Gearbox Design for Multi-legged Robots

Introduction

A multi-legged robot refers to a robot with six or more legs. These robots are an important research subject due to the many advantages they have when compared to bipedal and quadrupedal robots, such as increased stability. For this reason, the Biologically Inspired Robotics and Dynamical Systems (BIRDS) Lab at the University of Michigan analyzes data from arthropods and multi-legged robots created in the lab to develop models from animal and robot locomotion. BigAnt (see Figure 1), a cockroach-inspired hexapod robot that uses a single motor per leg, is one of the robots created and used in the lab. Some of the benefits of BigAnt are that its chassis is made with minimal tooling and $20 worth of materials, and it can be manufactured inside the lab using a laser cutter.

Figure 1: Side view of the original BigAnt robot created by BIRDS Lab

BigAnt's cost and ease of manufacturing have made it an important robot in the lab since its design can be modified to create versions that serve other research purposes, such as Stair Climbing BigAnt and Force Sensing BigAnt. BIRDS Lab and the Multi-legged Robots and Animal Motion (MuRoAM) team are currently working on FastAnt (see Figure 2), a new variation of BigAnt that will operate using T-MOTOR U8 100 U-Power Series motors, with the goal of modeling locomotion of hexapod robots at higher velocities. The T-motors used for this design are typically used for drones, so FastAnt will use a planetary gearbox to slow down the T-motors to an appropriate speed for robot locomotion.

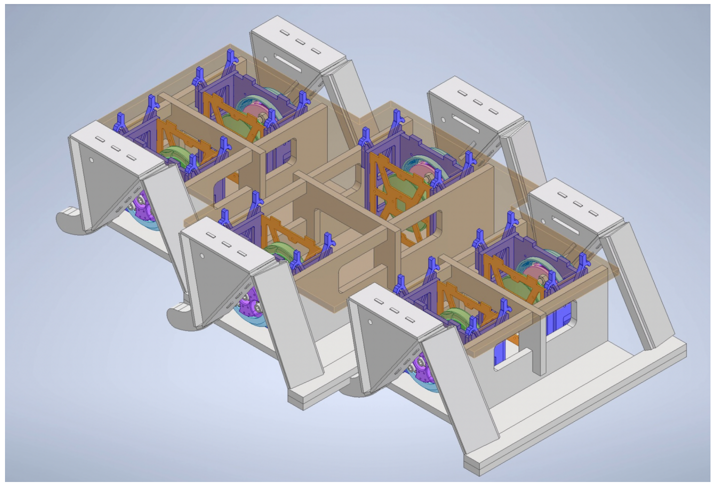


Figure 2: Current draft for FastAnt chassis design including a gearbox assembly for each leg.

While there are gearboxes that meet design requirements available in the market, they come at a high cost and low flexibility for future changes in design. With FastAnt's design still being developed, and with details such as weight and size still undefined, and ease of design iteration being part of BIRDS Lab's ethos, the team working on FastAnt started looking for gearbox options that could be manufactured in the lab. Such a design will allow for easier customization and changes as needed by the project or for future projects in the lab.

EMBiR Lab, another lab at The University of Michigan, published a design for a 3D printed gearbox for legged locomotion, described in their paper 'Design and Characterization of 3D Printed, Open-Source Actuators for Legged Locomotion' (see Figure 3). This design was used as a starting point for our design and was adapted to meet the design requirements for FastAnt.

