

RBE 530/ME 530 Soft Robot Project Competition

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Abstract—This paper presents the design, fabrication and performance of three soft robots created to traverse through a challenging multi-terrain competition course.

I. INTRODUCTION

In order to create a robot that can win a soft robotics mobility competition, a detailed analysis of the competition requirements must be done. We will note any difficult areas in the obstacle course and design the soft robot to be resilient to these challenges. To inspire our soft robot designs, we examined examples from research and real-world mobile vehicles.

A. Competition Course

The soft robot will have to move through a course consisting of a series of different terrain types. This might include flat terrain, unstructured terrain with some loose obstacles, and sloped terrain with possibly some water added. Additionally, the course may feature sections requiring the robot to steer to change direction. Here we will describe each major terrain type and potential challenges.

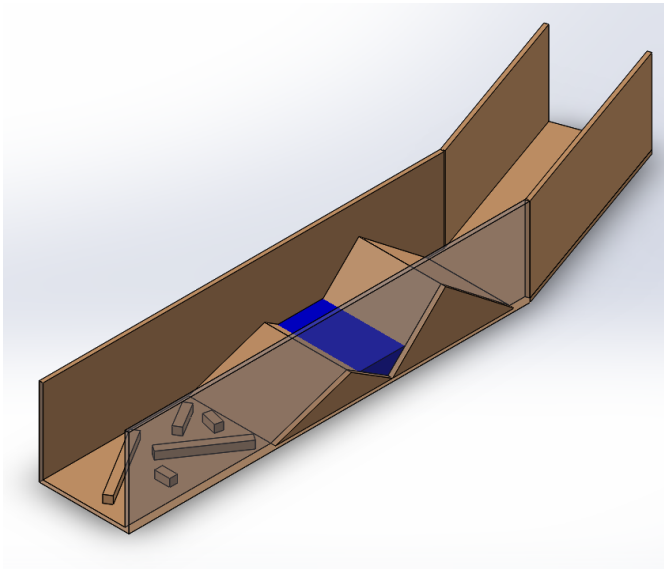


Fig. 1. This is a render of our prediction of the course for the competition. The beginning of the course is flat with obstacles, and then there are slopes with water, and then a bend in the course.

1) *Flat Terrain*: Flat terrain will be the easiest type of terrain for any kind of robot to traverse. In this section of the competition, we hope that the robot can focus on speed, moving in a straight direction.

2) *Unstructured Terrain*: Unstructured terrain refers to terrain that has loose unpredictable obstacles. We do not exactly know how big the obstacles are, but we may run into branches and debris collected from nature. We can predict that these obstacles will be no more than 1 inch in height, so this will have to be incorporated in the design. If possible, the soft robot can steer its way through gaps in the debris.

3) *Sloped Terrain*: During slopes, the robot will have to resist sliding. We will need to look at all the ways our soft robot can make contact with the ground, and optimize it for maximum friction. The robot must also resist rolling down the slope.

4) *Water Terrain*: We recently received news that water terrain most likely will not be added to the course, which significantly simplifies the design of our soft robot. However, in order to successfully beat this type of terrain, our robot would have to have locomotion that can swim through water, or float on top. We can also use some kind of sealant, such as silicone grease, to cover any exposed electrical components that would otherwise be damaged by the water.

B. Survey of Mobile Robots for Design Inspiration

We performed some review of existing mobile robots in hope that we could apply some design traits to our soft robot to win the competition. Our first obvious step was to investigate soft robots that could generally move quickly, and we found interesting works that used cheetahs as a source of bioinspiration, shown in Figure 2 [1], [2]. The actuation method seemed very simple, and consisted of a repeated 1-DoF bending cycle back and forth using pneumatics shape memory alloys combined with a bistable body structure. This was our first start, and we designed initial prototypes based on this concept.

With a simple bending concept in mind, we researched methods to maximize the speed and power generated by the robot. We found a robot that was able to jump up to reach extraordinary heights using a flexing body that could store and quickly release spring energy [3].

