Manufacturing the Tik-Tok/LegZ Foot and Shoe

Brian Lui
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Contact: Bl569@cornell.edu
Cornell Mechanical Engineering Undergraduate, Class of 2019
For all files and models, please contact the Author

Other group members: Ethan Kramer and MengYun (David) Shi

ABSTRACT

This report reviews the prototyping and manufacturing process of a carbon fiber foot and foam shoe for the Tik-Tok and LegZ robot. It builds upon the work done by Diana Chu, Ethan Kramer, and David Shi in the Spring 2017 semester and the foot had to be additionally designed and manufactured to allow for two printed PCB and pressure sensors to be placed inside the foot. This was done by making the foot in two parts using two 3D printed outer molds.

INTRODUCTION

The Tik-Tok robot is an open-source biped robot that aims to safe, robust and cheap. It is to have a Cost of Transport (the energy used per unit weight and distance) of 0.25. This is comparable to humans and is done by using high-efficiency chain drives and powerful brushless motors.[1] Tik-Tok is 1.5 m tall, weighs 30 kg, has 12 actuated joints, has a peak joint power of 2 kW, and is expected to be able to walk about 15 km on a single charge of its 300 W-hr 2 kg battery. The LegZ is a robot that has similar robustness as the Tik-Tok robot but with a target manufacturing cost fifty times cheaper, extrapolated to around $2,000 in mass production quantities compared to $12,400 for the Tik-Tok.[1]

Work on the robot foot was started by Ethan Kramer, David Shi, and Diana Chu in Spring 2017. The foot was designed using a Function, Constraint, Objective (FCO) model.[2]

- Function: To allow the robot to walk or run over various terrains while maintaining functionality of the robot.
- Constraint: Attach to given ankle geometry and withstand loads of a robot stepping on a rock. Provide a large, flat surface area for a 60 by 40 mm PCB. Provide a curved bottom surface of the foot to allow for smooth gait. Additionally, allow room for sensors along the bottom, back and front of the foot to detect foot placement. The foot must be able to be manufactured using available methods at Cornell University at this time.
- Objective: Minimize mass, provide a factor of safety in yield of at least 3.

Figure 1: Version 3.8 of the foot. This was the final design from the previous semester and the starting design the Author began working with.

Under these constraints, the final design from the Spring 2017 semester is the foot design in Figure 1. These constraints were constantly changing and reevaluated after each design iteration.

The work from the Spring 2017 semester helped decrease the amount of troubleshooting required. Wet carbon fiber was determined to be superior to prepreg carbon fiber for this application.[2] The primary difference between the two is that wet carbon fiber requires manual application of epoxy. After determining the material for the foot, manufacturing the foot could have been done in one of two ways—doing a layup around a core or to do a layup inside a mold.[2] The efforts in the Spring 2017 focused their efforts on doing a layup around a core with relative success. Although they were able to create a foot with most of the geometry of the foot intact, this manufacturing method made it difficult to put pressure sensors and PCBs into the foot. Constructing the foot such that sensors and PCBs could be put into the foot was the focus of this semester's project.

With David Shi and Jason Cortell's suggestion, the Author primarily pursued manufacturing the foot using the other method in order to overcome this difficulty. The Author made over ten models of the foot with varying degrees of success. This report focuses on refining the process of using a mold to do carbon fiber layups of the foot.

METHODS

Design

Foot Mold Design

Work on the mold of the foot was primarily done by the Author. Differing from the earlier mold work of Ethan Kramer, David Shi, and Diana Chu, the foot was created through an outer mold instead of an inner one. This allowed for the foot to be hollow and therefore have the space for pressure sensors and PCBs to be placed within the foot. The main considerations while designing the mold were to accurately capture the unique curves and features of the foot as well as minimize the material used to make the 3D printed mold.

In order to create a hollow foot, two halves of the foot need to be created and then combined using epoxy. The two halves were designed such that one piece of the foot fits completely inside the other, similar to a smaller box fitting inside a larger box. As such, they are referred to as the outer mold and the inner mold. The Author decided to split the two pieces of the foot into a left half and a right half; the overlapping region would occur at the top and bottom of the foot. This would put more layers of carbon fiber at the Achilles and ankle hole region, making the most failure prone region stronger. Because the foot was to be put together this way, the Author’s first design of the molds maximized the overlap region between the two halves of the foot in order to have a tighter bond between the two foot halves. Doing so would also reduce the unevenness at the boundary between the two pieces at the bottom of the foot. This can be seen in Figures 1 and 2.

Figure 1a. Inner mold made from the foot v3.8.

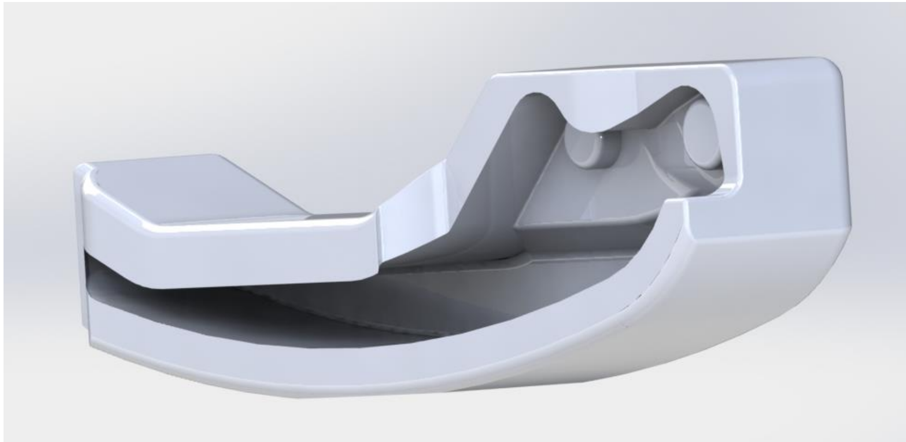

Figure 1b. Inner mold made from the foot v3.8.