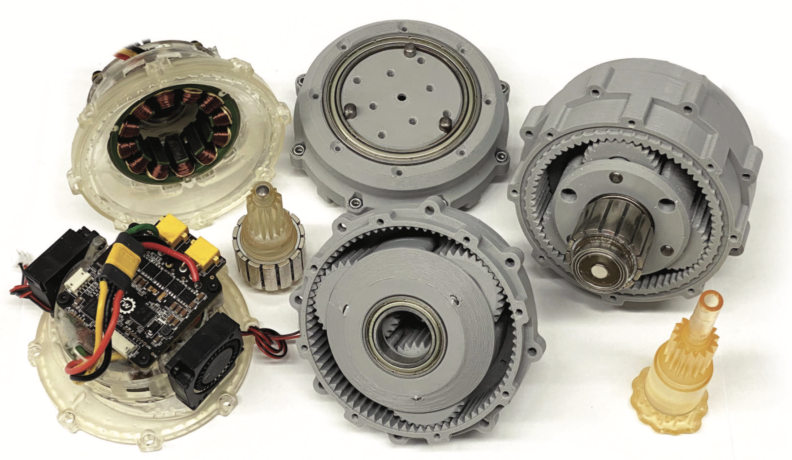


Figure 3: FDM-PLA 3D printed gearbox components created by EMBiR Lab (Urs et al. 2022)

While the 3D printed design by EMBiR Lab shows good performance for legged locomotion, it can not be directly used for FastAnt without first adapting it to fit FastAnt's motors and use materials available in BIRDS lab. Furthermore, 3D printing, while allowing for making changes to the design, still takes a significant amount of time to manufacture and make changes. For this reason, laser cutting was also considered as an option for the gearbox, which would allow for faster production of parts.

Design Requirements

The objective of this project is to design a drivetrain to connect the T-motors to the FastAnt legs, providing adequate speed reduction. To accomplish this, the gearbox assembly must meet the following criteria:

- Provide support for a T-Motor
    - A single motor mounts to the sun gear to drive the gearbox.
    - Gearbox assembly provides adequate heat dissipation.
    - Drive the existing FastAnt leg at an appropriate velocity
        - Gearbox assembly includes an output that can be attached to FastAnt's rotary links without requiring changes to the leg design.
        - The gearbox provides close to a 7.5:1 gear ratio
- Use standard parts, materials, and manufacturing processes authorized in BIRDS Lab.
    - Gearbox uses skateboard bearings exclusively.
    - All parts are attached using M3 or M2.5 screws.
    - Gearbox uses 5/16” bolts as shafts for the planet and sun gears.
    - 3D printed components can be manufactured using the Markforged 3D printer in the lab.
    - Laser-cut components should be made out of ABS in standard thicknesses.
- Easy to assemble, disassemble and replace
    - All parts are attached using screws, bolts, nuts, or lock nuts that allow for assembly and disassembly using standard tools.
    - Parts can be accessed without damaging other FastAnt components.

In addition to the previous requirements, the design should minimize complexity, using simple geometry and manufacturing processes when possible. A complete list of requirements for the FastAnt project can be found in the MuRoAM’s Google Drive.

3D Printed Design

The first design created for the FastAnt gearbox project was a 3D printed gearbox adapted from EMBiR lab’s gearbox to fit FastAnt’s requirements. The original 3D gearbox created by EMBiR lab encloses the motor inside the input assembly and provides heat dissipation using small fans. It is made up of two main subassemblies: an input assembly and a planetary transmission assembly (see Figure 4).