We also looked into robots that could switch between different configurations to best traverse over various terrain. We found a robot developed by Carnegie Mellon University, which is actuated using shape memory alloys to perform dynamic forms of locomotion, such as swimming, jumping, and rolling [4].

While these walking robots seemed promising at first, we also wanted to explore back up locomotion methods in case we were not able to properly actuate the bending structures,

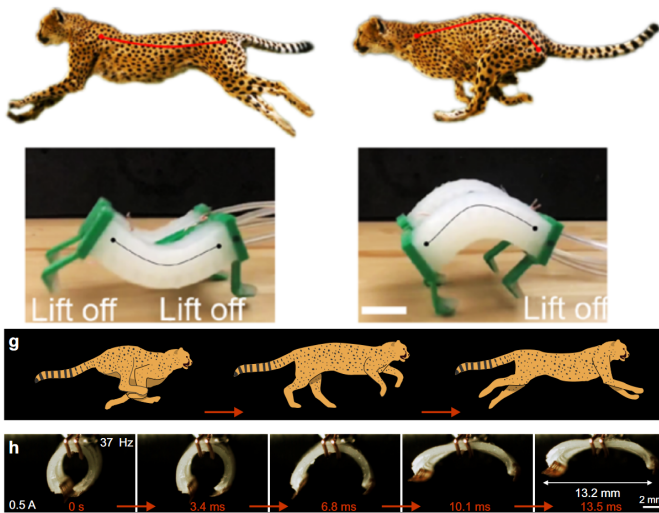


Fig. 2. Fast soft robots that are inspired by the cheetah [1], [2]. We started our initial designs based off of this class of soft robots that bends quickly to provide forward propulsion.

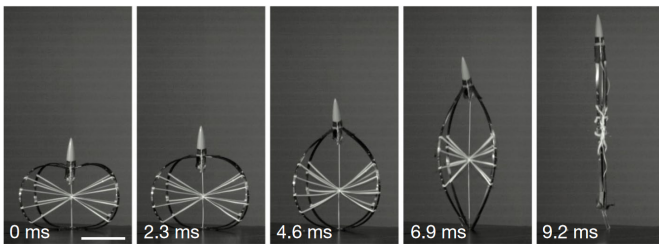


Fig. 3. Quick, forceful motions can be generated using the kinetic energy generated from the release of a cable tensioned flexing body [3].

let alone get the robot to move forward. We took inspiration from military vehicles that are deployed in challenging environments, such as the tank.

Of course, there is no way that we can create a full-sized tank for the competition. It would have to be miniaturized and designed in a way to incorporate the benefits of soft robots. We looked into examples of tank-inspired soft robots in research, and found a robot developed at Carnegie Mellon University that used sticky treads to not only traverse difficult terrain, but also climb walls [6]. It used a tail to maintain balance and resist flipping, which could be useful in sloped terrain and unstructured terrain.

Lastly, we took a look at previous winners in soft robotics mobility competitions. We were interested in a soft robot developed by Cambridge that used a tail and pneumatically expanding wheels to lift itself over unstructured terrain [7]. This design overlapped slightly with tank research that we found, which validated our decision to have a wheeled-tailed robot as a backup option.

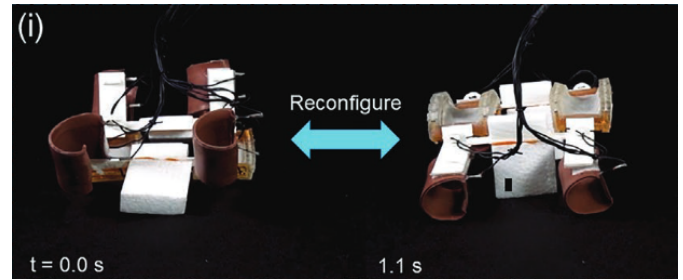


Fig. 4. Amphibious robots that can tackle both water and land might be suitable for this competition. This example is a quadruped that can switch between walking and swimming locomotion [4]. One of our preliminary designs is inspired by this work.