Figure 2a. Outer mold made from the foot v3.8.

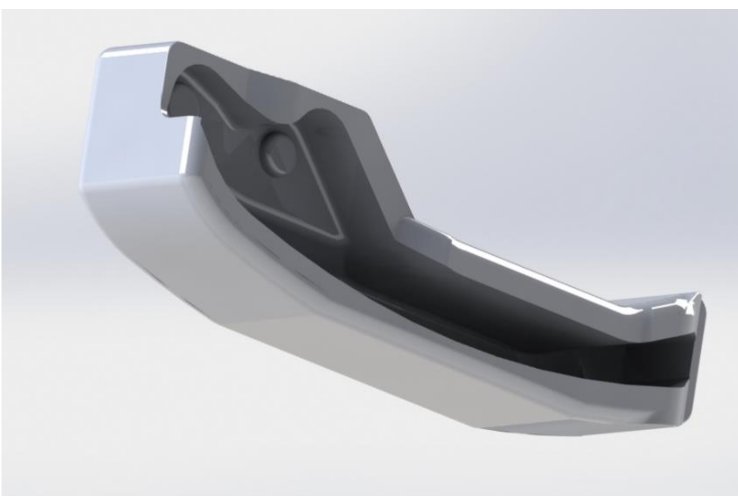

Figure 2b. Outer mold made from the foot v3.8.

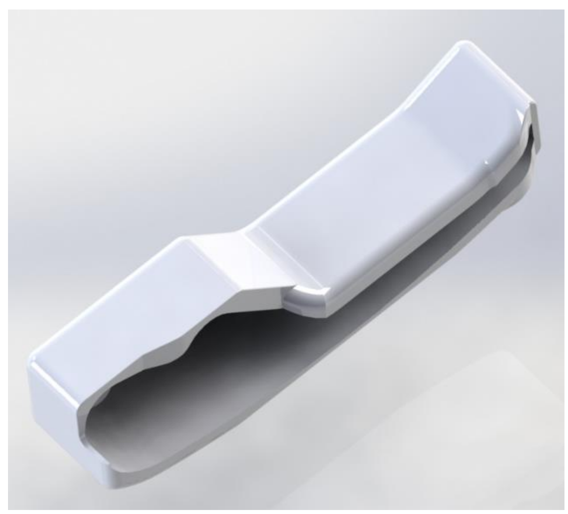

Figure 2c. Outer mold made from the foot v3.8.

The author added extrusions where the ankle and Achilles holes would be in the foot. This made manufacturing the holes easier because the carbon fiber could be wrapped around the extrusions, leaving a natural hole when the foot is removed from the mold. If the extrusions were not created, then the ankle and Achilles holes would need to be estimated and drilled using a hand drill. This would make it hard to align the holes on both side of the foot. The Author also added fillets to every edge to avoid puncturing the vacuum bag during manufacturing.

Each half of the foot will only be 2 layers of carbon fiber. The two molds overlap fully on the top and bottom of the foot, giving it 4 layers of carbon fiber on the top and bottom of the foot and 2 layers of carbon fiber on the sides of the foot. Although this is less than the 5 layers originally designed by Ethan Kramer, this version of the foot would also have a foam core in it. The foam core adds 18 grams of mass to the foot but would a greatly increase the strength of the foot. A better manufacturing practice should also improve some of the weaknesses in the previous prototype.

To create the CAD of these molds, the Split feature in Solidworks was used in XY, YZ, and XZ planes to cut and reassemble the parts of the mold desired. After each split, the Combine feature was used to piece together the relevant parts of the desired final mold. Although somewhat time intensive and must be redone from scratch if the design of the foot changes, this was seen by the Author to be the best way to reliably capture the unique geometry of the robot foot.

After a few layups using the two molds, the design of the inner mold was changed to that of Figure 3a and 3b. In order to give more space for the pressure sensors and PCB board to fit inside the foot, the bottom face of the foot was decreased so that the overlap region on the bottom face is only 5.5 mm. This distance was chosen such that it would not interfere with the two rows of pressure sensors that would be placed in the foot. Although decreasing the overlap region may weaken the bond between the two pieces of the foot, it did however improve some of the manufacturing issues (mentioned below) that the first two molds had. Doing so also made it easier to drill holes into the foot because holes would only need to be drilled into the larger of the two feet pieces; there was not a need to align the holes in the two pieces of the foot.

