3D-Printed Soft/Semi-Rigid Robotics

RBE 530 Group Project Report

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***Abstract*— Consumer FDM printers offer users the ability to design soft robotics components. Current printable designs use flexible materials, which are costly, and more difficult to implement for novices. This paper presents a cross examination between stiff material based compliant mechanisms and typically used materials.**

***Index Terms*—3D-printing, hex bot, compliance, soft robotics**

I. Introduction

A. Background

Within the soft robotics field, 3-dimensional (3D) printing allows for the construction of compliant and soft mechanisms, whether the technology is used for creating molds for silicone or making components of a robot. [1] Inspired by the Onal et al origami inspired printed robot, the team 3D printed a similarly designed robot with improved linear forward motion by introducing compliant legs that handle uneven terrain. The team used fused deposition modeling (FDM) printing to fabricate the design. Taking into account various loads on the robot, they considered varying materials to adjust the compliant leg's stiffness.

Many papers consider building compliance in their design as a means to build origami shapes and patterns. One such example is the origami inspired printed robot project, using established origami structures to be able to fold and make modules. For this work, modules are separated into a body and legs, and created by laser cutting slots in PET sheets. These laser sliced slots provided points where folding can take place passively. When the robot is actuated by motors, linear local motion is achieved [2]. Faal et al. used similar techniques for their project in the analysis of hierarchical kinematic designs for foldable hexapedal locomotion platforms [3]. The separation of modules into the body and leg can be seen here and applied to the team's design.

Designs that incorporate 3D printing and origami inspiration tend to consider the use of multi-material printers, such as a case of the Origami Inspired Twist Tower [4] or bridging techniques seen in 3DP-Ori [5]. The twist tower helps to highlight how stable connections between the rigid and flexible structures were maintained, and the justification for material usage in the structure [4]. Although the design achieves the desired effect, it would require a printer not accessible to the team or to the majority of consumers.

B. Material Analysis

Considering other materials, thermoPlastic Polyurethane (TPU) is a great filament to get a more durable and elastic material. TPU is a flexible rubber material that comes in various hardness. One of the pros to this material is you are able to print items that can flex or deform while maintaining its shape. This material is also great in shock absorbing and has been used in sneaker insoles and even helmet inserts thanks to its vibration dampening properties.

However, TPU can have difficulties on entry level printers due to its compliant properties. Printers can have a hard time extruding TPU, causing the filament to bunch up and cause the print to fail. TPU struggles in bridging due to it drooping even after it is cooled, making it not suitable for most overhangs. And due to its slow extrusion, retraction setting must be turned down causing stringing issues when traveling through empty space. Our paper contributes the work above by:

- Parameterizing the compliant legs
- Quantification and Simulation of Compliant Leg Properties
- Qualification of the use of stiff materials for Compliant Leg Design
- Qualification of compliant legs in use for handling uneven terrain

In the next section, we present the approach for the design and parameterization of the leg designs, and the body used to test the legs. Additionally, the facets and connecting modules will be discussed. In the results and discussion section, solidworks simulation of stress and displacement of the leg design is given, with variance in materials used. The data verifies the expected forces the compliant mechanism should experience. The physical test demonstrates the legs' usage in uneven terrain. The section provides the forces needed to fully deform the compliant legs, along with the resulting deformation due to use.

II. Approach and Methods

A. Leg Design

The central facet of the leg design was that we wanted to get linear locomotion out of a circular drive path. Traditional walking linkages often use complicated mechanisms that require substantial design to create a linear path approximation. By introducing just one degree of compliance, the design of the gait can be simplified immensely. The spider-bot legs have flexible knees where they mount to the frame of the robot that provide a range of motion with a hard stop at the top. This creates a fixed vertical travel distance for the foot that should match with half of the vertical travel leg. Since the bottom half

