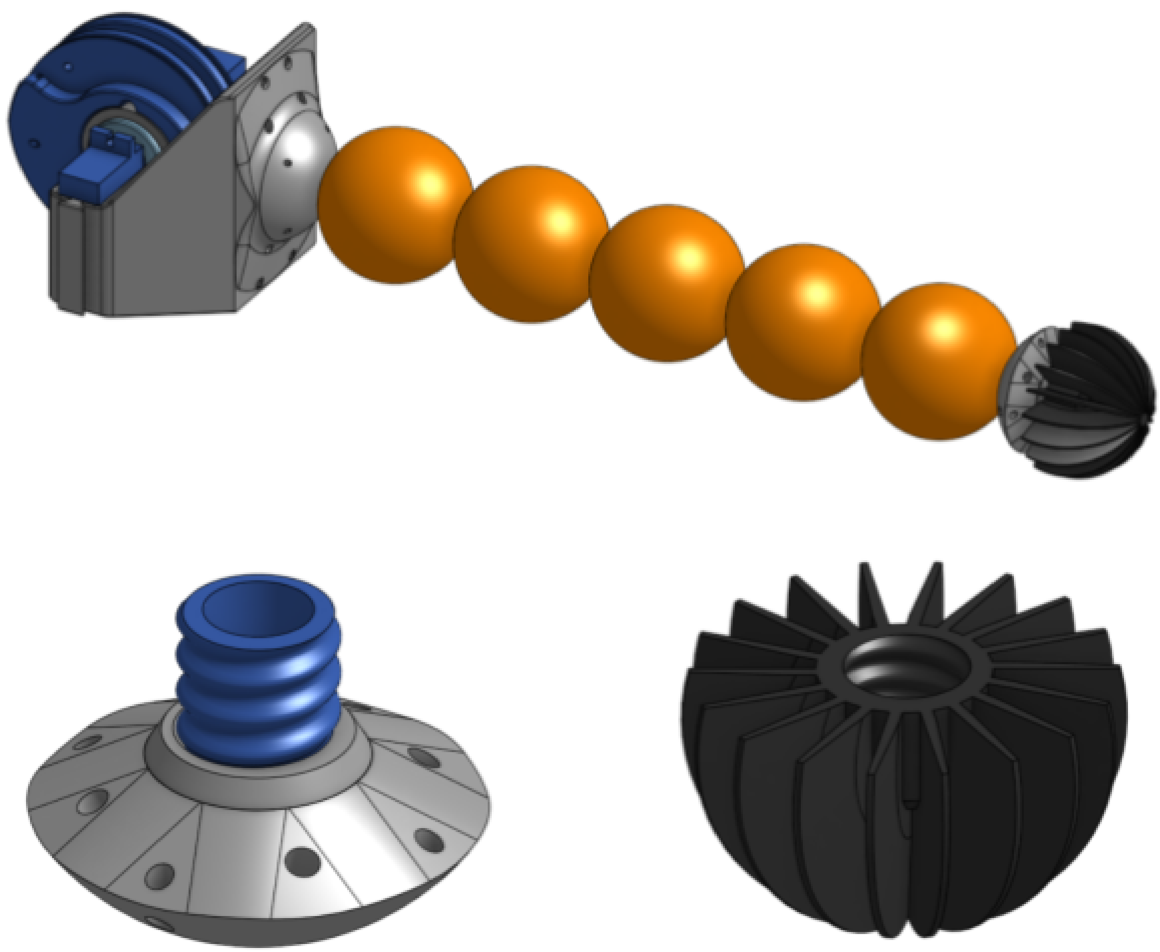


Figure 10: A CAD image of a full SUSA module. On the top, the full module including the actuator spheres and end effector with flexible foot. In the bottom left, a closeup of the partial sphere with machine screw holes, cable holes, and central screw interface. The partial sphere has a female screw interface for printability, with the male screw being printed separately. In the bottom right, a closeup of the finned, TPU foot. The thin (0.6mm) fins allow easy deformation around features.