Fig. 5. Military tanks are proven pieces of machinery that can go over complicated terrains, such as hills and valleys [5].

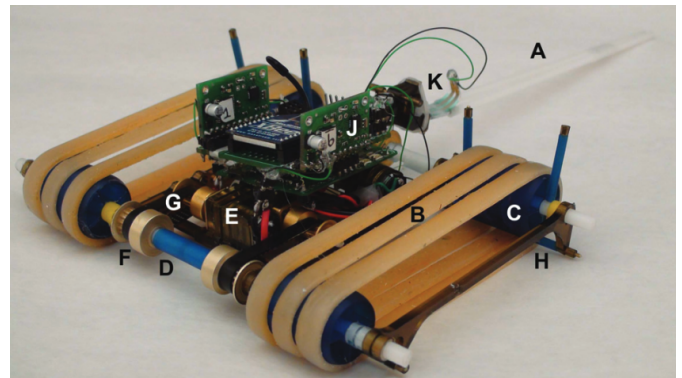


Fig. 6. This is a tank-like robot with a tail that can not only traverse difficult terrain, but also climb walls [6].

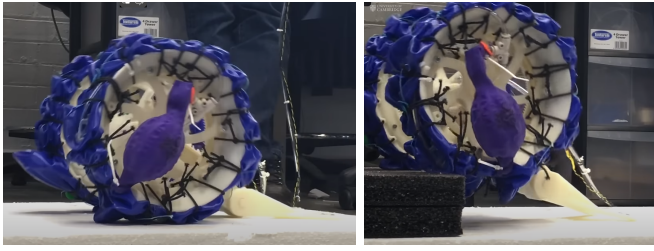


Fig. 7. This is a previous winner of the robosoft competition from Cambridge University [7]. It uses a large wheel that can expand pneumatically to improve climbing traction. A tail is added to provide support so that the robot does not roll backwards. Since our design is similar to a previous winner, perhaps we might have some luck in winning the competition.

II. APPROACH, METHODS AND MATERIALS

A. Worm

The first design that we experimented with was inspired by the bending soft robots and their quick deformations enabled by bistable mechanisms [1], [2]. We were also inspired by the jumping robots mentioned previously [3], and decided to design a robot that could harness the quick springing action of jumping robots, and combine it with the versatility and horizontal speediness of the bending soft robots.

We designed a 3D printed PLA chassis incorporating an arched compliant spring. A motor that rotates a spool to wind up the string, pulling the opposite end of the structure closer, storing spring energy in the spring. After a certain amount of string length is wound up, the post-wound geometry forces the string off of the spool, quickly releasing the spring energy, returning the robot back to the default state in one swift motion. We modified the robot's geometry to take advantage of this phenomenon towards forward locomotion by tuning the mass and center of mass with a weighted 9V battery, and by adding a frictional pad made of TPE to one end of the robot. In theory, when coiled, the robot shifts its center of mass towards the back leg, leaning on the TPE pad. During actuation, the robot pushes off of the hind leg to propel the robot.

The performance of this robot was quite surprising, considering that very few components were incorporated into the robot. The robot was able to traverse forward after each actuation cycle, regardless of the roughness of the surface it was on. However, the robot was observed to struggle in uneven terrain of as little as 5mm high ledges, which had a tendency to tilt the robot into a configuration not compatible with its actuation cycle. It could be implied that the robot would not perform well when subject to the slopes of the competition, which could be at least a 30 degree incline. Additionally, there is no way for the robot to steer in this current design, which is critical for good performance during bending section in the course. Several modifications and design studies would need to happen in order for this robot to perform well in competition.