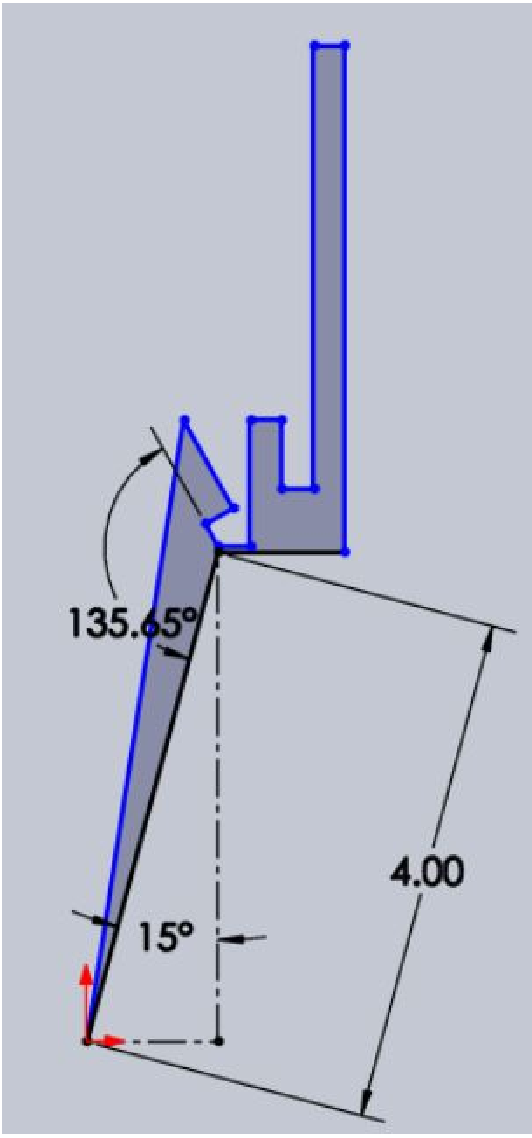

Fig. 1: The leg parameters for flexible leg design

of the circle is the portion where the foot is being dragged in the correct direction, that is the only portion of the motion where the robot wants to make contact with the ground.

The design of the legs and the drive mechanism is based on three parameters: leg length(L), initial angle (θ) , and desired vertical travel(d). First thing to look at is will the base of the frame contact with the ground at the full range of motion. Since the frame sits slightly below the leg connections, the vertical travel needs to be about an inch less than the height the frame sits at unflexed. The next consideration is what the final angle (ϕ) needs to be to accommodate the vertical travel. The initial height is L * cos (θ), and the final height is L*cos(ϕ) and therefore Lcos(θ)-Lcos(ϕ)=d. This gives ϕ = cos-1 [(d-Lcos(θ) / -L]. The last consideration is how to create the final angle and that is the angle of the hard stop at the top of the knee. This is fairly straightforward as the base frame has a vertical wall to collide with so the sum of phi and your upper knee angle simply needs to be 180. If for any reason a different stop angle is desired, then those two angles simply need to sum to your stop angle. For example, Fig. 1 has a θ of 15, a ϕ of 135, an L of 4 inches, and a d of 1 inch.

B. Body Design

In order to test the legs, the team needed to design a test platform. They decided on an 8-legged body that uses circular motion in the center legs to move the body. The four outside legs are statically mounted to the body to provide stability. The inner four legs are mounted to a 4-bar linkage to provide the circular motion that moves the body forward. The full assembly is shown in Figure 2 below.

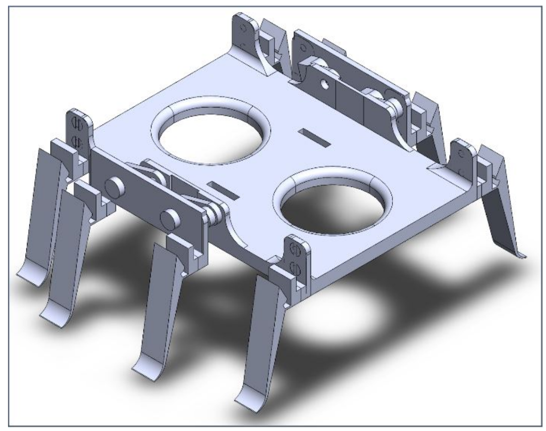

Fig. 2: The full robot body CAD Model.