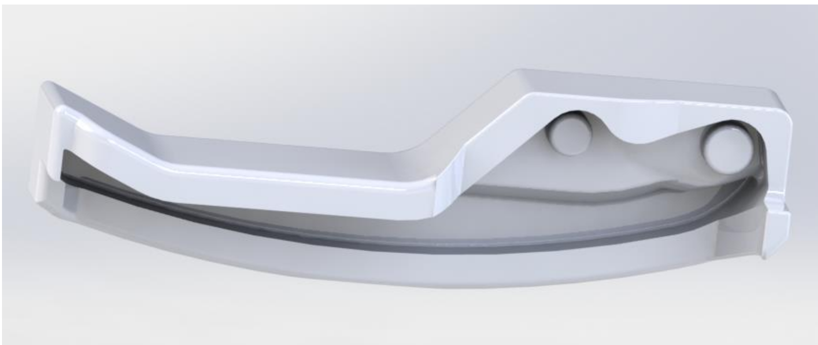

Figure 3a. Inner mold version 2 made from the foot v3.8.

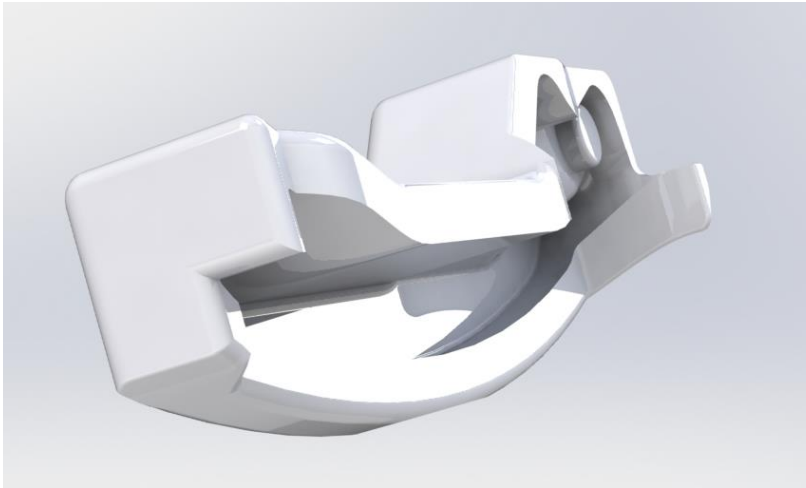

Figure 3b. Inner mold v2 made from the foot v3.8.

The foot design was changed, prompting the need to create new molds of the foot. The foot design changes are described below and were prompted by a desire to increase the strength around the Achilles and ankle holes. Ethan Kramer also increased the fillets and the space in the front of the foot to allow for better manufacturability of the foot. The process of creating the CAD of these two halves of the molds for this foot was the same as previously described. The current molds being used can be seen in Figure 4 and 5.

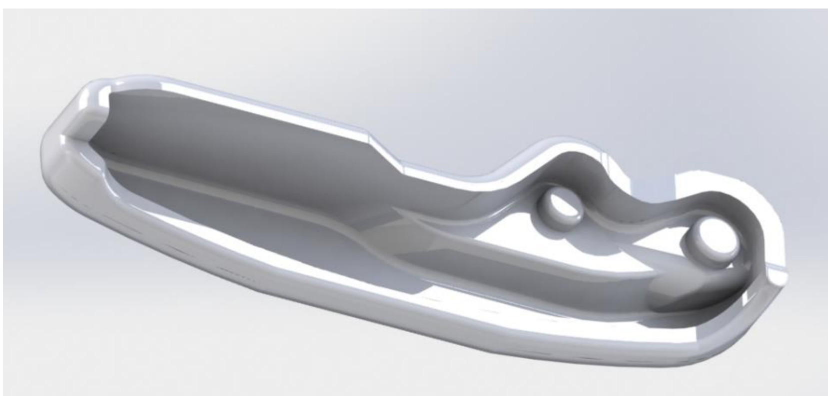

Figure 4a. Inner mold made from the foot v3.11.

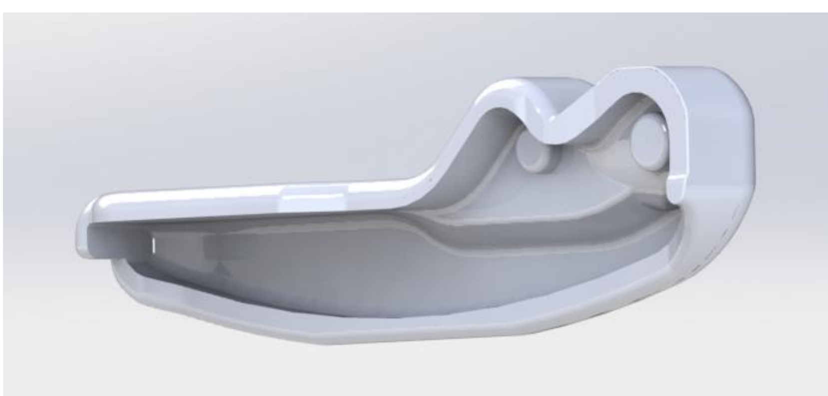

Figure 4b. Inner mold made from the foot v3.11.