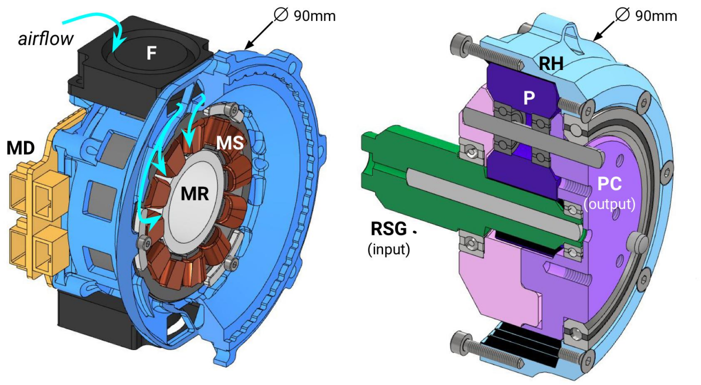


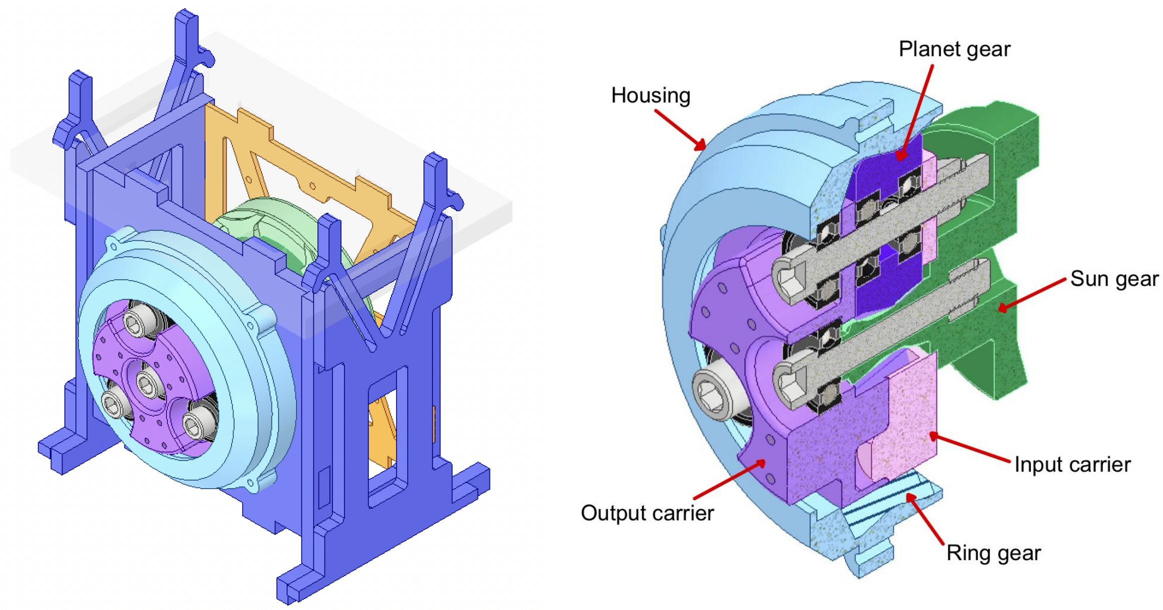
Figure 4: EMBiR lab's gearbox CAD. Input assembly is pictured on the left, including a fan (F), motor driver (MD), motor stator (MS), and motor rotor (MR). The right image shows the transmission assembly, including a rotor-sun gear (RSG), planet carrier (PC), planet(P), ring gear and housing (RH). (Urs et al. 2022)

Changes made for FastAnt's gearbox

The first FastAnt gearbox design was created by adapting EMBiR lab's gearbox to use components available in the BIRDS lab. The major changes were due to differences in the motors used. EMBiR lab's design uses a smaller motor with an outer surface that is part of the motor's stator (MS), this allows it to be fixed to the input assembly as shown in Figure 4a. The motor rotor (MR) in this design was directly attached to the sun gear. However, the T-motors that will be used in FastAnt have a rotating frame, making the back plate the only outer part of the motor that is not spinning. This meant that the T-motors in FastAnt's version had to be attached to the back of the motor, leaving enough space for the rest of the motor to spin without coming into contact with any surfaces.

The original gearbox also included a variety of bearings that were changed to skateboard bearings. This required changes in the shape of some components so they could fit the new bearings. The bearing on the output was changed for three skateboard bearings that contact the housing while rotating in the planet gear's shaft.

Other changes include relying on an outer assembly to constrain all gearbox components (see Figure 5a). This change was made with the intention of providing easy access to components and providing room for airflow. A metal plate was used for heat dissipation instead of the fans in the original design to reduce the number of electrical components. Finally, the gears were changed to helical gears. Figure 5b shows a section view of the final 3D printed gearbox design.