The circular motion is created using a 4-bar linkage. This allows the two inside legs to travel together and remain upright. The side links are a length of 1” and pivot at the same height as the stationary legs. This means that when the side lengths are parallel to the ground, all the legs are at the same height. When the side links are extended downward, the inner legs are 1” below the stationary legs, which lifts the robot up and pushes it forward. The inner legs contact the ground for the bottom 180° of their path.

Since an objective of this project is to make the robot fully 3D printed, a number of design and printing techniques were used to assemble the robot. The legs are attached to the body and the 4-bar using a slot design, where the legs slip onto the extruded element and hold their position there. The female end of the slot is on the leg, and the male end is on the body and 4-bar. The dimensions are standard across all the different material legs so that they can be easily swapped out for testing. This feature is shown in Figure 3 below.

The rotational elements, or the 4-bar linkage, were attached together using a pinch-bearing, which allowed for the pieces to snap together.

However, the team found that these pinch bearings were difficult to snap together, broke easily, and created a lot of slop in the linkage, so the team switched to a shaft and shaft collar design. The linkage pieces were redesigned to replace the pinch bearing with shafts that the other links can rotate on

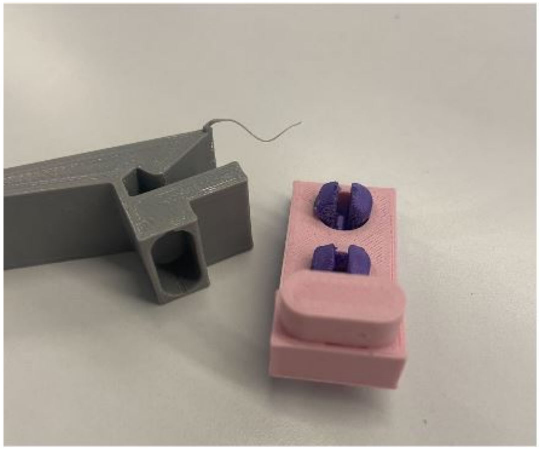

Fig. 3: The slot design used to attach the legs to the robot.

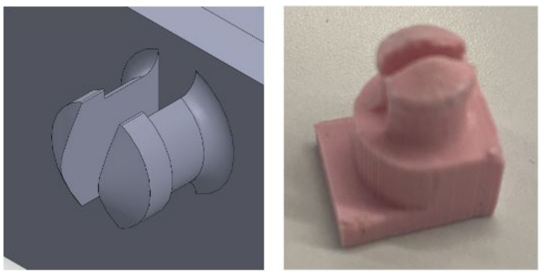

Fig. 4: An example of a pitch bearing used for attaching the four bar linkage.

(Figure 5). To keep the linkage together, the team designed and 3D printed TPU caps, which grip on to the end of the shaft (Figure 6). The compliance of the caps allows them to stretch around the shaft and grip onto it.

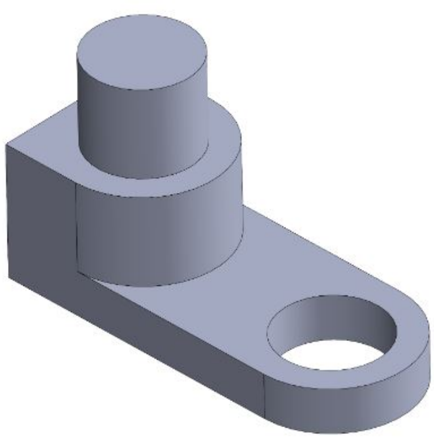

Fig. 5: The design of the new linkage piece, which has a pin instead of a pinch bearing.