B. Quadruped

Based on the performance that we observed in our worm robot, we decided to experiment further to improve on the

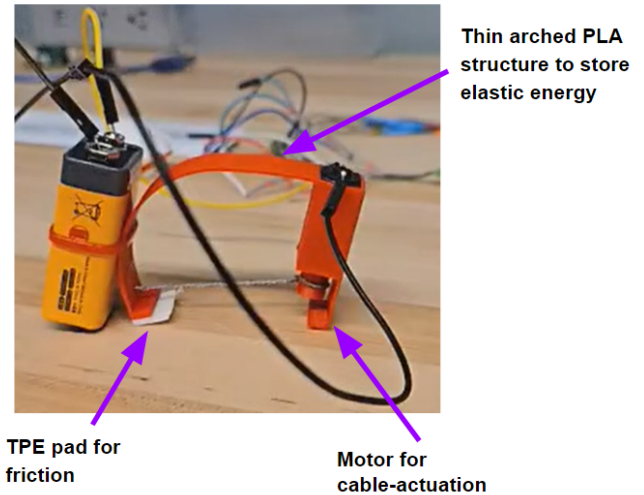


Fig. 8. A worm design was explored, consisting of a structure that can quickly actuate using a released spring.

design to attempt to make it suitable for the competition. For the competition, the robot had to be more stable across a variety of terrain types, and we took inspiration from the quadruped robot mentioned previously [4], which used curved legs to propel the robot through water and land. Because the curved legs in that paper looked similar to the worm robot, it made sense to create a robot using four of these legs.

Thus, we designed a quadruped consisting of a 3D printed flat chassis that connected four legs together using sliders. Each of the four legs is the worm robot structure rotated 90 degrees to allow the curved spring portion to make contact with the ground. The four legs would be connected to a central breadboard mounted to the top of the chassis, powered by a single 9V battery. When powered, each leg would actuate independently of each other.

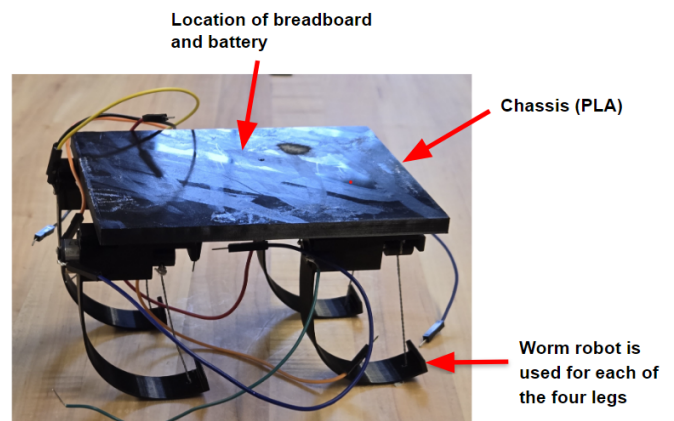


Fig. 9. A quadruped design was explored, which uses four individually actuated worm structures for legs.

There was little to no forward locomotion observed from this type of configuration, which was a great learning ex-

perience. From the worm robot, we saw that very specific sequential events were required to provide movement, such as shifting of COM onto the friction pad, rotation of the worm, and the final spring. While it made sense to use the same springing actuators in a parallel configuration, several parameters were changed at the same time without much consideration, such as the COM of the robot and total mass. Each leg was randomly actuated, with no type of encoder or control to synchronize pairs of legs to resemble a walking gait observed in other quadruped robots. Additionally, the robot was top heavy, which may result in limited performance in slopes due to tipping. We decided to scrap this idea and brainstorm designs for robots that had a more reliable and proven locomotion method.

C. Tank Robot

Inspired by military tanks, we decided to explore the possibility of designing our own competition-ready tank, infused with the advantages that soft robotics can offer. On a traditional military tank, there are some moving elements that significantly contribute to effective locomotion, which can be made soft. First, the treads on a tank must be able to not only wrap around the drive train, but also grip the ground. Second, a tank has a robust suspension system that can absorb shock and reduce disturbances from the environment. Thus, a tank was a viable choice to base our final soft robot design.