Major changes in module design were labeled 'milestone versions'. These versions can be seen in Figure 6. From the proof of concept to initial spool testing, there was a major change in control. Control was adapted from a simple, marionette-inspired two-stage controller to a multi-wind spool. This represented a) a change of discretizing x and y motion and position, and b) a movement toward electrical actuation, afforded by the discretization of x and y motion. The Initial Spool Testing stage was defined by two dimensional testing as a simpler analog for later, three dimensional testing.

Major advancements were made in moving into Spool Testing V1. The greatest of these was a defined movement into electrical actuation. This catalyzed multiple other changes. For example, spooling was changed from multiple winds to only ±90°. Additionally, cable feeding and overall structure was made more complex. Instead of making simple 2D frames, Spool Testing V1 required a full frame to be designed to hold servos, spools, cables, and the initial sphere. This version was defined by electrification.

After testing the module made in Spool Testing V1, there was a major problem with rigidity. The spools were supported by the axle of the servo on one side, and by a flimsy frame and bolt on the other side. Testing showed major problems with keeping tension, or undue stress on the servo. Based on this test, Spool Testing V2 redesigned the bottom frame to hold servos more rigidly, redesigned the top frame to attach to the bottom frame more rigidly, and implemented bearings on either side of the spools to impart the load of the cable tension directly onto the frame, rather than the servo. This version allowed for much smoother motion of the spools, and revealed the variable tension and friction issue discussed earlier. The module was, however, able to drag itself across a surface, further proving the viability of the actuator as a continuum leg. As discussed earlier, in an effort to resolve the friction problem, the spool was redesigned to reduce the change in tension (Figure 7), but this change caused derailment.

Based on the variable tension and friction problems of Spool Testing V2, cams were adopted. The change to Cam Testing V1 required a full frame redesign, recalculation of cam radius with respect to actuation angle, and starting cam design from scratch. As discussed earlier, these changes allowed the total envelope to shrink from 123 x 123 x 82mm to 98 x 98 x 82mm, while also solving the problems of cable tension and derailment. Overall, the first cam module solved all of the problems associated with the helical spools. This version was defined by the switch to cams, keeping the same principles in place to ensure robustness (e.g. supporting all cams by bearings on both sides).

Once it came time to implement the module into a quadruped, however, the Cam Testing V1 module proved too complex. Designing for multiple stages introduced unnecessary complexity and size. To accommodate a second stage, each ball of the first stage would need to have all control cables for the second stage routed through it. This would come with the added complication of requiring tension management systems to the second stage's control cables to allow them to maintain tension through a movement of the first stage. This is an important example of reduced complexity afforded by single stage modules. Based on this decision, the next version was Cam Testing V2, which is the SUSA. The details of this module have been discussed, but the major points that defined this milestone version were the reduction of control stages and improved modularity. This is also the version that was fully implemented into the CRoQ, creating a fully untethered platform, with power and control systems (which will be discussed in the next section) onboard.

Control and Power Systems

The power and control systems of the CRoQ are onboard the robot, allowing it to operate fully untethered. For all versions previous to the CRoQ/SUSA, the power and control systems were not fully implemented, and the module was tethered to a computer providing power to the board via USB.

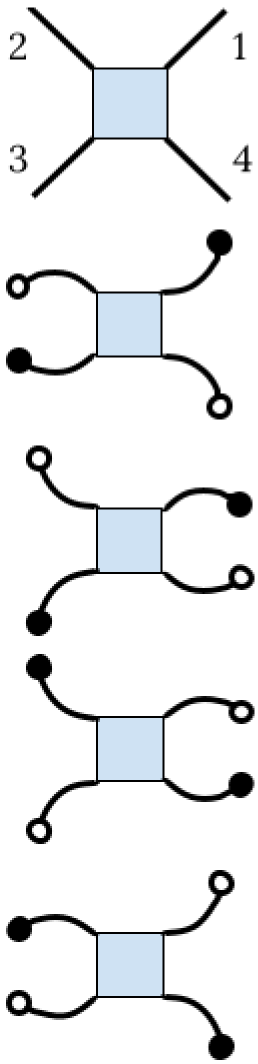
The control system of the CRoQ is an Adafruit Itsy Bitsy M4. This board was chosen for its low cost and high versatility. The board has 18 pins that can be used for PWM [6], allowing it to uniquely control up to four two-stage modules (four servos each), or 9 SUSAs.