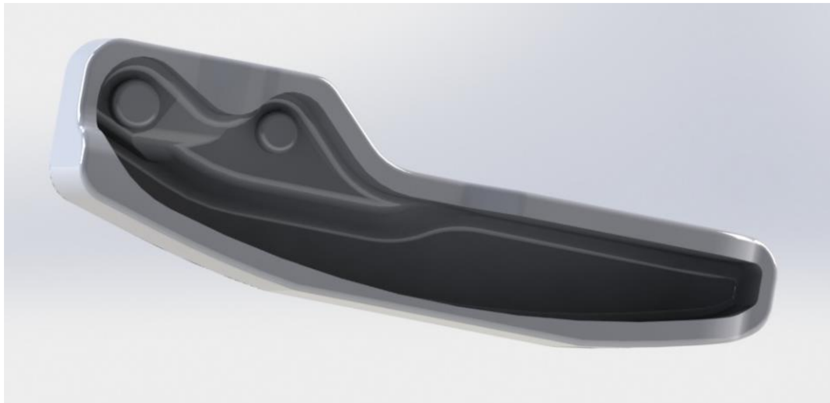

Figure 5. Outer mold made from the foot v3.11

Foot Design

Work on the design of the foot was primarily done by Ethan Kramer. After a few layups were done using the foot design in Figure 1, a few design changes were necessary to better satisfy the constraints of the design. Doing so also inadvertently improved the manufacturability of the foot. The current design of the foot can be seen in Figure 6.

The foot was modified to have a larger distance from the top of the foot to the Achilles hole. Doing so increases the strength of the foot at that point because that is the point that broke during the stress test done in the previous semester.[3] There is also more room in the front of the foot to more easily place the PCB into the foot. Larger fillets were also added on the corners of the foot. All of these changes increased the space within the mold, allowing for greater ease of entry of fingers for doing a layup. A top view of these design changes can be seen in Figure 7.

Figure 6. Version 3.11 of the foot. There is increased space in the front of the foot for the PCB. There is an increased thickness from the Achilles hole to the top of the foot. There are larger fillets in the front and back corners of the foot.

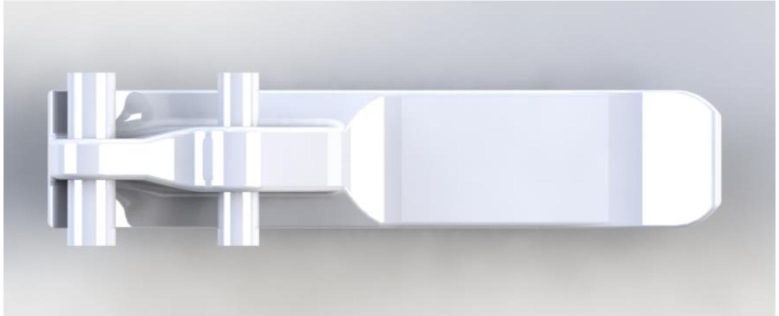

Figure 7a. Top view of foot version 3.8. The extrusions at the ankle and Achilles holes are shown. They are used to help create the 3D molds.

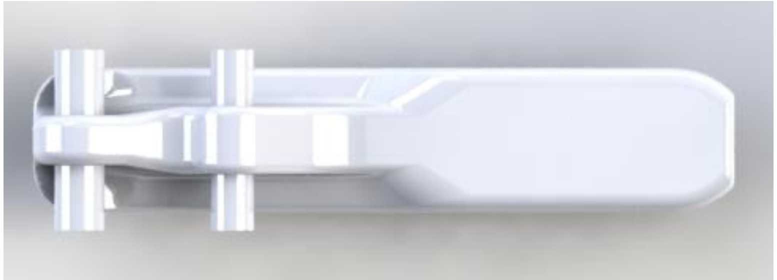

Figure 7b. Top view of foot version 3.11. The extrusions at the ankle and Achilles holes are shown. They are used to help create the 3D molds.

Hole Cutting Jig

The hollow foot needs to have holes in it for the pressure sensors to stick out the bottom of the foot. To do this, the Author initially tried to introduce the holes during the layup process by introducing it in the mold. This can be seen in Fig 8. However, due to concern about whether the foot could be removed from the mold without being damaged, this idea was not pursued. Instead, a jig was created to facilitate cutting holes into a foot half. This jig would be used after the outer mold was created. The extrusions on the jig mark where holes need to be cut out of the jig, and then the jig will be used to drill holes into the outer mold. The circular extrusions in the jig was decided such that the pressure sensors would be equidistant from the sides of the foot and each other.

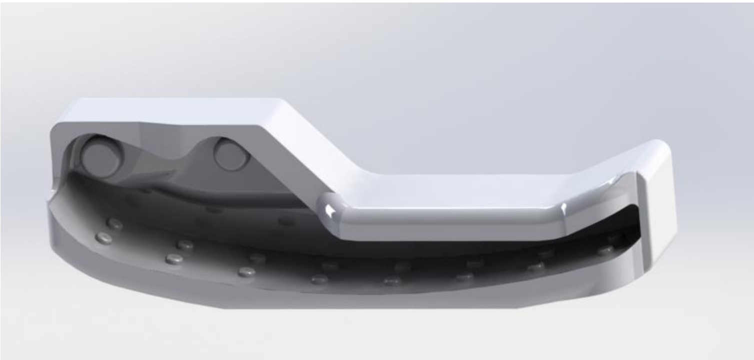

Figure 8a. Attempt to create a version of the foot piece that would have holes in the bottom of the foot.

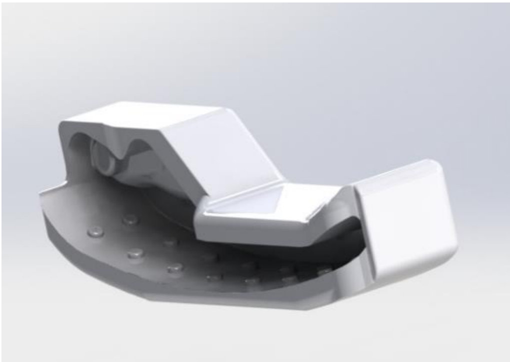

Figure 8b. Attempt to create a version of the foot piece that would have holes in the bottom of the foot.

