Pipe-Traversing Continuum Soft Robot

1st Pranav Jain
Robotics Engineering
Worcester Polytechnic Institute
Worcester, MA
psjain@wpi.edu

2nd Jonathon Chang
Robotics Engineering, Electrical and Computer Engineering
Worcester Polytechnic Institute
Worcester, MA
jchang2@wpi.edu

3rd Jason Gee
Robotics Engineering
Worcester Polytechnic Institute
Worcester, MA
jrgee@wpi.edu

***Abstract*—This paper presents a tele-operated continuum soft robot for use in a simulated IEEE RoboSoft Competition. This competition tasks robots with navigating a course with several obstacles. We considered designs for a soft robot that address different obstacles throughout the course. We considered several key factors, including the robot's turning, locomotion, and control. On competition day, our robot did not traverse the course due to several issues we observed. After reviewing our initial design, we were able to improve some of these issues and improve the robot's performance.**

I. Introduction

During this course, our team has worked to design and fabricate a robot capable of traversing through a predetermined course, consisting of a pipe with many turns and a few obstacles. Over span of roughly a month, we designed, fabricated, and demonstrated the robot, ending on April 30th, 2025, in our simulated RoboSoft competition. We competed against other teams, including those from our university and schools such as Arizona State University (ASU), the University of Michigan (UMich), and Yale University. Our team presented a semi-rigid continuum robot to traverse throughout the competition course.

A. Competition Information

The RoboSoft competition itself is based on the 8th IEEE RAS Robosoft Competition. Competition details can be found on their website. There were 3 sub-competitions that were taking place: In-Pipe Locomotion, Harvesting of Delicate Fruits, and Medical Screening and Intervention. While we did not compete at RoboSoft 2025, we participated in a friendly intervarsity competition based on the details of the In-Pipe Locomotion challenge.

The official RoboSoft competition lists eight tasks, which can be seen in Figure 1 and are listed as follows:

- Task 1: A straight segment.
- Task 2: A 90-degree turn.
- Task 3: A segment with rubble on the walls.
- Task 4: A segment with flexible walls.
- Task 5: A 180-degree turn.
- Task 6: A downward slope.
- Task 7: A sand pit.
- Task 8: An upward slope

For the intervarsity competition, a common set of materials were used to build a replica of the track. These included

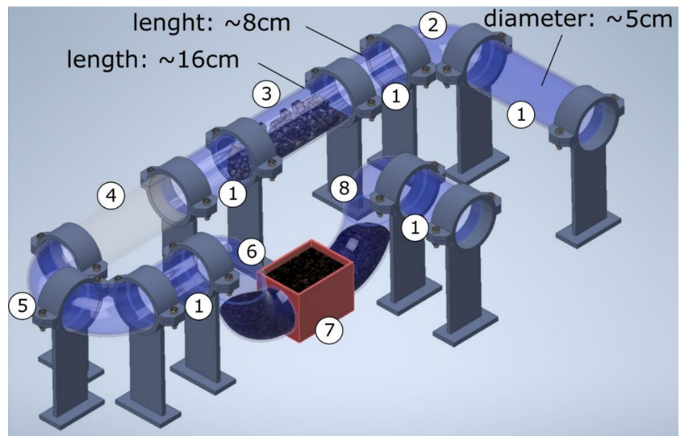


Fig. 1. Obstacle course for in-pipe locomotion challenge. This contains several different portions, including rigid segments (1), horizontal 90-degree turns (2, 5), a gravel section (3), a deformable section (4), vertical 90-degree turns (6, 8), and a sand pit section (7).

hamster tube modules from Amazon, 3D printed stands based on the 3D model of the competition, the sand, and the rocks.

II. Methodology

A. Design Ideation

While coming up with designs ideas to solve the various tasks, our team recognized four main challenges that we needed to address:

1) Turning: The robot would need to bend and change direction, as seen in Task 2 and 5 of the challenge. To complete this task, we came up with 3 main ideas:

- Origami Robot: This design was inspired by the origami robots in the Soft Robotics Lab (SRL) and a previously made pipe traversal robot in the SRL. We considered having an origami section that would allow the robot to bend in all directions. However, there were multiple issues that would have made this difficult. At the time, there were issues with the laser cutter used by the SRL, and the laser cutters in Makerspace could not cut to the same degree of accuracy. Also, there would be a lot of post-processing with bending the laser-cut seams. Hence, due to the time limitations of the project, our team decided not to move forward with this design. An example of an origami mechanism is shown in Figure 2.