A semi-rigid robot chassis is constructed out of PLA, housing two DC motors that are connected through a single stage gear transmission to a grippless wheel also made of PLA. Both motor-bound wheels make up the wheel track and are situated in the front. The are two additional non-connected wheels at the back. Each of the two sides of the chassis is connected to each other through a bridge made of NinjaFlex Edge TPE (83A) that allows for either chassis side to individually react to terrain underneath, ensuring better ground contact. A soft, bendable conveyor treads, 3d printed out of NinjaFlex TPU (85A) is wrapped around both wheel bases, that when actuated through the PLA wheels, translates the robot forward. A long sponge-tipped tail is then added to the chassis at a positive angle to the ground, which was inspired by works that we found [6], [7]. To control the robot, a motor driver chip is connected to an Arduino UNO. Two buttons are also connected to pins on the UNO that help reverse the direction for each DC motor. The entire system is powered by a 9V battery.

1) *Soft Treads:* The initial print of the treads used TPE and was printed with default flex filament parameters of the Cura Slicer. This yielded a print with many large gaps on the sides of the fins. These gaps can weigh down the robot during water traversal as water can enter the fins, causing difficulty traversing and exiting the water and reduce compliance of the fins when on land. The initial print speed was 15 mm/s, with print temperature at 240 degrees Celsius, and nozzle retraction set to On. To achieve a finer treads print, we switched to 85A TPU, reduced the print speed to 10 mm/s, reduced the print temperature to 235 degrees Celsius, and turned nozzle

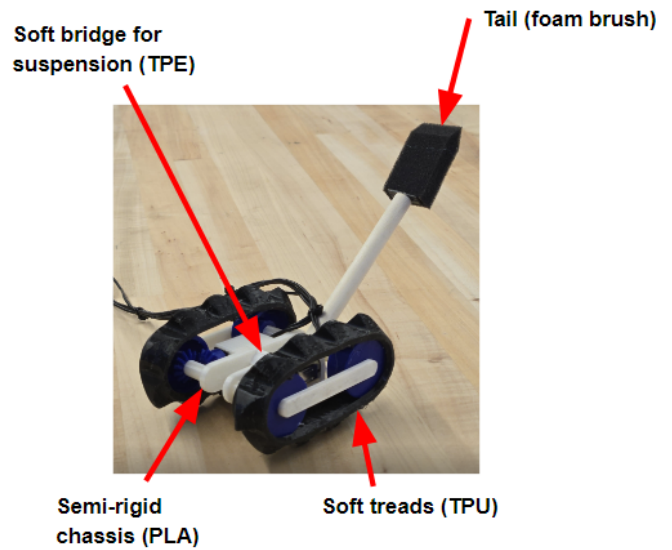


Fig. 10. The final design was a tank-like soft robot that uses a tail for stability.

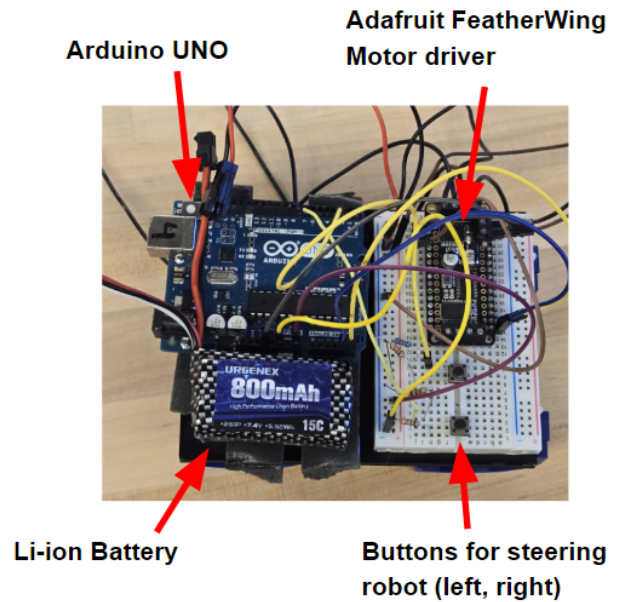


Fig. 11. The robot is controlled using an Aduino UNO microcontroller and an Adafruit FeatherWing motor driver. Two buttons enable steering through bidirectional motor control. The control panel is powered with a 800 mAh Li-ion battery.

retraction off. Figure 14 shows the prints with default flexible filament parameters using TPE and with tuned parameters using TPU.