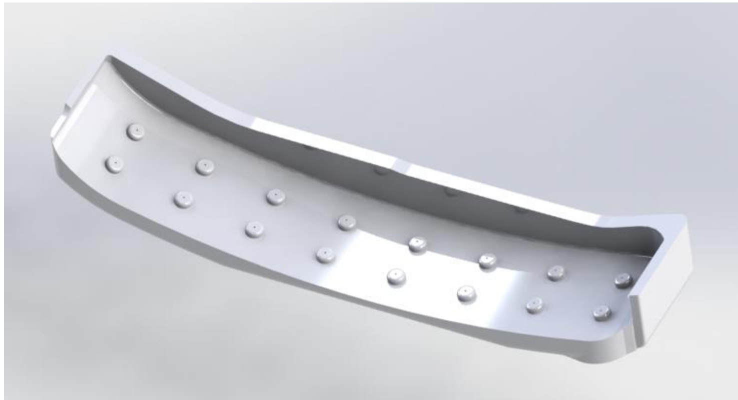

Figure 9. Jig used to create the holes for the pressure sensors in the outer mold.

Manufacturing

1. Applying the Mold Release Film

Materials

- #1016 Partall Paste #2 (rexco-usa)
  - $12.25 for 24oz tin from Fibre Glast
- Fibre Glast #13 PVA Release Film
  - $10.75 for 1 quart

Three layers of the Partall Paste was applied to each mold with less than 5 minutes between each application.[4] This is most effectively done by wearing a glove and applying the wax on the mold as if you are applying lotion to skin. Then three coats of the PVA Release Film was applied, with 15 and 30 minutes between the coats.[5] The PVA Release Film must dry before a layup can be attempted, otherwise, the mold release will not adhere to the mold well. Although the data sheet says that this should happen in 45 minutes, the Author found it required a little longer than 45 minutes to dry completely. After the mold release has dried, the color of the mold changes into a visible shade of green as can be seen in Figure 10.

Figure 10. The molds after the mold release is applied. The mold release turns the initially white mold into a greenish color. This color change is less apparent if the mold is not white to begin with.

2. Doing a Carbon Fiber Layup

Materials

- 1069-A 3K, 2x2 Twill Weave Carbon Fiber Fabric
  - Cost: $55.95 for 1 yard roll from Fibre Glast
- Low Temperature Release film
  - This is the boundary between the carbon fiber and the breather material. Allows for easy removal of vacuum bagging material.
  - Cost: $19.95 for a 3 yard package
- Breather and Bleeder Cloth
  - This cloth allows for vacuum pressure to be applied evenly across the entire surface of the laminate, permits any gases released during cure to escape, and absorb excess resin applied during the lay-up process.
  - Cost: $16.95 for a 4 oz, 3 yard roll
- Stretchlon ® 200 Bagging Film
  - Vacuum bag. Good for use up to 250°F.
  - Cost: $13.95 for a 3 yard roll
- Fibre Glast 2000 Epoxy Resin.
  - This is used to harden the carbon fiber into the desired foot shape. Room temperature epoxy.
  - Cost: 44.95 for a quart (2 lbs)
- Fibre Glast 2060 60 Minute Epoxy Cure
  - This is used to harden the carbon fiber into the desired foot shape.

    - Cost: $21.95 for a ½ pint
- Yellow Sealant Tape
    - This is used to create an airtight seal for the vacuum bag process
    - Cost: $7.95 for a single roll
- Double sided tape
    - This is used to help improve the shape of the foot.
- Two hollow cylindrical rods with diameters similar to the Achilles and ankle hole (12 and 14 mm).
    - This is to help improve the shape of the foot around the two holes.
- Long blunt rods with as small of a diameter
    - This is to help improve the shape of the foot at tight corners.

The carbon fiber layup process is not unique to this application. Therefore, although the steps of doing the layup is discussed, most of the discussion will focus on the issues encountered and tips to prevent them from occurring.

3. Preparing the Material

The carbon fiber, release film, breather material, and vacuum bag must be cut from the large roll it comes in. Two pieces of carbon fiber should be cut from the roll, large enough to cover the mold easily even after accounting for the depth of the mold. Masking tape should be used to prevent fraying at the ends of the carbon fiber, as can be seen in Figure 16. The same applies for the release film and breather material. The vacuum bag should be large enough that it can be folded in half and still comfortably cover the mold. The carbon fiber, release film, and breather layers should be close in size, and the vacuum bag should be a little more than twice the size of the other material. If unsure about size of the material to cut, err on the side of larger.

The epoxy and epoxy cure should be poured into two separate plastic cups. There should be 100 parts of the epoxy to 27 parts of the epoxy cure by weight after taking into account the weight of the plastic cups.[6]

4. Preparing the First Layer

There were some common issues that occurred:

- Because of the depth of the mold, the carbon fiber had issues conforming to the tight corners. This resulted in sparse carbon fiber in those regions, or a foot created that has regions of only epoxy. This can be seen in Figure 11 and 12.
- The narrow width at the front of the molds based on foot v3.8 were often troublesome to get the carbon fiber into. This increased the occurrence of sparse regions of carbon fiber.
- The region around the ankle and Achilles hole often came loose and could not keep the shape of the hole.