C. Printer Constraints/Parameters

When establishing the filaments that the team would be testing, they had to think about what their printers could work

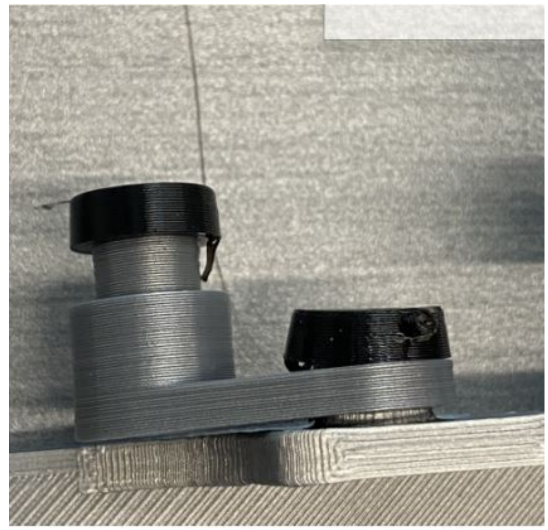

Fig. 6: 3D printed TPU caps to keep the linkage pieces together.

with. There are 3D printers out there that can print very soft materials, but entry level printers will struggle more as you venture away from more rigid materials. Printers like an Ender 3 or Prusa, who utilize bowden tube printing, tend to run into issues when getting to softer materials like NinjaFlex 85A. This following section will talk about some easy tips and parameters to help print these types of filament.

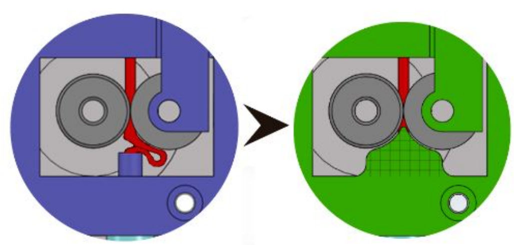

Fig. 7: Common issue with stock extruder gear mount (Left). Can be mitigated with an aftermarket one that accounts for the negative space (Right). [6]

One of the biggest issues with softer filaments can be seen in Figure 7. This is caused when the filament buckles within the gap between the gears and the pathway of the filament. Once this issue starts, the print has failed and will not correct itself. The easiest preventative action for this issue is to change the retraction on the slicer to 0. This will stop the printer from retracting the filament when traveling the empty space. The downfall is this causes extensive stringing in the print. Another solution to this problem would be getting a better base for the extruder gears, which can be done by purchasing one or 3D printing one from preexisting STL files. This will get rid of the gap as seen in Figure 7 (Right). Additionally, depending on the printer, switching the stock bowden tube out for a more uniformed and precise one, like the Capricorn tube, is another inexpensive preventative action to aid in printing softer materials as it reduces the friction.

When switching filaments of various properties, it is paramount to adjust the e-steps (extruder transmission ratio). Different filaments get pulled in the gears differently. A softer material tends to stretch making the amount extruded much less than if it was more rigid, like PLA. Online calculators will help aid in this process. If your printer does not allow this, you can adjust the flow rate in most slicers to account for under extruding.

The following table displays the print parameters we used to successfully print each material without an issue.

Material	Print Speed (mm/s)	Print Temp.(°C)	Bed Temp.(°C)	Retraction (mm)	Print Time (min)
PLA	55	202	50	6.5	40
98 A	30	235	50	2.5	47
95 A	30	240	50	2.5	47
85 A	25	240	55	0	52

Fig. 8: Print parameters used on the different filaments

III. Results and Discussion

A. Leg Materials

For testing the leg materials, the team utilized a few different brands of filament. For PLA, the team used Hatchbox PLA, which retails for approximately $24 per kilogram. The TPU 98A was from Flexfill by filllamentum, which retails for $82 per kilogram. For both the TPU 95A and 85A, the team used Ninjatek brand filament. TPU 98A is their cheetah line, and TPU 85A is Ninjaflex, both retail for $85 per kilogram. Each leg used about 5 grams per print, below is the cost per print:

Material	Cost per Print
PLA	$0.12
TPU 98A	$0.41
TPU 95A	$0.425
TPU 85A	$0.425

Fig. 9: Comparing the costs of the materials used in each leg print.