In an attempt to create more friction with the ground, especially needed for slope traversal, the TPU driving treads were first coated with Eco-flex 30A silicone. The silicone coating will also seal in small gaps/openings in the treads that water can seep into during the water traversal phase. Since we did not know for certain if the silicone would adhere to the

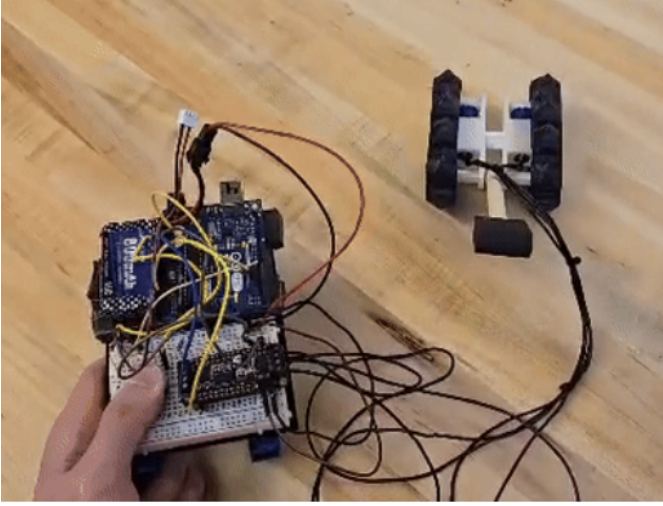


Fig. 12. One handed operation of the tank robot using the handheld control panel. The robot is tethered by a series of wires extending out of the back.

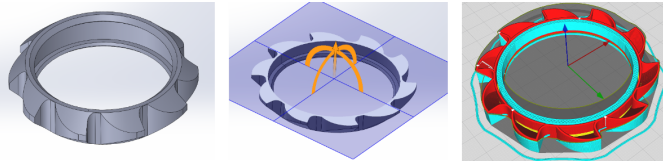


Fig. 13. Design and slicing of the tread design for 3D printing. The tread was designed as a solid body, and the printing settings were configured to low infill with 1 mm wall thickness to make the body hollow.

TPU treads, the silicone was coated all around the inside and outside surface of the TPU tread. Due to unsatisfactory results, the silicone coating was removed from the TPU tread, and the tread was coated with stick-based glue instead. A comparison of the performances between these two coating types is shown in Figure 17.

2) *Soft Bridge*: It is important for the soft robot to have equal contact with the ground at all times, especially when going over unstructured and rough terrain. If contact between the treads and ground is lost, the robot can slip and not be able to proceed further in the obstacle course. We aimed to solve this problem by designing a compliant flexing element connecting the left and right drive trains of our tank, shown in Figure 15, which acts as a form of suspension. Additionally, the soft bridge works well to absorb any vibrations and shock that might be encountered during locomotion, minimizing disturbances that would harm our robot's performance.

This soft bridge is designed in a way to lock into both sides of the chassis. There are extruded grooves radially extending from the body of the soft bridge which line up with grooves cut out from the chassis. When uneven forces are encountered by the tank robot, such as when going over a bump, the soft bridge experiences torque or bending moments that result in deformation. When the disturbance goes away, the soft bridge is able to restore back to its default state quickly and consistently thanks to the TPE material.



Fig. 14. Before and after adjusting print parameters and design to improve manufacturing quality. The main changes were that supports were enabled during printing, and flat surfaces were minimized in the design.