Both pieces of the foot needs two layers of carbon fiber on it. Below are some suggestions to have a good layup of the first layer.

- Do things carefully, and only once. Once the carbon fiber strands are shifted, it is hard to return it to its original shape. If a hole appears in the middle of the carbon fiber sheet, trying to remove the hole will more often than not make it worse than better.

- Do not use sharp objects to adjust the carbon fiber into tight corners. Sharp pointy objects tend to separate the carbon fiber instead of pushing the fiber into the corner. Use long, thin, and blunt instruments to get the carbon fiber into such spaces. In order to get a better shape around the ankle and Achilles hole, hollow rods with diameters similar to the holes were used. The tools used by the Author to do this are in Figure 14.
- Double sided tape should be used to hold the first layer of carbon fiber in place as seen in Figure 11. Enough double sided tape was used so that the carbon fiber would not shift in place much when disturbed. Although time intensive, it makes future steps easier, especially when the layup is done by one person.
    - Theoretically, tape does not need to be used because the vacuum bag step should cause the carbon fiber to conform to the mold. However, because of the depth and tight corners of the mold, this does not always occur nicely, sometimes resulting in regions with little carbon fiber as seen in Figure 12.
- The strands of carbon fiber can be shifted so that there is high strand density in the middle of the carbon fiber sheet, such as is seen in Figure 16. This decreases the occurrence of sparse carbon fiber when the carbon fiber is put into the mold.

When complete, the carbon fiber should look like it does in Figure 17.

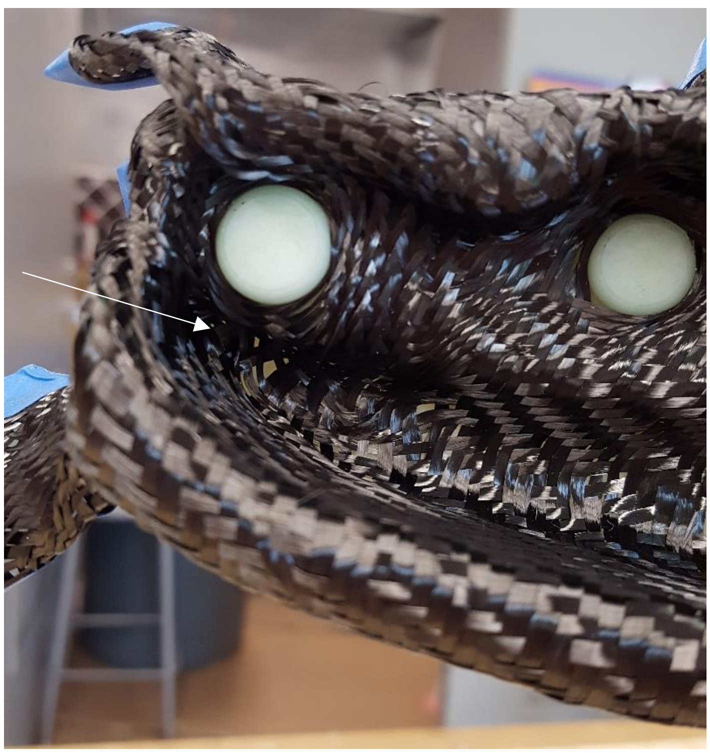

Figure 12. The carbon fiber wrapped around the ankle and Achilles hole extrusion. The carbon fiber in the bottom corner of the foot is sparse, marked by the arrow. This issue was a common issue in both the front and back of the mold made from foot v3.8.

Figure 13. A region of no carbon fiber can be seen, marked by the arrow.

INSERT FIGURE SHOWING THE TOOLS USED. NEED TO STOP BY THE HUMEC LAB
Figure 14.

Figure 15. Double sided tape was applied on the mold before the first layer of the carbon fiber is placed into the mold.

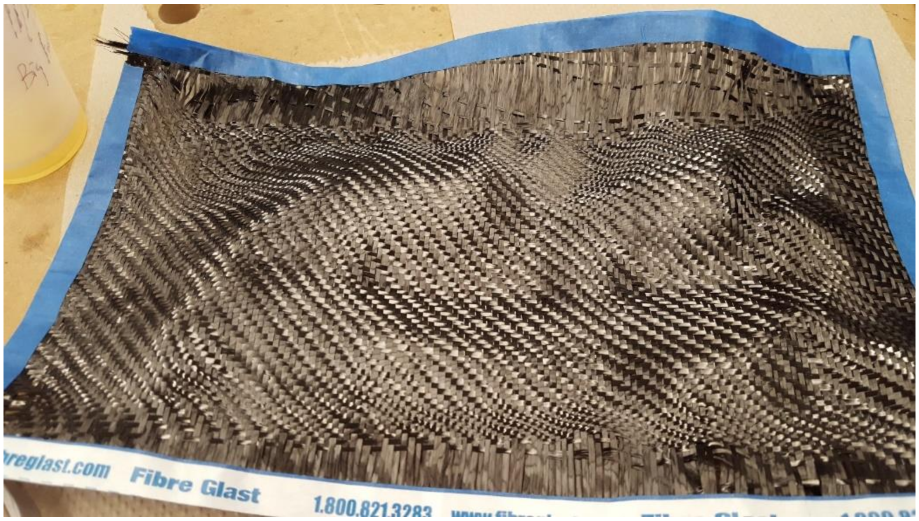

Figure 16. Moving strands of carbon fiber into the center to increase the density of fibers in the foot.