The control board is placed onto a breadboard with a power rail attached. The power rail allows the servos to be powered in parallel directly by the battery, increasing their potential current draw and improving their load capacity. Each servo is connected to its own PWM output. In an effort to improve cable management, each servo connector is adapted to male, allowing it to plug directly into the breadboard, reducing the need for jumper cables.

The programming for the CRoQ is very basic. Due to time and power constraints, the current walking gait for the robot is completed by sending a waypoint to each leg, with incremental via-points. The current walking gait is a trot gait, meaning that diagonal pairs are touching or lifted at the same time. Based on the desired trot gait, waypoints are determined by hand and trial-and-error to find a position at which each leg is lifted and forward, touching the ground and forward, touching the ground and backward, or lifted and backward. An example of this walking gait can be seen in Figure 11.

As can be seen in Figure 11, there are six positions (A/B spool couplets) that are used for each movement. This is because the position of a leg is simply a rotation of the opposite leg, meaning that positions can be used for multiple legs in different overall positions. Additionally, an XY mirror of a leg position (ground contact is maintained, but curve is reversed) can be found by simply multiplying both the A cam and B cam angle and switching them.

As mentioned before, each waypoint is chosen, and followed through a set of via-points. These via-points are important for the strength of the actuator, because they cause the servo to carry a load through the movement, as opposed to simply going slack between each waypoint. The results and future work on this basic walking gait will be discussed in later sections. The waypoints are sent to the control board using the Arduino coding language and the Arduino servo library.



Cam/Leg:	1	2	3	4
A cam	0	0	0	0
B cam	0	0	0	0

Cam/Leg:	1	2	3	4
A cam	30	-60	90	0
B cam	-60	0	0	60

Cam/Leg:	1	2	3	4
A cam	90	0	30	-60
B cam	0	60	-60	0

Cam/Leg:	1	2	3	4
A cam	0	60	-60	0
B cam	60	-30	0	-90

Cam/Leg:	1	2	3	4
A cam	-60	0	0	60
B cam	0	-90	60	-30

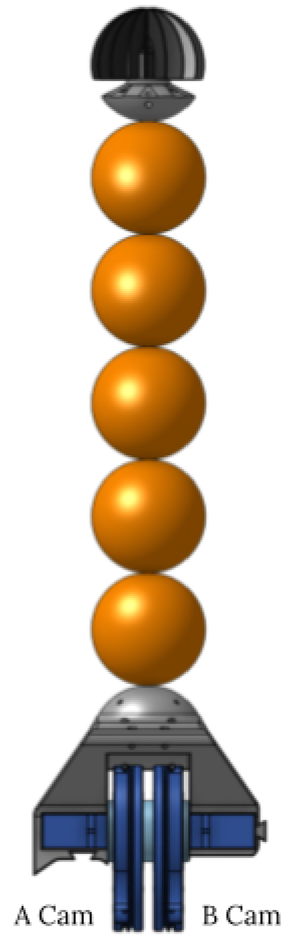


Figure 11: A diagram showing the four positions the robot takes when completing a walking gait (far left). Each leg is depicted as a curve with a circle on the end. A filled in circle denotes a foot touching the ground, while an empty circle denotes a lifted foot. On the right, a top view of the SUSA that labels the A and B cam, whose positions (degrees displaced from neutral position) are shown in a table for each walking position.