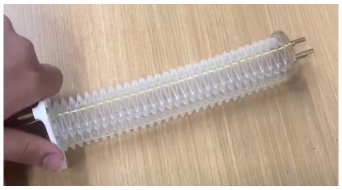


Fig. 2. Origami mechanism in the SRL

- Continuum Robot: We drew inspiration from the arm movement of octopi and elephant trunks, which allow bending movement in any direction. To replicate this movement, we considered developing a continuum robot that would be based on a semi-rigid, deformable body, similar to the one shown in Figure 3 [3]. Given the time constraints, we found that this design would be one of the easiest to implement, as the actuation could be achieved by running strings throughout the robot's continuum mechanism. However, this design might require an external covering to protect the continuum mechanism, especially in sand.

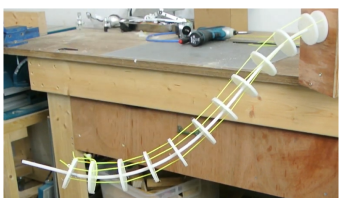


Fig. 3. Continuum mechanism [3]

- Ribbon Robot: We considered some of the designs discussed in the literature review written by Sun et al. [2], including the pneumatically actuated inchworm robot. Taking inspiration from this design, we investigated a design that would move similarly to the inchworm robot. The robot would contain a similar pneumatic actuator in the middle and two rigid segments that could rotate the body, as shown in Figure 4. The pneumatic actuator would bend the robot up or down, and the rigid segments would change pitch and yaw. Additionally, this robot would have passive wheels, which would make contact with the tube. This design would allow for a highly deformable soft section that could easily conform to the course geometry reliably. However, it might struggle in some sections, such as the sand segment, where it might not have been able to fully burrow beneath the sand.

2) Rubble: The robot would need to move past rubble inside the tube, as seen in Task 3 of the challenge. To complete this task, we came up with 2 main things to consider:

- Size of the robot: To allow the robot to easily traverse the rubble section, the maximum diameter of the robot should be smaller than cross-section of the tube minus the cross-section of the rubble. This is illustrated in Figure 5.

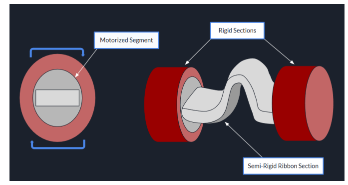


Fig. 4. Rough diagram of the ribbon robot concept.

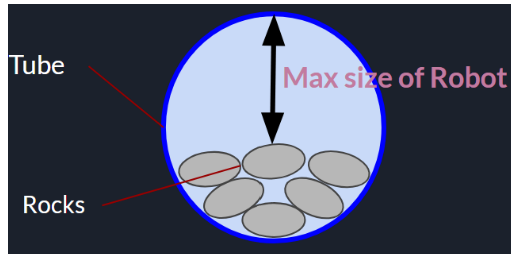


Fig. 5. Maximum possible size of the robot within the competition tube.

- The wheels would need to be compliant and/or supported by compliant mechanisms, such as springs.

3) Soft section: For the soft section referenced in Task 4 of the challenge, the tube can deform under load. To complete this task, we came up with 2 considerations:

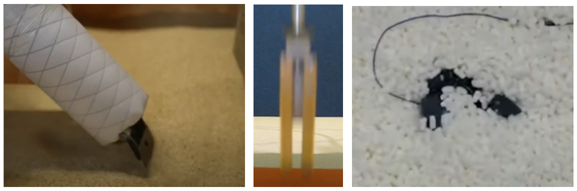
1) The robot would go slower.
2) The robot needs compliant wheels/wheel mechanisms, similar to the rubble section.