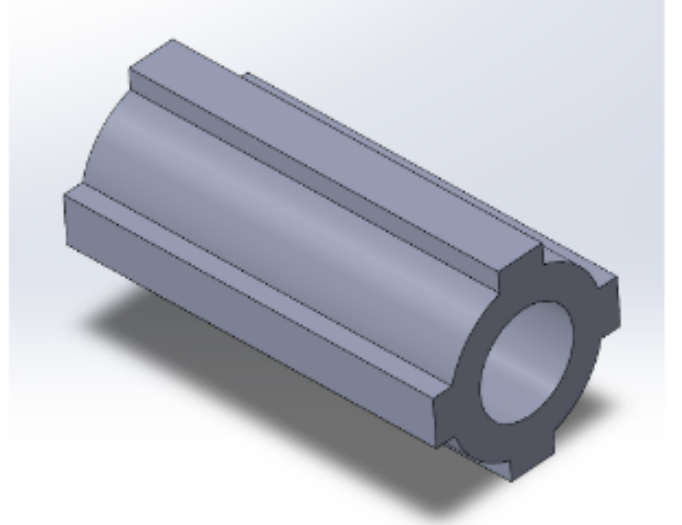


Fig. 15. A soft bridge was designed and printed out of Ninjaflex TPE 83A to allow both sides of the tank to passively flex when traversing over rough terrain.

III. RESULTS AND DISCUSSION

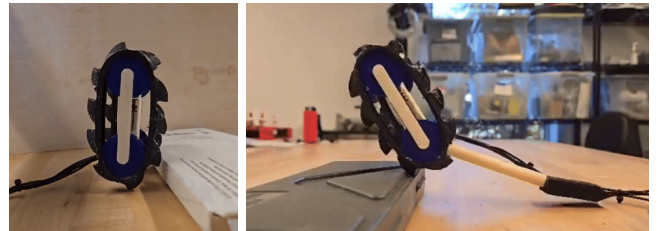


Fig. 16. The robot attempts to traverse over a small obstacle of around 5 mm tall, which results in flipping over (left). With a tail, climbing performance is significantly improved, and the robot is able to not only resist tipping, but also climb obstacles of more than 10 mm (right).

The initial version of the soft-treads driven robot traverses well on flat terrain. However on sloped and unstructured terrain, the robot is unable to maintain enough friction with the ground and thus slips. When the sponge-tipped tail is added to the overall chassis, the tail is off the ground when in flat ground and therefore does not add unnecessary friction that slows down the robot. However, when entering the slope, the sponge-tip of the tail rotates into the ground and

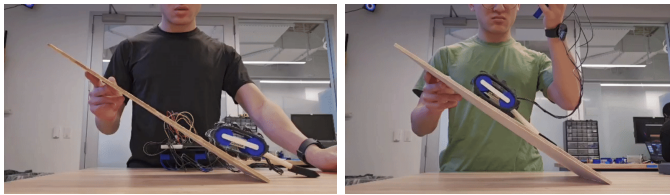


Fig. 17. The soft treads were tested with a variety of coatings to explore traction improvements. A silicone coating left residue from uncured material and lubricated the contact surfaces, reducing traction (left). A coating of flexible fabric glue allowed for decent performance up the ramp (right).

provides additional friction needed for improved slope traversal. The silicone coating actually provided a more smoother surface than the TPU tread's surface (in part due to print imperfections/roughness). Inversely, the stick glue when dried, provided an increased rough finish and retained some of its adhesion. From Figure 17, it can be seen that these properties contributed to better friction and traction when climbing up unstructured and sloped surface. Because the robot is tethered to its microcontrollers and battery, the wires going into the robot provide resistance to forward movement. Therefore, it is required that the tethered operating system be held above. To prevent the force from holding the control system above the robot relieving normal force acting on the robot (and therefore relieving friction), slack in the tether wires needs to be maintained.