The power system of this robot is even more basic than the control system. The power system is simply a 3.7V 1100mAh LiPo battery. This battery was chosen due to its light weight and high discharge capacity, allowing it to power all of the servos at once. The battery is connected to the power rails of the bread board, which subsequently powers all of the servos and controller in parallel. This allows all components to draw the voltage that they need. Using the battery, the full robot can be powered and controlled without a tether.

Results and Discussion

The results of this project are a novel continuum actuator (SUSA), and an implementation of the actuator into a quadruped platform (CRoQ). The SUSA uses serially controlled spheres rolling against each other to give the actuator rigidity, while also giving compliance from the underactuation of the spheres.

The final implementation of the SUSA is able to drag itself independently, though does require tethering to a power and control system. Based on this finding, the SUSA could be used for a variety of applications, supported by the included interfacing points. The potential versatility of the SUSA will be discussed further in the future work section. The SUSA also shows a slight Fin Ray effect, which may be useful in the future for traversing rough terrain, as the robot can better conform around obstacles.

The final implementation of the CRoQ is unable to walk fully. This is due to the limited strength of the 9g servos. The robot can, however, drag itself. This shows promise for future work in implementing stronger actuators into the SUSA modules to allow the robot to walk with a normal trot gait, as opposed to a gait more similar to a starfish.

Additionally, based on the dragging gait, the robot does not show any decrease in mobility with the loss of one of the modules. This has important ramifications in terms of robustness and serviceability, because it shows that the modular nature of the robot works to its benefit. By creating a modular platform, the CRoQ is able to work under a variety of configurations, including those that are not conventionally supported.

Based on the objectives set at the beginning of the Development section, this project was largely successful. First, a major outcome of the project was a novel actuator that was developed from a concept (the SUSA). Second, the novel actuator was effectively implemented into a modular quadruped (the CRoQ). Finally, a budget of $100 was maintained (a BOM can be found in appendix A). This was a major limitation in the strength of the actuators, and a compromise on this objective in the future will open the door for stronger actuators and more complex control systems, including sensors, mapping, and adaptive control.

The only objective not met was being able to traverse rough terrain without the need for complex control systems. This failure was untestable due to the weak servos, but in the future, this may be testable with stronger actuators.

Overall, the project had the major outcome of a fully developed novel actuator that maintains rigidity while maintaining a level of compliance through underactuation, and a robust, modular quadruped that is able to complete a dragging gait.

Future Work

Future work on this project as a whole can be split into two categories. The first category is work on the CRoQ platform. This category consists of improvements to the existing platform to advance it to a working prototype. The second category is work based on the SUSA. Opportunities for future work with this actuator are vast.

Improvements that can be made to the CRoQ consist of power and control upgrades. The major priority would be to use stronger actuators to move the cams. This would allow the robot to exert appreciable force on the ground and other objects, allowing it to complete a full walking gait. Other physical improvements include adding a second stage to each leg. This would require a redesign of the SUSA, but would enable each leg to be a 4 DoF actuator, increasing its versatility. Technological improvements include adding sensors, such as lidar, to allow the robot to navigate its environment, or adding adaptive control to allow it to dynamically choose walking gaits based on its environment or walking media. Finally, the platform could be waterproofed, allowing it to operate amphibiously. The dragging, starfish-like gait shows promise for underwater navigation, because it allows the robot to avoid currents that occur further from the ocean floor.

Potential applications for the SUSA are nearly endless. The rigidity afforded by the spheres allows it to fit into some applications that currently require hard robots, while the underactuation gives it properties that allow it to fit into the current focus of soft robotics. Essentially, the SUSA bridges the gap between hard and soft robots, allowing it to fulfill requirements in both domains.

In the rigid robot domain, the SUSA could be used for mapping of complex environments, including (as mentioned previously) ocean floors, collapsed buildings, and extraterrestrial bodies. Its relatively low cost means that it can be deployed without fear of loss, and its compliance gives it extreme durability in those environments where there may be dynamic external forces, such as strong currents, falling objects, or moving debris. The SUSA could also be used to enhance existing rigid robot functionality. This school of thought can be seen in commercialized soft end-effectors, which allow a rigid industrial robot to grip delicate objects. The SUSA could be adapted similarly to create a compliant gripper for delicate objects (due to its Fin Ray properties), or a wrapping gripper for long or complex objects. Another version of this is using the SUSA as a tail on a rigid robot to allow it to quickly change its angular velocity and center of gravity, allowing it to dynamically balance and spin in free space.