4) Sand: Task 7 of the challenge required the robot to burrow into, through, and out of a sand-filled section. The difficulty with this task is that the sand contains a lot of mass. This mass must be displaced by our movement to traverse the obstacle. Additionally, sand is known to be damaging to mechanical systems. We decided to add a conical shape to the front of the robot. This would help the robot displace sand and help break the surface. We considered using a pneumatic air pump that would blow sand under and above the robot, similar to the vine robot seen in Figure 6a. [1]. We also considered allowing the robot to vibrate for burrowing, inspired by a clam robot as seen in Figure 6b [5]. Finally, we decided to use the turning section of the robot to create a sinusoidal motion to allow the robot to dig and move through the sand, inspired by desert snakes, as seen in Figure 6c [4]. However, this does not address the issue of damage to mechanical components. We considered sealing or covering the mechanical components with silicone or some fabric to protect them from damage.

B. Main design

In the design process, we focused on making two systems: a locomotive system and a turning system, to give us control and be able to move through the pipes.

We wanted our robot to be relatively low-cost and easy to implement. Hence, we decided to use off-the-shelf parts to make this easier. To achieve simplicity, we decided to use an RC controller and receiver.



(a) (b) (c)

Fig. 6. Different methods to traverse a sandy terrain. We explored several robots including a vine robot (a), a clam robot (b), and an undulating robot (c) [1, 4, 5].

C. Fabrication and Assembly

Once a locomotion and turning method had been selected for our robot, we planned a basic continuum robot and ordered parts to build the robot. The components used to construct the robot are listed below.

- 1 x 90mm Flexible tube
- 1 x 4 channel nano receiver
- 3 x DC brushed electronic speed controller (ESC)
- 1 x RC plane transceiver
- 4 x 100mm Yellow fishing string
- 1 x 7.4V Lithium battery
- 4 x U-shaped geared N20 DC motors

The rest of the parts making up the robot were designed in SolidWorks and 3D printed in SRL using PLA, except for the wheels which were printed out of TPU.

While assembling our robot, we ran into a few issues. Most of these issues came from 3D printer imprecision at sub-millimeter scale. This was mostly caused by XY shrinkage, where pieces printed on 3D printers will shrink slightly in the X and Y axes.

This proved problematic for our gears. We want tight connections with our motor shafts and axles so that the gears would not slip. To solve this issue, we iteratively printed the inner diameter of our gear with varying sizes so that we could experimentally figure out which offset fit best with our motor shafts. We also tried different sizes with our housing to make sure the gears were meshing properly. The different sizes of gears can be seen in Figure 7.

Another difficult part of the robot to produce was the continuum mechanism. Due to the limited volume that we had to work with, it was difficult to create a mechanism that is compact and robust enough to meet our needs. We tried many different designs, including different spool width, different motor positions, and different motor orientations before we ended up with our final spool and housing assembly. The iterations of the design can be seen in Figure 8.

D. Actuation

1) Locomotion: Locomotion was performed by two sets of wheels printed of Ninjaflex TPU, totaling four wheels. Two wheels were attached to either end of the continuum mechanism. These wheels are driven by the N20 motors, and are attached to 3D printed axles with 3D printed gears connecting them to the output of the N20 motors. Throughout our design process, we experimented with different iterations as shown in Figure 3. We adjusted parameters such as the size, wall thickness, and the inner hole diameter to an appropriate fit for each. Initially, the outer diameter of the wheels was too large, so Pythagorean calculations were used to design the second set of smaller wheels. The wheels placed on the robot are therefore too small for the robot to move on a flat surface. They are specifically designed for this 5 cm diameter pipe. The test wheel and final wheel used can be seen in Figure 9.

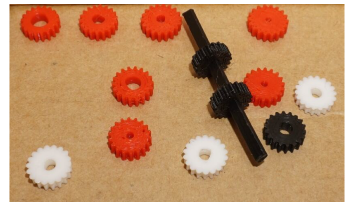


Fig. 7. Gear revisions, with successful gears mounted on axle.