(a) (b)

Figure 5: 3D printed gearbox design for FastAnt. (a) Full assembly containing the gearbox, T-motor, and mounting assembly: metal plate for heat dissipation (orange), and front and side plates that attach to the FastAnt chassis (dark blue). (b) Labeled section view showing the housing (light teal), sun (green) and planet gears (dark purple), output carrier (light purple), input carrier (pink), bolts, and bearings.

Prototyping

We 3D printed the initial gearbox using the Markforged 3D with Onyx filament, a high-strength thermoplastic with high heat resistance (see Figure 6). The components took approximately 40 hours to print, but we had some problems printing with the Onyx filament, which resulted in bumpy surface finish. A second prototype was created by the Fabrication Studio using a Forms 3 resin 3D printer.

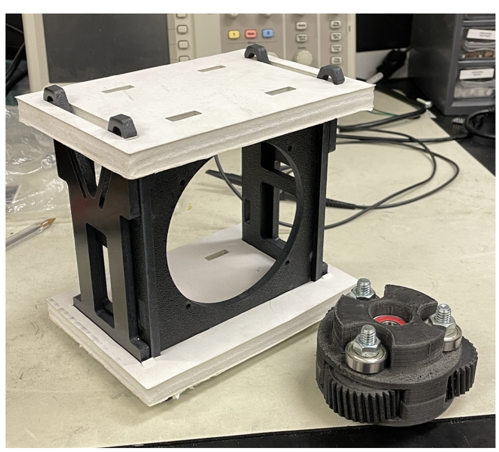


Figure 6: 3D printed Onyx filament prototype created using the Markforged 3D printer in BIRDS lab pictured with the laser cut mounting assembly.

Laser Cut Design

The laser cut gearbox design was created based on the 3D printed design, aiming to solve some of the problems we noticed during prototyping by using a different manufacturing method. While laser cutting requires the design to have more components due to the amount of layers needed, the overall time it takes to laser cut components is shorter than that of 3D printing. Additionally, the use of layers also makes it easier to make alterations to the design by only swapping layers as required instead of having to fabricate a new gearbox. Reducing the number of layers was still a priority to make this version of the gearbox to make it easier to manufacture and assemble. The laser-cut gearbox design CAD is pictured in Figure 7 below.

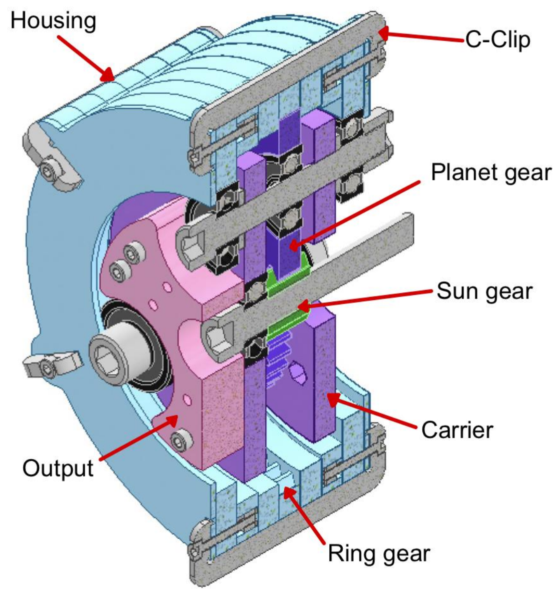


Figure 7: Labeled section view of laser-cut gearbox CAD showing the housing (light teal), clamps(gray, outer), sun (green) and planet gears (dark purple), carrier plates (light purple), output assembly (pink), bolts, and bearings.

Housing

The subassembly with the most layers is the gearbox housing, so only layers with key functions were kept for the design. Figure 8 shows an exploded view of the five different layers in this subassembly. The housing has a symmetrical design, so layers 1-4 are the same as the four layers after the ring gear layer. The function of each of the layers, as numbered in Figure 8, is as follows:

1. Constrain bearings. This layer prevents the carriers' bearings, and thus the other inner layers, from sliding axially.
2. Contact bearings. This layer contacts the carriers' bearings to reduce friction from carriers' rotation relative to the housing.