In the soft robot domain, the SUSA could be used to enhance existing robot functionality by providing a foundational platform. This could be in the form of an adaptation to exhibit more soft behaviors, as legs for an otherwise fully soft robot, or as a soft robot itself. The SUSA could show particular promise in medical and geriatric robotics, because its rigidity allows it to apply force on a patient, though with enough compliance that it will not harm them.

Conclusion

Overall, the SUSA and CRoQ are first steps in a wide range of applications of the concept of serially actuated spheres. They show a fully developed novel actuator, along with a basic application. The future applications of the SUSA are broad and on the cutting-edge of robotic applications. Through multiple versions, the SUSA shows an application of mechanical design fundamentals, as well as concepts learned through real-world, hands-on prototyping. The platform shows a highly developed system with vast possibilities of future advancement.

References

[1] M. A. İ. Kalın, C. Aygül, A. Türkmen, J. Kwiczak-Yiğitbaşı, B. Baytekin and O. Özcan, "Design, Fabrication, and Locomotion Analysis of an Untethered Miniature Soft Quadruped, SQuad," in *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 3854-3860, July 2020, doi: 10.1109/LRA.2020.2982354.

[2] M. W. Hannan and I. D. Walker, "The 'elephant trunk' manipulator, design and implementation," *2001 IEEE/ASME International Conference on Advanced Intelligent Mechatronics. Proceedings (Cat. No.01TH8556)*, 2001, pp. 14-19 vol.1, doi: 10.1109/AIM.2001.936423.

[3] G. Immega and K. Antonelli, "The KSI tentacle manipulator," *Proceedings of 1995 IEEE International Conference on Robotics and Automation*, 1995, pp. 3149-3154 vol.3, doi: 10.1109/ROBOT.1995.525733.

[4] Shepherd, R. F. et al. Multigait soft robot. *Proc. Natl Acad. Sci. USA* **108**, 20400–20403. (2011).

[5] Chen, T., Zhao, X., Ma, G. *et al.* Design of 3D-printed Cable Driven Humanoid Hand Based on Bidirectional Elastomeric Passive Transmission. *Chin. J. Mech. Eng.* **34**, 76 (2021). https://doi.org/10.1186/s10033-021-00595-y

[6] Ada, L., Halbert, D., Burgess, P. *et al.* "*Pinouts.*" Introducing Adafruit ItsyBitsy M4. https://learn.adafruit.com/introducing-adafruit-itsybitsy-m4/pinouts?gclid=CjwKCAiAjs2bBhACEiwALTBWZbkarHe9KLevtGB35qTDut94W_Cs4fn2wQMENcelsMCKrB0YpmBFURoCjLwQAvD_BwE

Appendix

[A] The full bill of materials for the CRoQ:

Item	**Qty/Cost**	**Total Cost**
1.75mm PLA Filament	(376g at $0.0144)	$5.43
20 x 27 x 4mm Bearings	(16 at $1.805)	$28.88
9g Servos	(8 at $1.988)	$15.90
Ping Pong Balls	(20 at $0.1858)	$3.72
150lb Fishing Line	(16ft at $0.0171)	$0.27
Small Machine Screws	(32 at $0.021)	$0.67
1.75mm TPU Filament	(36g at $0.01589)	$0.57
1 x 2mm Teflon Tube	(1ft at $0.74)	$0.74
3.7V 1100mAh LiPo Battery	(1 at $6.50)	$6.50
Itsy Bitsy M4 Control Board	(1 at $14.95)	$14.95
400 Pin Breadboard	(1 at $1.665)	$1.67
Total		**$79.30**