B. SolidWorks Simulations

To test the differences in the materials, the team did a SolidWorks Simulation for the legs. The simulation was conducted by applying a 100 N/m^2 pressure to the bottom of each leg (the curved portion) in an upwards direction. First,

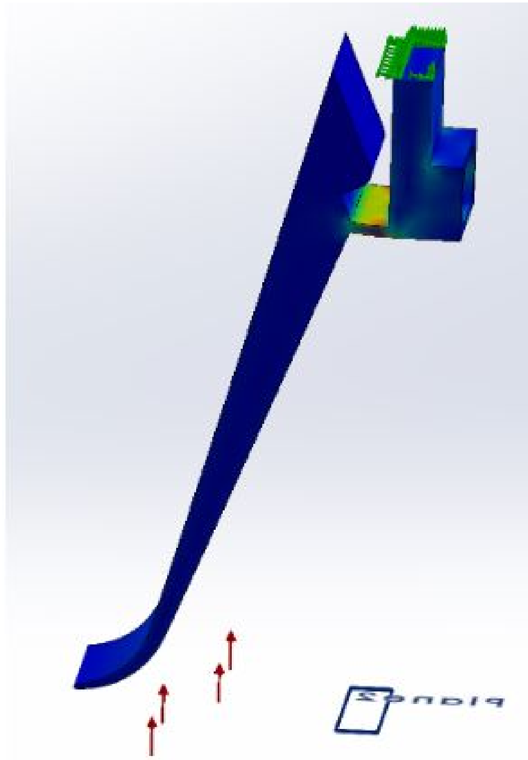

Fig. 10: Strain analysis of the leg shows most of the strain is in the knee bend.

the simulation showed that the majority of the strain was concentrated in the knee bend, shown in Figure 10.

The team then looked at the displacement of the leg for each material. Figure 11 shows that a majority of the displacement happens at the tip of the leg (where it is red) and there is little displacement at the top of the leg (where it is blue). The results in Figure 11 show that as the materials become more compliant, the displacement increases. More specifically, the displacement of the TPU 98A leg is more than 10 times greater than the displacement of the PLA leg, meaning the team will see a large difference in the performance of the two legs.

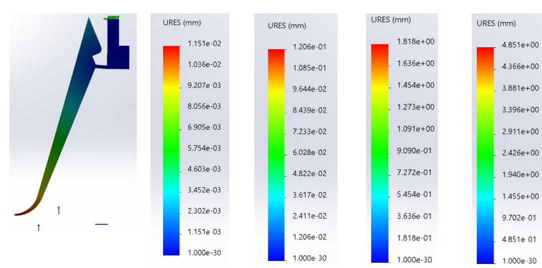

Fig. 11: The displacement of the leg when 100N/m^2 of pressure is applied on the foot. Materials shown from left to right: PLA, TPU 98A, TPU 95A, TPU 85A.

C. Physical Tests

The physical test consisted of three main experiments. The first test was a terrain conformability test, which was less of an individual material comparison test and more of a test on the basic concept of the leg design created. Second, was a force test, where the team analyzed the amount of force needed to actuate each leg fully. Finally, a durability test consisted of repeated actuation for approximately the same time per leg.

Terrain Test

The terrain test, shown in Figure 12 below, was proven to be successful. The compliance of the leg design allowed all the legs to remain in contact with the ground or raised surface.

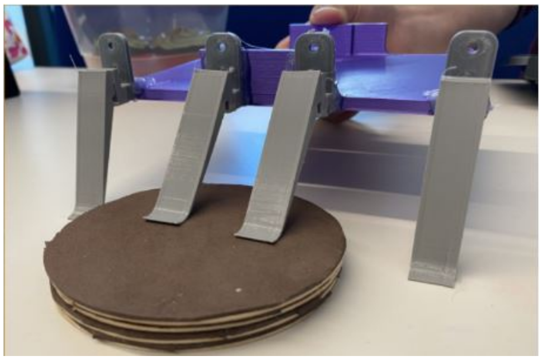

Fig. 12: This shows the conformability of the leg design, which allows for four legs to be in contact with the ground, stabilizing the design by acting as a suspension.