3. Hold locknut for C-Clips. This layer has hexagonal cutouts that fit an M2.5 locknut. When all layers are aligned the C-Clip can be positioned on the outside and held in place by screws fastened to the locknuts in this layer.
4. Constraint planet gears. This layer prevents the planet gear from sliding axially.
5. Ring gear. This layer contacts the planet gears to provide the appropriate gear ratio.

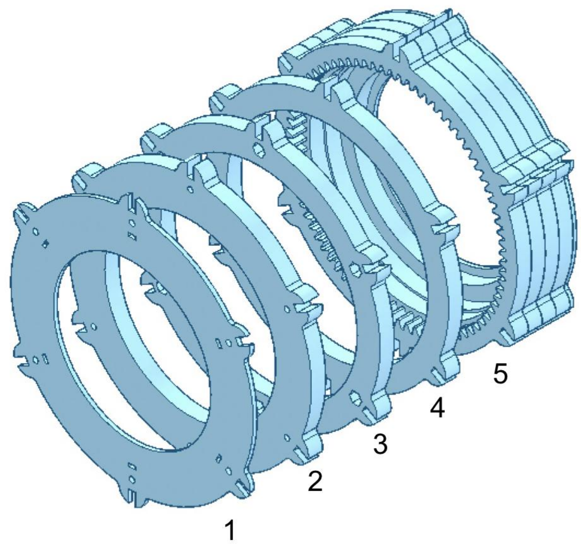


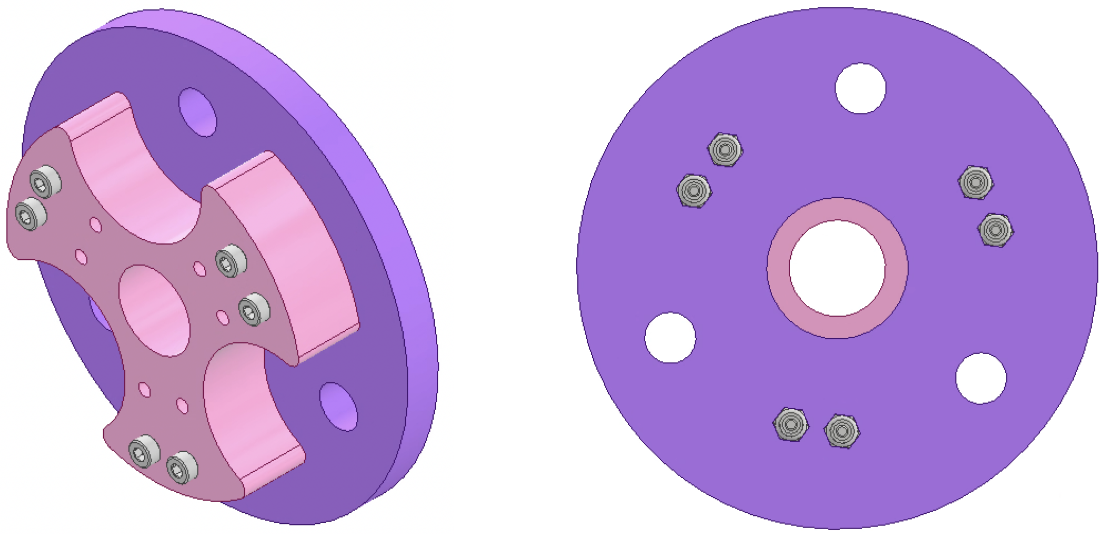
Figure 8: Housing exploded CAD showing the five types of layers needed for the design. Layer 1 is 1/16" in thickness, while all other layers are ¼" in thickness. Layers are numbered 1-5.

For ease of manufacturing, all housing layers are either 1/4'' or 1/16'' in thickness, but these might be changed in future iterations of the design as needed to ensure functionality while also minimizing weight.

