ME568 Final Report: ”Skippy”

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I. Project Idea and Synopsis

Given the challenge of navigating different terrains with a soft robot we considered several potential solutions from a rolling wheel to a sea anemone. Skippy was initially inspired by the cockroach locomotion analysis in [1]. The cockroach is able to navigate over obstacles quickly and with minimal controls by leveraging it’s morphological computation. This is not a novel approach in soft robotics. [1]–[3] and many others have explored bio-inspired locomotion. The key adaptation of Skippy is that it’s leg movement is uni-planar. This is more reminiscent of a turtle on sand or a paddling motion [4], [5] with the legs simply moving forwards and backwards. Skippy is then able to navigate over obstacles by relying on the embodied intelligence of the legs. The friction differential and deformation of the silicone causes legs to go over obstacles on the upstroke and dig into them on the downstroke. The redundancy of legs means that if any particular leg does not have traction it will still move forward.

By simplifying the required actuation to uni-planar forwards and back Skippy can prioritize actuation speed. Soft robots are often slandered as slow. While this is not universal, there are only a handful that are capable of fast movement along uneven or rough terrain.

Part of Skippy’s embodied intelligence is the modularity of the design. This was a core principle of our design and is present in the everything from the molds to the skates and spine. The molds are parameterized so legs can quickly be redesigned for different environments, robots, and even functions. A leg can be redesigned to fit through a smaller gap or to function as a grasper simply by passing a new vector to the CAD design. All of the relevant attachments between the skates, spine, and legs rely on deformation of flexible materials to fix them in place and can be easily changed. For example: going over a short incline we can increase the spacing between the legs so that the rear legs will remain on the level ground while the front leg crests the hill. On a rougher terrain the legs can be placed closer together to decrease energy losses in the spine.

II. Background and Inspiration

III. Intellectual Merit

Although the reputation of soft robots as slow is not entirely true, it is a limiting factor for many robots in the field. Skippy is able to reach remarkable speed on a variety of surfaces 11 cm/s or one body length per second. This is limited by the use of regulators and manufacturing inconsistencies in the legs. Integrating bi-stability and a faster pressure source will likely improve the speed substantially.

This is made possible through the morphological computation of the legs and feet. By simplifying the controls required for stepping Skippy is able to effectively swim on land rather than having to take slow deliberate steps with each leg. This by itself would simply cause Skippy to rock back and forth, but the anisotropic friction of and pneumatically feet enable locomotion. The use of ski-skin in robotics is not novel [6], but we could not find any reference in soft robotics. [7] and others have tried bio-inspired silicone molded surfaces, but these have several drawbacks. They require micron precision molding, are fragile, and highly dependant on the normal force. We tested several simplified examples and found that while effective, they would only work in extremely particular configurations. Any change in the height of the leg or surface resulted in failure.

Ski-skin on the other hand is designed to excel in a variety of conditions and performs well when wet, on different surfaces or even on surfaces with granular rheology (snow or sand). Our working theory for why it has not yet been used in soft robotics is that it requires at least some roughness on the surface. This means that it does not work on lab tables.

IV. Design

The final design was arrived at via an iterative process. Each element of the robot was tested, refined, and changed multiple times.

A. Legs

The legs went through a large number of iterations. This was made possible through parameterized CAD designs that we could quickly experiment with new variants to better understand the behavior of the serpentine channels. Abaqus was helpful, but real testing was required throughout. We managed to find a design that allowed us to bend to our target angle of 40^{circ} with minimal pressure, and was stiff enough to lift the robot over obstacles. We further improved the design by combining the left and right leg into a single piece. This reduced the amount of hard parts required, increased robustness, and allowed for longer legs which increases speed. Leg length was a key factor in our maximum velocity.

Late in the design process we realized that we could improve our effective stroke length by not extending the channels to the distal end of the foot 8. This reduced the portion of the stroke perpendicular to the spine which does not produce any effective movement. For an analytical explanation see 4. The U1 (movement parallel to the spine) remains roughly linear and all other movements are minimized. Functioning as a leg this actually works better than the original CCM design.

The legs were based on [8]. The original goal was to adapt the serpentine channel and spring combination to function as a leg rather than a spine 7. The hope was to remove the rigid plastic required in the [8] by integrating an elastomer spring into the leg. Integrating bi-stability would greatly improve the speed, but we decided to focus on other aspects of the design first.