Force Test

The results of the force test can be seen in Figure 13, with PLA taking 210 g, TPU 98A taking 50 g, 95A taking 18 g, and finally 85A taking 5 g to fully actuate.

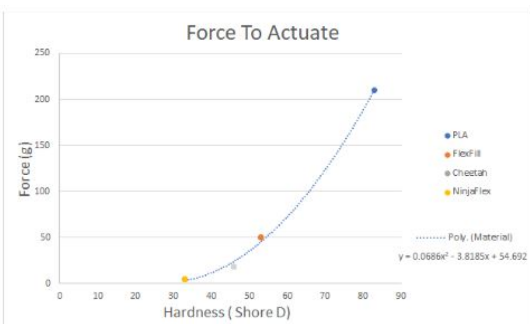

Fig. 13: The plot of the force compared to hardness in the Shore D scale.

Durability Test

Out of all the materials tested, PLA retained a bend which was about 40% reduction of its full actuation distance. The bigger issue is the plastic deformation seen in Figure 14. It is clear that a PLA leg is stronger, but its lack of elasticity properties will soon cause a failure when used in a compliant mechanism.

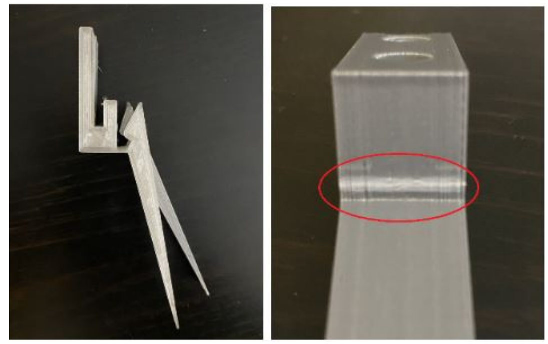

Fig. 14: (Left)The retained bend of the PLA leg (Back) and 98A (Front). The plastic deformation and visual deterioration of the PLA at its bend (Right).

IV. Conclusion and Future Work

A. Summary of Results

This paper highlights how a robot can be created at the consumer level with the use of 3D-printing. With the exception of the motor, the team was able to create not just a simple robot, but a partially suspended walking robot. With some iteration, this highlights that beginner printing techniques can create a robot capable of conquering complex terrain and keeping potential payloads stable. Advances in printing technology and the accessibility of soft materials make the use of this or similar work trivial in terms of skill. The hope is that this work could be implemented in environments of difficult terrain for minimum cost, such as remote search and rescue or in education on compliance and soft robotics.

With the results found in the experiments conducted, it can be concluded that the spider-bot platform is successful at uneven traversal or supporting additional payloads for even traversal. For most practical purposes, the PLA is too fragile and brittle to be used in flexible capacity, but could be used on mostly flat terrain where some slight suspension is needed to prevent catastrophic failures. On the other end, extremely flexible materials like Ninjaflex do not have enough support to practically operate under heavy loads without compromising the inherent shape and structure of the legs. The most reasonable operating range comes from the harder elastic materials from 95-98A Shore hardness. They provide the rigid structure in the thicker parts of the component while preventing the plastic deformation that PLA suffers from. Each material has potential uses but as far as widespread practicality the harder TPU is the most realistic.

B. Future Work

Future work for this project has a few avenues of approach. One step would be to get the robot to move on its own using motors. Another addition would be to replace the 4-bar linkage with a compliant mechanism for the motion of the legs, more similar to the ant-bug the team was inspired by. Once the robot is capable of teleoperation, the team would like to start exploring the route of 3D printing sensors utilizing Ninjatek's conductive filament eel.

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