Carrier and Output

While the 3D printed gearbox had an input and output carriers that fitted together to hold the planet gears, such a design was not possible to laser-cut due to the three dimensional features. Thus, the laser cut version of this part was changed to also be symmetrical, having a single type of carrier for both the input and output sections. Instead of relying on contact of these two carriers for spacing inside the gearbox, the necessary spacing from the planet gear is provided by the housing, which constrains the position of the planet gears. Laser cut spacers were also needed to keep the bearings from directly touching the carrier, which would result in additional friction.

The output was designed to be a separate part. This version has the same output shape and bolt pattern as the one in the 3D printed gearbox version. Additionally, the carrier has the same hexagonal cutouts as the housing, which allows for screws to be easily fastened. If the required output shape were to change in the future, the new design would still be compatible with this gearbox given it follows the bolt pattern. Figure 9 shows the carrier and output subassembly CAD.



(a) *(b)*

Figure 9: Carrier (light purple) and output (pink) subassembly including the M3 bolts and locknuts connecting them. (a) Isometric view of the assembly. (b)Back view of the assembly showing six locknuts fitted inside the hexagonal cutouts in the carrier.

Gears

The gears for this design are contained in a single layer, so they can be easily changed if a different gear ratio is needed. The current design has a 20° pressure angle and gear ratio of 7.5:1, with a sun gear with 12 teeth, a planetary gear with 33 teeth, and a ring gear with 78 teeth. All gears were created using the *Spur Gear* tool in Autodesk Inventor. Figure 10 shows the layer containing all the gears in the assembly. The planet gear pictured is a placeholder for the final planet gear design, which is currently being made by other lab members to ensure that it can properly attach to the motor.

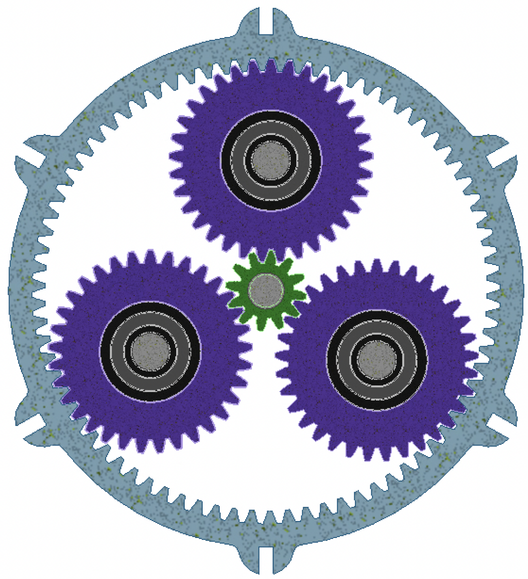


Figure 10: Planar view of the layer containing all gear components, showing the ring gear on the inner surface of the housing housing (light teal), and the sun (green) and planet gears (dark purple).

C-Clip

Unlike the 3D printed version, the laser-cut gearbox was designed to be a closed gearbox, meaning the gearbox is its own subassembly and components cannot fall out when the gearbox is not mounted to FastAnt. This change was made due to difficulties when assembling the 3D printed prototype, and also due to the increase in the amount of parts. To close the gearbox and hold all the housing layers together, the design uses C-Clip that can be laser-cut and fits into the outside of the housing and is held in place by both a snap lock in the front housing layer and by a screw. This C-Clip also makes the design more flexible since layer thicknesses can be changed without needing to purchase a different bolt length. For now, the design is as simple as possible with a uniform thickness. However, a future version of the gearbox might need to have a C-Clip with variable thickness to better accommodate the hexagonal cutouts in the housing, which are currently too close to the part's edge. With this in mind, the C-Clip file also has a Finite Element Analysis (FEA) in Autodesk Inventor that shows the stress concentrations and deformation of the C-Clip so future lab members working in the gearbox can see the effects of any changes they make. Figure 11 shows the C-Clip design in the FEA.