Figure 17. The first layer of the carbon fiber is placed into the mold.

5. Preparing the Second Layer

The epoxy in the two cups should be mixed well for at least one minute.[6] Epoxy should be brushed to the first layer, then the second layer of carbon fiber should be placed into the mold, and then another layer of epoxy brushed onto the second layer.

Here are some observations about applying the second layer:

- This step required the Author to move quickly. Brushing the epoxy on caused the double sided tape to lose some of its stickiness, causing the first layer to come off the mold a little.
- It is useful to have a second person help with the layup starting from this step. The second person should hold down the carbon fiber while epoxy is applied and transferred to vacuum bagging to help the carbon fiber maintain its shape.

- Be very liberal with brushing the epoxy onto the carbon fiber. The Author used too little epoxy during the first few layups, resulting in a foot that was not strong enough, as can be seen in Figure 23a. The breath layer of cloth will absorb any excess epoxy.

Figure 18. Vacuum bagging.

6. Vacuum Bagging

The process of vacuum bagging is described in Ethan Kramer’s report from Spring 2017. Note that the epoxy used has a different pot life than the one discussed in Ethan’s report in Spring 2017.

Here are some additional observations about the vacuum bagging step:

- Moving from the second layer to the vacuum baggin step should be done as quickly as possible to prevent the carbon fiber from coming off the mold. This is more so the case when the mold has deep areas that may not vacuum bag nicely.
- The vacuum bag can and should be adjusted when the pressure shows a reading between 5-15 inHG. The vacuum bag should be shifted such that there are no folds on the vacuum bag. This ensures that sufficient vacuum bag pushing down on the corners of the mold and around the ankle and Achilles holes and decreases wrinkling on the foot. If wrinkling cannot be avoided, then it should be pushed to the front of the foot away from the ankle and Achilles hole as best as possible, as can be seen in Figure 20.The tools in Figure 14 should be used to do so; be extra careful not to puncture the vacuum bag.
- Before the epoxy has cured, the mold is inverted for about 10-15 minutes. This helps ensure that the epoxy is evenly distributed on the foot and does not just pool on the bottom.

- The pump’s filter sometimes would drip oil, creating a potentially dangerous envionrment. This is because oil would get into the filter. To deal with this, use paper towels to wipe the exterior of the filter until no more oil can be soaked up by the paper towels. An oil-resistant garden house can also be attached between the pump and filter so that oil can drip into a container.
- Normally, the pump is left running for 24 hours to ensure that epoxy have enough time to harden. However, the Author notes that the epoxy has hardened in as little as 18 hours, potentially more, as noted by a witness cup left by the excess epoxy in the cup. The witness cup shows whether the epoxy inside the foot has fully hardened.

Figure 19. The mold is inverted once the pressure in the vacuum bag is sufficient in order to make sure the epoxy is distributed through the entire foot and is not just pooled on the side of the foot.


Figure 20. The wrinkles in the vacuum bag are pushed to the front of the foot.

Figure 21. Black spots of excess epoxy pockets can be seen on the mold.

Figure 22. The filter in the pump used.

7. Cleaning Up the Carbon Fiber Foot

Although a release mold was used, the foot was still difficult to remove because of the geometry of the mold. Special care should be taken to not damage the parts of the foot that would be used for the foot. The Author has found a long slotted screwdriver to be useful in removing the foot from the mold.

Twice, removing the carbon fiber broke the mold at the ankle/Achilles extrusion, probably because not enough mold release was applied to that region of the mold. Luckily this did not hurt the foot, and the broken piece of the mold could easily be superglued back onto the mold.

Therefore, it is very important that the preparation steps be done well to decrease issues at this stage of the layup.

Figure 23a. An insufficient amount of epoxy was used to create the foot. Some parts of the foot still has the texture of the woven carbon fiber.

Figure 23b. A sufficient amount of epoxy applied.

Figure 23c. A sufficient amount of epoxy applied.

To remove the excess carbon fiber from the mold, a scissor, X-Acto knife, and Dremel rotary tool was used. The scissor is good for removing the carbon fiber that did not bind with the epoxy. The X-Acto knife is good for cutting the foot along straight lines, such as along the bottom of the foot. The Dremel is good for cleaning up hard to reach regions of the foot, such as around the ankle and Achilles hole. Sometimes there was carbon fiber where the hole of the foot should be. This can be cleaned up very easily with the X-Acto knife.

The fit of the two halves can be tested by seeing whether there is any deflection when the two pieces of the foot is put together. Delrin rods created by Ethan Kramer in Spring 2017 semester in the exact size of the holes can be used to test whether the holes are concentric. Although ideally there should be no deflection, this may be hard to do without cutting into the foot piece a little. It is especially important that proper PPE (minimum gloves and goggles and face mask) be used in this step because carbon fiber dust is generated when the foot is cut.

Figure 24. Both halves of the feet after being trimmed of excess carbon fiber.

8. Pressure Sensor Holes

Using C-clamps to hold down the jig in Figure 25 with the extrusions facing up, holes were drilled at the points of the small extrusions. Step up the drill bit used to ensure that the holes are accurate. The outer half of the foot should be then placed into the jig and clamped down with the jig side up. Holes can then be drilled into the carbon fiber foot. The final result on the outer foot can be seen in Figure 26.