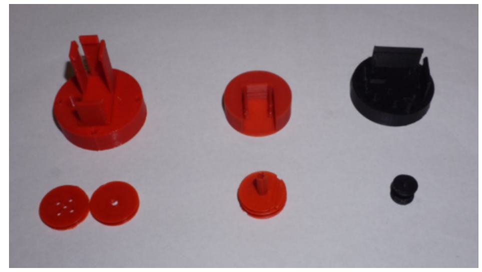


Fig. 8. Design iterations of the spool and housing assembly

2) Turning: Turning was achieved with a continuum mechanism. This continuum mechanism consisted of a semi-rigid spine made of clear surgical tubing. At regular intervals of 25mm along the surgical tubing are spaced hard disks with guide holes in them. Strings are passed through the guide holes and affixed to disks at either end of the continuum mechanism, as seen in Figure 10. By shortening the length of a string, the distance between disks is reduced, causing the spine to bend towards the part where the string is being pulled.

Throughout various iterations, it was difficult to make the continuum mechanism robust enough to withstand many cycles. The main issue was that while reversing direction after actuating to one extreme, the string on the spool would become slack and fall off the spool. The solution to this was to orient the spool perpendicular to the plane formed by the two strings.

Fig. 9. Larger wheel, and final (smaller) wheel

Fig. 10. A disk used in the continuum mechanism

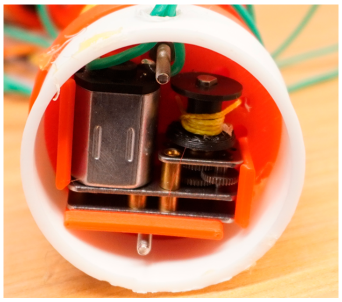


Fig. 11. Steering assembly for the continuum mechanism. A 3D printed spool attached to a N20 DC motor. The string actuates the mechanism.

This allowed the slack string that unraveled to unravel in a manner such that turning the axle further would pull the string inward towards the spool around its axis of rotation. This resolved the issue and resulted in a robust system that is able to withstand many more actuation cycles.

In order to achieve turning in all four directions, a total of two strings were used, allowing for turning in pairs: up and down, left and right. Each pair was actuated by a single N20 geared motor with a spool on the end of it. A single long string for each pair direction was wrapped around the spool and fed into the proper channel for its direction. Turning the motor would allow for a string on one side to be lengthened while the other side contracts. This allows for turning in each pair direction to occur. One turning motor assembly was placed at each end of the continuum mechanism. A complete assembly of the steering mechanism is shown in Figure 11.

3) Control: To control the robot, the nano-receiver and three electronic speed controllers were used. Therefore, three of the four channels on the nano-receiver were connected; the last channel was used to connect headers to power the receiver. The nano-receiver was paired with the Flysky remote transceiver, shown in Figure 12. This would allow us to tele-operate the robot. Therefore, we did not need to integrate and program a microcontroller. This would also give us more control over the robot, allowing us to adapt to any problems with the robot inside the tube.

The remote contains many functions, but for the control of our robot we are only concerned with two inputs: the left and right joysticks. Each of the left and right joysticks is encoded to two channels, one for the left and right motion of each joystick and one for the up and down motion of each joystick, giving us a total of four channels.

Fig. 12. The controller used to remotely operate the robot.

We wired both drive motors to a single ESC, which was connected to the up and down on the left joystick channel. The remaining two ESCs were each hooked up to a single motor responsible for controlling the continuum mechanism. They were connected to channels such that the left and right motion on the joystick would correspond with the left and right motion on the robot, and the same with the up and down direction.

Our robot was tele-operated with the remote which connected to the robot via a nano-receiver. It is untethered and powered by a single 7.4V battery.

III. RESULTS

A. Competition Results

Prior to the competition, we were able to successfully turn the robot using the continuum mechanism. However gears in the drive train skipped. Unfortunately, we were unable to test the robot in the tube before the competition. We did not account for the force the tube applied to the wheels as the robot drives. Additionally, we were unable to make the wiring compact due to time constraints, and some wires ran along the sides of the robot rather than internally. Consequently, the actual diameter of the robot was slightly larger than planned for, and the robot struggled to move through the tube. However, by performing a sinusoidal motion with the continuum mechanism, the robot was able to move slowly forward. The continuum mechanism worked successfully. Figure 15 shows robot as seen in the competition.

An unexpected result came about because of the physical properties of the course itself. The document providing the details of the competition included a 3D file was provided which shows the pipe as being smooth on the interior, as seen in Figure 13. However, the physical pipe used has ridges and holes, as seen in Figure 14. These ridges negatively impacted the performance of our robot as the sharp corner on the front of the robot would get caught on the ridges, impeding its movement.