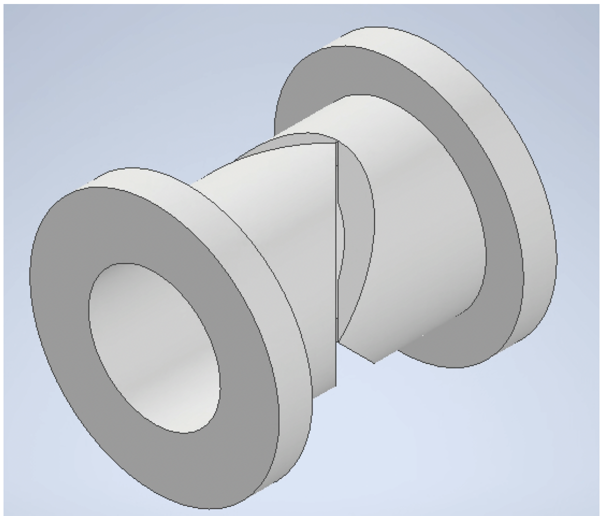
Figure 11: Finite Element Analysis (FEA) of the C-Clip design. The pictured analysis shows the deformation and stress due to an applied pressure on the inner surfaces of the clip.

Prototyping

To laser cut this design in the intended dimensions, all CAD dimensions were adjusted by 0.005'' to account for the thickness of the laser (laser kerf). Some of the dimensions were adjusted according to how the initial laser cut parts fit together. All CAD files include a second solid body named 'Laser Cut', which was made using the *Thicken/Offset* tool to have the correct dimensions for laser cutting.

Testing Setup

Part of this project was creating a testing setup for the gearbox assembly that allowed the motor to operate at various torques to characterize gearbox and motor characteristics such as efficiency. This type of testing is normally done using a spool pulling up a load to provide the fixed torque. However, for higher torques this would require either a very high load, a big enough radius, or both. Since we do not have a way to manufacture a part with big dimensions in the lab, we created a 3D printed half bushing with sharp points that can be punched through foam core board to hold bolts in a circle and provide the same effect as a spool (see Figure 12). This limits the size of the spool to the size of the foam core board.



(a)

(b)

Figure 12: 3D printed half-bushing. (a) Two half bushings with sharp points to punch through foam core board that fit together with an adequate distance for the foam core board thickness. (b) Example of the half bushings being used in ¼" foam core board.

Figure 13 shows the testing setup made to test the 3D printed gearbox. Testing will be done in the Flight Lab in the Robotics building.We have not finished testing the 3D printed version, but some of the initial tests can be found in the MuRoAM Google Drive, in a document titled 'Gearbox Test Cases'.

(a)

(b)

Figure 13: Testing setup for constant torque testing. (a) Front view showing the circular bolt pattern and a string connected to one of the bolts. As the foam core board rotates, this string wraps around the bolts. (b) Back view of the testing setup showing gearbox assembly attached to the foam core board.

Future Work

The FastAnt project will continue next semester, with other team members working on some of the other components. Some of the main tasks for now, aside from the gearbox design, are creating a reinforced chassis and designing and modeling legs with spring-steel for more efficient energy use, all of which are projects that other lab members are currently working on.

In terms of the gearbox project, the 3D printed gearbox is still undergoing testing, and a new version might be created if its performance far surpasses that of the laser cut gearbox. The laser-cut gearbox is still in the prototyping stage and will be tested by lab members next semester. A future version of the selected gearbox will have to be redesigned to meet more specific requirements as FastAnt progresses, such as withstanding the expected loads and having the right size to work with the rest of the robot.

References

K. Urs, C. E. Adu, E. J. Rouse and T. Y. Moore, "Design and Characterization of 3D Printed, Open-Source Actuators for Legged Locomotion," 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Kyoto, Japan, 2022, pp. 1957-1964, doi: 10.1109/IROS47612.2022.9981940.