B. Foot

The foot proved to be the most difficult portion of the design. We initially planned on a flexure design that would only push the robot forward on the down-stroke, but found that minute variations in the path of the leg would cause this to fail. We then explored pneumatically actuated feet so that we could control when they were in contact with the ground. These proved difficult to consistently manufacture. A simple channel in the foot resulted in a ballooning foot that would roll on the ground rather than push and had a small contact area. We managed to manufacture a few feet that were designed to inflate to a flat foot, but were never able to consistently manufacture them. In the end anisotropic friction using ski-skins proved to be the most effective. The current design is a combination of pneumatic and ski-skin feet that allows us to control the normal force of the feet for a tighter turning radius.

C. Spine and Vertebra

This portion of the design was relatively simple. After a few struggles with different methods for connecting the legs, keeping the spine flexible, and ensuring the legs were level, we decided to use a thin flat piece of PLA. This proved flexible which allowed us to wedge the spine under the vertebra. This connection was sturdy enough for the robot to walk, but still allowed for easy modifications(number and spacing of legs). The skates were given a turned nose to help navigate over obstacles and placed near the ground to allow for multiple gait strategies.

V. Manufacturing

A. Leg Actuator

The manufacturing process for the final version of the individual leg actuators was elaborate. This process was arrived at via trial and error with earlier iterations of the legs failing due to poor bonding layers, leaks, or accidentally sealed channels.

Molds were made in onshape for each layer. The onshape model was fully parameterized allowing for quick iteration and redesign. Dragon skin 10 was poured for the outer layers of the leg and a blue silicon with a Shore hardness of 30A was used for the inner layer. Both were poured into molds and cured in an oven at 70°C for 45 minutes.

The outer layers were then removed from their molds and placed face down on a thin layer of blue silicone and cured again for 25 minutes at 70°C. This allowed us to seal the serpentine channel and avoid any surface tension induced creep of the blue silicone used to bond to the mid layers.

The mid layer and the now sealed outer layers were adhered together with more blue silicone and placed in a jig to keep them aligned. This was then placed in the oven and cured again for 45 minutes at 70°C.

After this final cure rigid blue tubing was inserted at the center line of each leg, connecting to each channel. A syringe was used to test each channel and ensure it was intact.

B. Vertebra and Spine

The Vertebra skates and their placement on the spine was meant to be easily changed. We wanted to have control over spacing to find optimal placements and to add and remove legs as needed. The 3d print for this one rigid component of the robot was oriented on the print bed such that the layers aligned with the vertical stems of the skate, ensuring strength and no breakage at the layer lines.

The Spine was actually a repurposed plastic shipping strap used to hold large crates closed in transit. It was highly flexible in one axis and rigid in the others. We also made 3d printed versions of these with the dimensions of 1 centimeter by 1 millimeter and variable length for different challanges.

VI. Modeling Component

Abaqus proved useful for designing the legs and feet. We were able to rapidly iterate different designs without wasting silicone and PLA as well as saving a significant amount of time. Testing slight variations in leg channel dimensions was fast and efficient. In particular the pneumatic foot design that inflated to a flat surface was only possible through testing in Abaqus. The foot was able to successfully extend and form a flat surface, but also highlights a shortcoming of relying only on computer simulations; the feet broke constantly. Upon reviewing the Abaqus outputs there is substantial stress near the corners which is where the feet tended to break. For future work Abaqus could be useful to find a version of the foot that distributes the stress more evenly, but it would still require extensive physical testing.

All materials were modeled using Yeoh Coefficients found in [9]. Yeoh coefficients were chosen for their ability to accurately model large deformations and multi-axial stress. We were unable to find specific Yeoh coefficients for the Blue Sapphire and decided to copy the coefficients from Dragon-Skin 30 as it has the same shore hardness. This proved accurate enough for our purposes. Tests were run following the tutorial in [10]. Outputs of Abaqus modeling are in X

VII. Testing

A. Ski-Skin

Testing the ski-skin on the plywood used in the competition we found that the ratio of maximal friction μ_{large} to minimal friction μ_{small} was 4.713. Specifically μ_{large} = 0.3455 N/cm^2 and μ_{small} = 0.0733 N/cm^2. This was tested by placing the skin between two pieces of plywood with a 200 gram weight on top. A string was then tied to the end with weights attached until the skin began to slide.