We also measured the bend angle of the continuum mechanism. However, kinks in the spine reduced the measurable bend angle of the robot before it began buckling. To calculating the bend angle, markers were placed on the robot, and

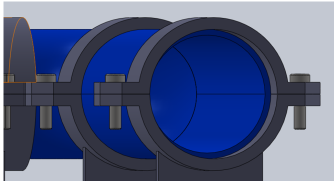


Fig. 13. CAD model of the competition pipe

Fig. 14. A bent pipe segment used in the competition

were filmed as the robot bent in all directions. The video was then imported into Physlet Tracker to determine the x and y coordinates of the trackers at the maximum bend angle in all directions. Finally, the coordinates were used to calculate the bend angle. The equations of which can be found in the Appendix. The bend angles were measured as seen in Table I.

B. Post-Competition Improvements and Results

Following the competition, there were some immediate issues that were easily resolved. While some issues like the kinks in the tubing could not be easily resolved, we found that our improvements improved its control and traction.

Most of our movement issues during the competition were due to the gear train. Due to the print quality of the gears and the flexibility of the axles. They couldn't maintain power, as they would constantly slip or the gears would skip. Power was not effectively transmitted from the motor to the wheels. In order to resolve this, we reinforced the gear mechanism,

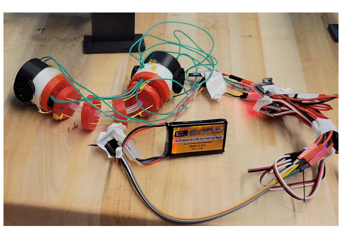


Fig. 15. Robot used during the competition

TABLE I
THE MEASURED MAXIMUM BEND ANGLE BEFORE BUCKLING

Rotation	Bend Angle
Right	143.8°
Left	18.6°
Up	28.5°
Down	83.8°

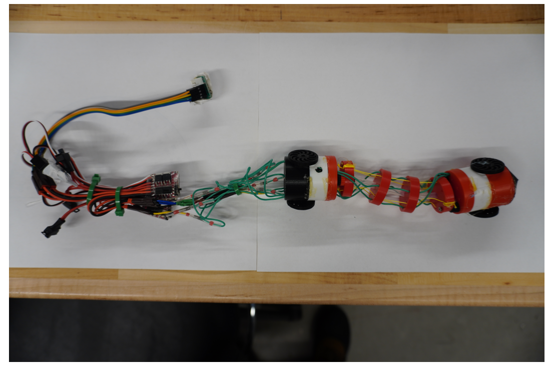


Fig. 16. Robot after improvements have been made

adding a brace to the housing so that the axle would not be able to flex away from the driver gear, causing the wheel to slip. This change allowed the wheels to maintain much higher output torques before the gears started skipping again.

Another issue we observed during the competition was that the wires were on the outside of the robot. This caused them to drag on the ridges within the tube. As mentioned earlier, this caused unwanted friction and made it much more difficult for the robot to move. To address this issue, we rerouted the wires through the robot so that they would no longer drag on the outside of the robot.

In addition to addressing these issues, we bundled up the wires at the rear end of the robot, consolidating them so that they would not spread and add more friction to the rear end of the robot. If we had more time, it would be beneficial to cut the wires properly to exactly the length needed.

Following these improvements, we tested the robot on the competition course again to see if we could get better results. Unfortunately, the robot still could not travel through the pipes, as its wheels did not make sufficient contact with the walls of the tube. However, we successfully solved the internal problems with the gear train, which was able to transmit much more power. The robot was able to better force itself more effectively into the soft section of the tube, which we had attempted previously during the competition. These results can be seen in the videos attached in the appendix.

IV. Discussion

Overall, our robot was unable to perform adequately enough for the competition. However, we corrected its largest flaws so that it could drive and turn more effectively.

In comparison to other universities, the robots from WPI were less polished. Given that most universities would receive roughly 15 weeks rather than 7 weeks to assemble a robot, we believe that our robot was satisfactory for the given timeframe. If we had more time, we would have improved the robot's overall functionality and attempted every task.