IV. CONCLUSION

To overcome the different terrain challenges presented by the competition course, different designs of soft robots, inspired from previous work were prototyped and analyzed. A single body worm robot, a quadruped robot and a soft-treads driven tank robot were fabricated and tested. Both the worm and quadruped robot use soft properties such as stored spring energy to actuate, while the tank robot uses its softness passively, to conform to uneven terrain and obstacles. The worm robot was scrapped because of its proneness to tipping over because of its minimal surface contact and narrow body. The primary issues with the quadruped robot were its slow locomotion due to inefficient use of springing force from its legs and its top-heavy structure. The soft-treads driven tank robot was used as the final design for the project since its actuation delivered constant movement and not in phases like the previous two robots. Its structure allowed for good balance, low profile and versatility to making modifications for optimizing travel in certain terrain. Modifications made including adding a support tail and coating the treads to increase friction.

Although the most recent iteration of the soft-treads tank robot can traverse through the course, further improvements could be made to the overall design and structure. Currently, the entire main chassis housing the DC motors of the robot is made of PLA. Inspired off of previous work such as the Soft Mechanism Driven Quadruped Robot, the entire chassis could instead be printed from TPU to allow for more compliance

and conformability when traversing uneven terrains and slopes [8]. In addition, removing the tether should be a high priority. However, in order to house the control systems within the robot, the overall structure of the robot must be made larger, which could yield in lower mobility of the robot. The robot could then be remotely controlled, through using a Wifi based Arduino microcontroller instead. To make the robot fully autonomous, the control buttons used for turning (through reversing each motor) can be replaced by pairs of sensors or photoresistors, that can react to differential sensed distances of surfaces in front of the robot. For the water phase of the competition, electrical components within the robot should be coated with silicone to seal it from water contact.

The soft-treads tank robot, with its additional improvements can be used for traversing multiple challenging terrains in real life. These uses include search and rescue missions and exploration missions. It could replace robots custom designed for each separate challenging terrain, and would allow for easier inter-terrain transport. Additionally, due to the compliant nature of its soft-treads, terrain traversed by the robot will experience reduced harm and deformation.

REFERENCES

- [1] Leveraging elastic instabilities for amplified performance: Spine-inspired high-speed and high-force soft robots. (2020). *SCIENCE ADVANCES*.
- [2] Mao, G., Schiller, D., Danninger, D., Hailegnaw, B., Hartmann, F., Stockinger, T., Drack, M., Arnold, N., Kaltenbrunner, M. (2022). Ultrafast small-scale soft electromagnetic robots. *Nature Communications*, 13, 4456.
- [3] Hawkes, E. W., Xiao, C., Peloquin, R.-A., Keeley, C., Begley, M. R., Pope, M. T., Niemeyer, G. (2022). Engineered jumpers overcome biological limits via work multiplication. *Nature*, 604(7907), 657–661. <https://doi.org/10.1038/s41586-022-04606-3> <https://doi.org/10.1038/s41467-022-32123-4>
- [4] Patel, D. K., Huang, X., Luo, Y., Mungekar, M., Jawed, M. K., Yao, L., Majidi, C. (2023). Highly Dynamic Bistable Soft Actuator for Reconfigurable Multimodal Soft Robots. *Advanced Materials Technologies*, 8(2), 2201259. <https://doi.org/10.1002/admt.202201259>
- [5] Here's How You Can Buy a Russian Tank — WIRED. (n.d.). Retrieved April 28, 2024, from <https://www.wired.com/2015/06/heres-can-buy-russian-tank/>
- [6] Unver, O., Sitti, M. (2010). Tankbot: A Palm-size, Tank-like Climbing Robot using Soft Elastomer Adhesive Treads. *The International Journal of Robotics Research*, 29(14), 1761–1777. <https://doi.org/10.1177/0278364910380759>
- [7] Cambridge University (Director). (2016, April 29). Soft robotics competition entry. <https://www.youtube.com/watch?v=d-pVYqNBXhk>
- [8] Aygul, C., Guven, C., Frunzi, S., Katz, B., Nemitz, M. P. (2024). A Framework for Soft Mechanism Driven Robots. DOI: 10.21203/rs.3.rs-4109720/v1