B. Bending vs Pressure and Soft Resistor Tests

Fig. 1 shows a linear relationship between pressure and the resulting bending angle of one of the legs. We adhered a soft resistor to the front of one of the legs and observed the voltage with respect to differing bending angles. Fig. 2 shows a linear relationship where voltage decreases as bending angle increased. If we integrate soft resistors into every leg, we can monitor the voltage in real time to keep track of the position of every leg. If the plot deviates from this linear relationship we will know if a leg is stuck on an object. With this knowledge, we will be able to send the appropriate commands to free the leg. We can also us this information test the manufacturing quality of our legs, if a leg does not conform to this linear relationship we will know that it is defective.

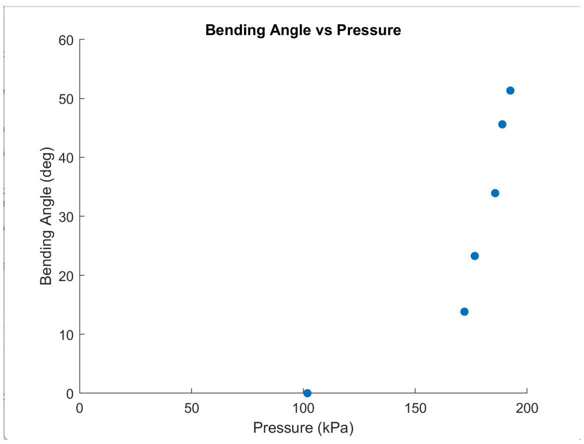

Fig. 1. Angle that the leg bent as a result of pressure.

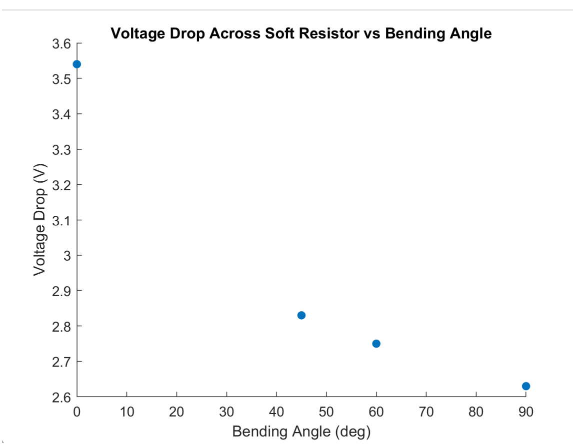

Fig. 2. Voltage drop across the soft resistor as the bending angle of the leg increased

C. Grip Strength and Stroke

We pressurized both sides of a leg so that it would wrap around a paper cup to test the grip strength. We then filled the cup with water until the leg failed, see Fig. 10. The leg was able to support up to 0.86 N of force before the cup slipped.

To find the maximum forward force the leg could deliver we tested how much weight a leg could lift to the desired bending angle $(40°$. We found that one side of one leg can support up to 220g of weight tied to the distal end and still maintain the desired angle.

We limited the stroke of our legs to 80 degrees, 40 degrees on the up stroke and 40 degrees on the down stroke. The legs are capable of bending more then this limit, but that extra inflation would not contribute to productive movement and would therefore be wasteful motion.

VIII. Broader Impact and Future Work

A. Future Work

1) Cam: Continuing with the theme of adapting outdoor equipment for soft robotics we have considered replacing Skippy's anisotropic feet with a cam 9 to allow him to climb vertically. This device wedges itself between two walls and can support up to 15kn. This could either be soft or rigid based on the desired function. A key feature of cams are able to "walk." Skippy could easily push the cam forward while not compromising any of the security of the cam.

2) Bi-stability: Adding bi-stability would have a number of positive effects. In our tests on bi-stability the leg required a much smaller pressure to flip from one region of stability to the next. In the current model manufacturing inconsistencies and connecting the legs in series causes some legs to bend more than others. Setting the bending angle by tensioning the spring may mitigate this problem.

3) Reducing Hard Components: Currently the vertebra is the only rigid component onboard. As its only purpose is to connect the spine to the leg this could likely be adapted as a soft part, but we were unable to come up with a modular soft design. This would significantly improve Skippy's durability and ability to squeeze through tight spaces.

B. Knowledge Gained

The majority design process was making mistakes and learning from them. This is unavoidable, but many of the lessons are applicable in other robots as well as future iterations of Skippy. Potential failure points should be tested as soon as possible and optimization should be left to the end of the process after first making an proof of concept in case components are more difficult than expected (feet). For example testing the legs individually with syringes did not reveal the problem of connecting the legs in series until far too late to address it. Further, briefly testing the legs in series with a syringe did not result in the fatigue failures that almost prevented Skippy from competing. The working model will also give a much better understanding of what needs to be improved rather than working on parts individually.