As mentioned earlier, the robot's large diameter and poor power transmission to the wheels negatively impacted its performance. While the robot was able to move via actuating the continuum mechanism, the kinks within the robot's central spine hindered its maneuverability. Our post-competition improvements addressed these issues, but the robot still had difficulty turning and driving. In future iterations, we could attempt to reduce the size of the robot and use metal gears and axles instead of 3D printed components. The increased rigidity of metal components would prevent skipping and would allow the robot to drive more effectively. To improve the robot's turning, we could have boiled the spine beforehand to remove kinks.

Additionally, efforts can be made to rearrange the robot's electronics. As seen in Figure 16, the post-competition revision runs the wires through the interior and bundles wires at the rear using zip ties. A quick improvement would be to trim the wires to size to fit within the robot chassis. Large components such as the ESCs and receiver could be replaced with a smaller custom PCB that integrates all of them.

V. Conclusion

Ultimately, the project was only partially successful. While we were able to design a robot that is theoretically capable of achieving the task, in practice, the robot still has many shortcomings that can be improved. One factor that can be improved is the size. If we had more time to implement the robot, it would have been beneficial to custom design PCBs to fit the necessary electronics on a smaller footprint. In comparison to other groups from our soft robotics class, we were able to achieve around the same level of functionality in the competition. Despite our immediate fixes to the robot drivetrain, we encountered other difficulties such as weak contact with the wheels and dragging cables. We were able to create a minimum viable product, but it needs more refinement before it can meet performance expectations. There are many areas that can be improved, but need more time to fully resolve the issues.

References

[1] Inside Science. *Robot inspired by plant roots burrows underground*. en. URL: https://www.youtube.com/watch?v=LyO8aK3lep0&t=77s.

[2] Yinan Sun et al. "Soft mobile robots: A review of soft robotic locomotion modes". en. In: *Curr Robot Rep* 2.4 (Dec. 2021), pp. 371–397. DOI: https://doi.org/10.1007/s43154-021-00070-5.

[3] Kris Temmerman. *Snake Arm / Elephant's Trunk experiment*. en. URL: https://www.youtube.com/watch?v=EUEp-AfvvzE&t=159s.

[4] The Faboratory at Yale University. *Grand challenges for burrowing soft robots*. en. URL: https://www.youtube.com/watch?v=AtW663xQLug&t=139s.

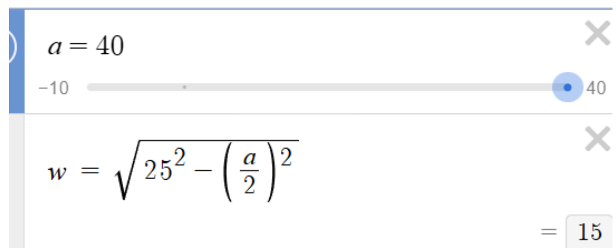
[5] Amos Winter. *RoboClam video*. en. URL: https://www.youtube.com/watch?v=bztw9PUiRss.

Appendix

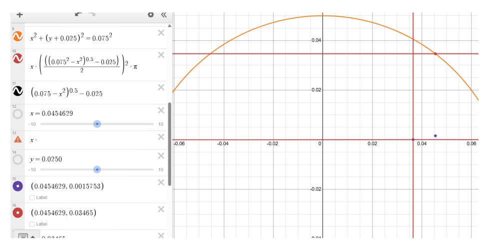
A. Bend Angle Calculations

```
x = 16.33; % Units: mm
y = 64.26; % Units: mm

alpha = acos(x / sqrt((x .^ 2) + (y .^ 2))); % Units: rad

theta_in_rad = 2 * ((pi/2) - alpha); % Units: rad
theta_in_deg = theta_in_rad * (180 / pi); % Units: deg

radius = ((x .^ 2) + (y .^ 2)) / (2 * x); % Units: mm

length = theta_in_rad * radius; % Units: mm
```

B. Wheel Diameter and Shaft Length Calculation



C. Rigid Section Geometry Optimization Calculation



D. Additional Videos and Photos

Additional media, including videos of the robot's performance before and after the competition can be found here: https://photos.app.goo.gl/GDyyf3mQK1MYAyiJ8