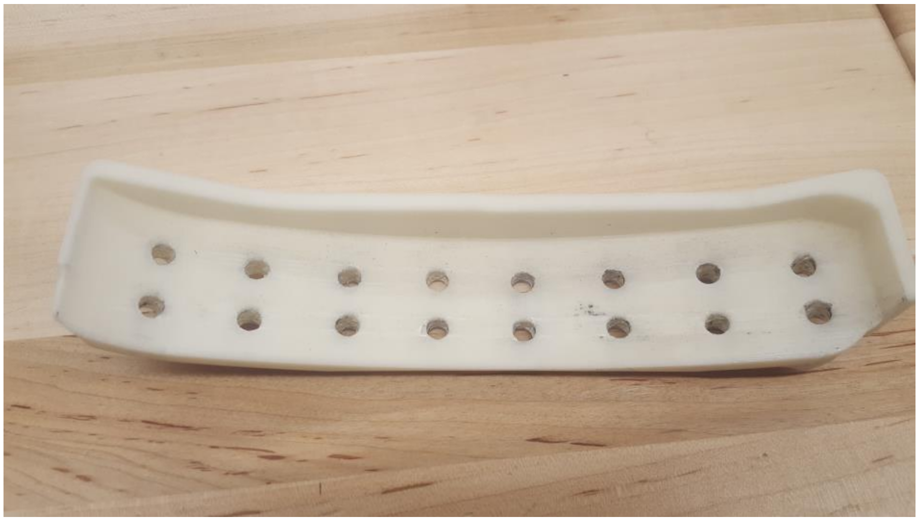

Figure 25. Hole making jig.

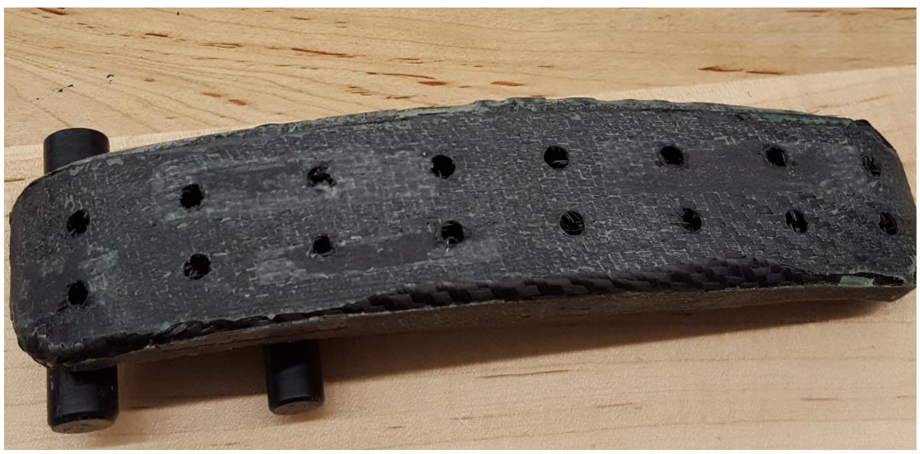

Figure 25. The holes on the foot after being drilled out using the jig.

9. Assembling the Foot

Once both halves of the foot has been laid up and cleaned up, the two sides of the foot can be put together. This can be done by following the same steps as doing a carbon fiber layup except that no material needs to be cut up and that epoxy only needs to be applied to the interface between the two pieces; do a vacuum bag with the two pieces of the foot.

Figure 26a. Assembled foot. The Delrin rods are used to make sure that the holes are the right size.

Figure 26b. The side profile of the assembled foot.

10. Pouring the Foam into the Foot

For details on this step, please consult section 2.2.1 of Ethan Kramer's report from Spring 2017.[2] The foam was poured in through the ankle and Achilles holes. The final result can be seen in Figure 27.

Figure 27. The foot after foam has been poured in. The foam can be seen on the exterior of the foot because the two pieces of the foot were not vacuum sealed properly before the pouring of the foam.

11. Creating the Foam Shoe

The purpose of the foam shoe is to protect the pressure sensors on the foot as well as to distribute the pressure applied on the foot such that a sensor is able to pick up a reading when any point on the shoe is touched. The current plan is to pour foam onto the shoe, then pour a thin layer of polyurethane over it to protect the shoe from puncturing. The foam after being poured onto the shoe can be seen in Figure 28.

Testing of foams for the shoe was primarily conducted by Ethan Kramer. Ethan Kramer designed a jig to assist in pouring foam onto the foot. The Author assisted with the pouring of foam onto the foot. For more details on the shoe of the foot, please consult Ethan Kramer's report.

Figure 28. The shoe of the foot.

Testing

Testing of the sensitivity of the pressure sensors was started. Please consult Ethan Kramer's report.

CONCLUSION

Manufacturing of the foot in two pieces using an outer mold is more than using an inner mold. By taking a few extra steps to prepare the layup and the vacuum bag, there is less variability in the quality of the feet produced. This process has produced a hollow foot that allows for the placement of pressure sensors in the foot, satisfying the FCO for this project.

FUTURE WORK

- Design of the PCB boards that will be placed in the foot.
- After the PCBs for the foot is designed, pressure sensors and the PCB should be placed into the hollow foot before the foam is poured in. Testing should be done to see whether the heat from the expanding foam affects the pressure sensors and PCB.
- Testing of the sensitivity of the pressure sensors should continue.
- Stress testing the foot so that it does perform as intended.
- Making the final two feet that would go onto the robot.

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