Aside from design process we had an in depth lesson in silicone molding and design, especially how to iterate with molds in order reduce the number of failed legs. The method for connecting removable tubing that was also capable of holding high pressure was also a welcome innovation after failing to plug leaks with silpoxy. Repeated failures were a inspiration for making the design and "plug and play" as possible. A key design goal for the skates and spine is that they can be easily adapted both for different challenges, and to allow us to quickly replace a broken component.

C. Benefits

In his current iteration Skippy is a fast and adaptable robot capable of navigating over difficult environments and sustaining considerable damage before breaking. The only fragile component onboard is vertebra. The tubing, and spine are more likely to become disconnected than actually be damaged. The legs are able to sustain extremely high impact force before showing any sign of wear. We have repeatedly drop tested Skippy and even thrown the legs against a wall with no effect. Potential applications include:

- Construction (snaking wires, inspection)
- Mapping constricted environments
- Manufacturing inspection

Skippy could replace people in dangerous, dirty and dull jobs. Snaking wires in particular would not require many improvements. Currently workers have to crawl through tight spaces exposing themselves to potentially hazardous temperatures or dust. Sometimes construction has to be demolished just for wires and piping to be placed. Skippy could carry the wire along with his pneumatic tubing and save workers from dangerous and miserable work. Contractors will already have pressure sources on site for other tools so Skippy would be perfect for this environment.

IX. Conclusion

In summary, the design and manufacturing of the robot involved iterative processes and problem-solving across all components. The refinement of the legs through CAD designs and real-world testing resulted in a design meeting bending angle requirements with minimal pressure and increased manufacturing speed and consistency through component consolidation.

Foot design challenges led to the integration of ski-skin technology for improved ground interaction and maneuverability along with simplified controls.

The simple spine and vertebra design provided structural integrity and flexibility using repurposed and 3D-printed components.

The manufacturing processes, particularly for leg actuators, required iteration to streamline the process and reduce failures. This also involved simple practice to gain the necessary skills.

Overall, the journey from design to manufacturing to competition reflected a growth in skills, experience, resilience in problem-solving, and

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X. Figures

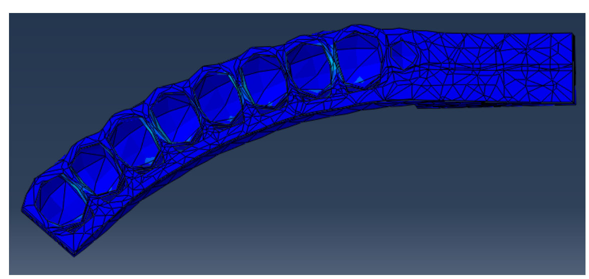

Fig. 3. Deformed Leg. Channel opposite inflated present, but compressed

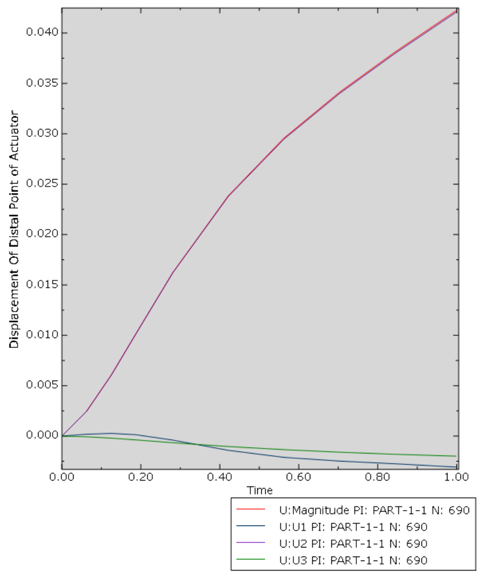

Fig. 4. Displacement

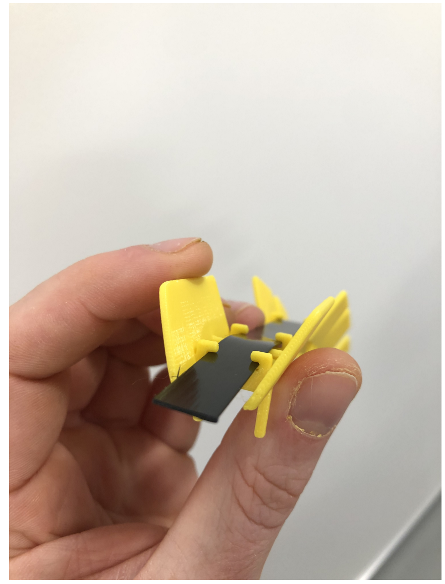

Fig. 6. Spine Connection

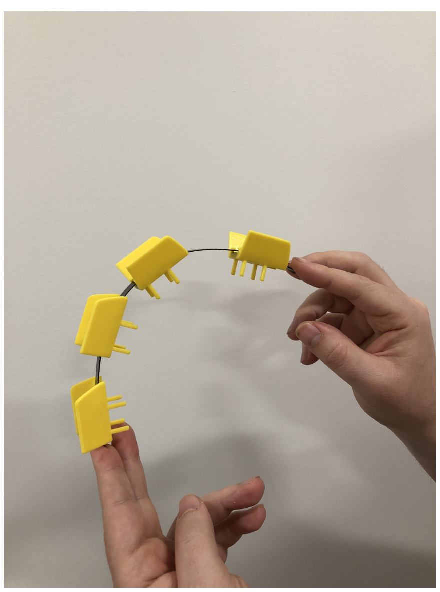

Fig. 5. Flexible spine

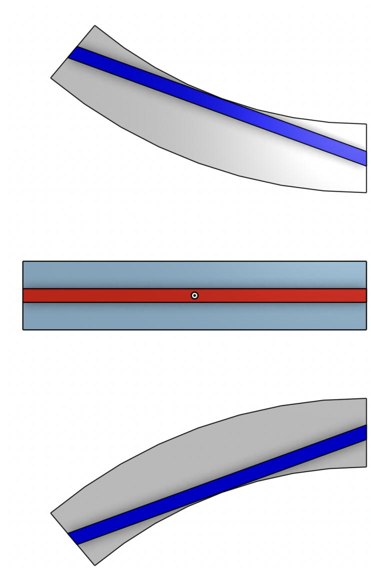

Fig. 7. Bi-stable Design. Spring in tension is red, relaxed spring in blue

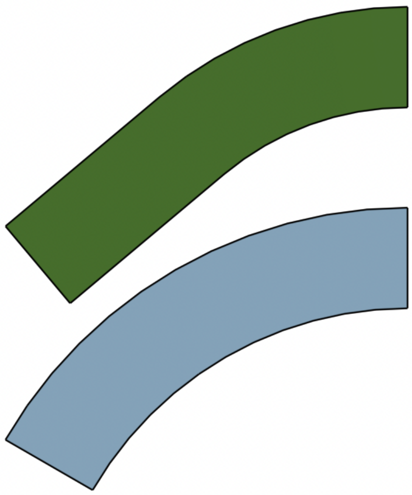

Fig. 8. Comparison of Legs, Original Blue, Current Green

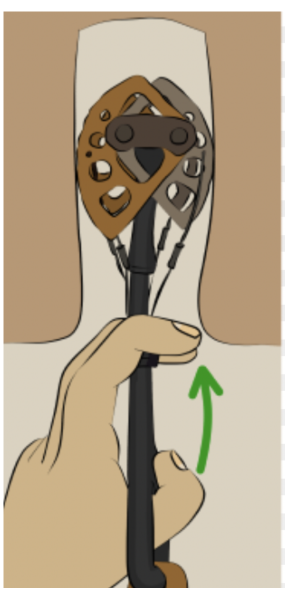

Fig. 9. Cam

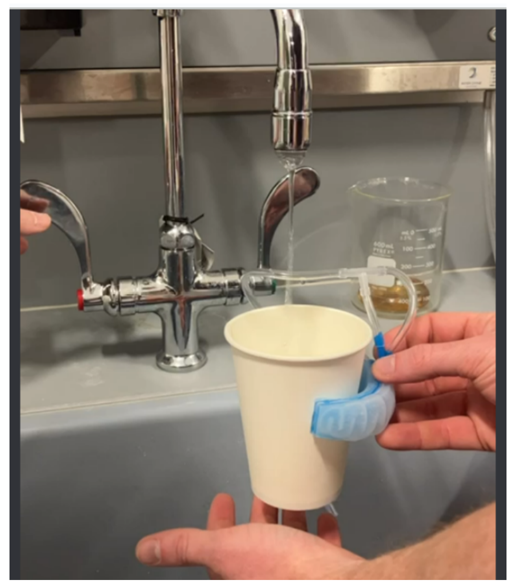

Fig. 10. Testing the grip strength of a leg by filling a cup with water