6-Axis Mobile Construction 3-D Printer

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Abstract

Construction sites are typically associated with the need for caution, adherence to protocols, and manual labor. This project explores the development of the PRIMO (mobile printer) - a 6-axis 3D printing construction robot - with the potential to revolutionize the construction industry by enabling printing in remote locations and improving these aspects of construction. The six-legged (hexapod) robot can walk and its main body has six degrees of freedom, facilitating non planar printing on an almost limitless print bed size. In Addition, the robot is equipped with a custom concrete extruder and brick placement mechanism, enabling the printing of entire structures with minimal human intervention, one after another.

Acknowledgements

We would like to thank Professor Agheli for his support and his guidance throughout the project; his expertise on hexapods and legged robotics was invaluable to the success of our project. We would also like to thank Professor Nemitz for his knowledge and advice during the development of the project. Without their help the project would not have been able to be completed.

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Executive Summary

The research outlined in this report is the development of a 6-axis mobile printer robot that can extrude concrete and lay bricks as it moves. This robot is designed to be used in construction areas to build structures autonomous from human intervention. While similar types of robots exist, they either are not a mobile robot and have to operate on a gantry, or they use a material other than concrete. This robot is one of the first of its kind designed for these tasks.

The design of this robot uses 6 legs, each with 3 joints, around a circular base with a storage tank and actuator in the center, and the brick mechanism in the back of the robot. Each joint is actuated for a total of 18 servo motors for locomotion that allows for complete range of motion and movement along axes.

The final joint of the legs have a single point of contact to help reduce sliding of parts while the robot is in motion. They had been redesigned from previous iterations to allow for more range of motion for the joint around the leg and were made to hold the extra weight of the robot when concrete was added in.

The concrete tank was initially designed to fit between the top and bottom plates of the robot but with the limited space it was redesigned to sit on the bottom plate of the tank and stand above the top plate, necessitating new versions of those plates. The extrusion method chosen was utilizing a swirler to keep the concrete flowing in the tank, which would allow the robot to extrude the concrete evenly as it walked and allowing the extrusion speed to match the walking gait of the robot.

The brick laying mechanism designed used a vertical storage tank and a paddle that pushed them out similar to a PEZ dispenser. Over the course of the project the paddle was changed from a rotational acutaition to that of a linear one, as the bricks could only be placed in a singular orientation. While the design was able to push the bricks out with ease, the bricks were unable to stick to the concrete so a

pusher was added so that when the bricks are placed on the concrete the pusher would help the bricks sink into the concrete more to help adhesion.

The software protocols developed for the robot can both gyrate the robot in place as well as using a wave gait trajectory to move the robot. Once the robot was able to move successfully the extrusion and brick laying mechanisms were added onto the robot. The robot was able to successfully lay concrete as it moved in a square pattern during its gyration protocol and was able to print concrete in a straight line as it walked.

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1.0 Introduction

Robotics exists today to aid with three major types of jobs; those that are too dangerous, dirty, and dull for humans. These three D’s of robotics stem to many fields, as there is a plethora of work that can be made easier by the advent of robotics. One of these areas is construction, where architectural robots work with humans to assist in the construction of buildings.

Architectural sites are known to be dangerous, requiring workers on site to wear hard hats, steel-toe boots, and reflective clothing. Construction work is also physically tolling, with potential long term health issues as a result of such work. Architectural robots can minimize these downsides of construction work, as well as making sites safer and more sustainable for workers. It is faster than conventional construction, uses less man-power, and it is cheaper when it comes to cost of materials.

Our robot is an omnidirectional hexapod that can print concrete as it walks. By having six legs, the robot will be able to traverse rough terrain and step over its own prints to aid in printing housing and parts. As each layer of concrete is printed, bricks are placed on top of the concrete in order to construct each layer as a wall.

2.0 Background

2.1 Architectural Robots

Construction robots can carry out more complex tasks and can handle the production and assembly of complex parts that would be difficult for a person or even group of people to handle. This is especially the case as parts and structures can be generated in 3d modeling software and sent directly to the robot to begin production.

As well as being able to handle complex parts and structures, they can also handle errors that are prevalent in the architecture industry. Robots can account for material expansion as certain materials can warp as they are exposed to different weather conditions. Depending on how the particular robot can sense its environment, it can potentially make adjustments in real time to account for such distortions.

Additionally, for longer projects, architectural robots have the capability of creating an environment that they can easily traverse to aid in their construction, similar to scaffolding on large buildings. This can allow for more robots to work more efficiently on a system.

The type of construction robot that is most relevant to this project are concrete 3d printers. These robots typically come in two varieties: robotic arms and gantry system. Robotic arm systems typically consist of multiple rotational and sometimes prismatic joints with a concrete extruder as the end effector of the arm. Gantry systems are more straightforward where they are closer to a normal 3d printer or cnc machine on a cartesian system typically. There are also delta concrete printers though they are not as prevalent as the aforementioned two.

An example of a concrete 3d printer is one from Mudbots. They offer gantry style printers ranging from 15 feet by 15 feet to 100 feet by 100 feet. According to their website, one of their printers can print a 25 feet by 12 feet house in only 5.5 hours using only $873 worth of cement. While that may seem cheap, the prices for both arm and gantry style printers can range anywhere from $20,000 on the small side, to over $1 million for larger printers. What additionally needs to be taken into account is the type of mix. Mixes from multiple different distributors can range in terms of fluidity, bonding, seismic resistance, curing, strength, and even more.

Figure 1: Mudbot gantry style concrete 3-D printer

It should also be noted that there is also a lack of certification and safety regulations when it comes to 3d printed houses.

2.2 What is a Hexapod?

Six legged robots, otherwise known as hexapods, have become more practical within the last decade as more companies and hobbyists decide to develop them further. Other than being able to traverse over rugged terrain, the gait of a hexapod has less limitations than that of other legged robotics. For example, in cases where a hexapod may have to traverse a minefield, having a variable walking pattern is extraordinarily useful when trying to avoid such dangers. Hexapods can also make use of certain terrain characteristics such as footholds that allow them to traverse even further. This is all the while the hexapod is not required to use all six of its legs for locomotion. If there are cases where it needs to use one of its legs to perform a different action from walking, that can be done.

However, hexapods don’t come without any physical downsides, however they can be difficult to run and understand. Controlling 18 motors to all move in unison the way that you want is easier said than done. They are also more power inefficient, requiring a lot of power to run all the motors that drive the movement of the robot. And lastly, hexapods are just slow, especially compared to their wheeled counterparts. Luckily, for this project, speed is not an issue due to the somewhat slow drying nature of concrete.

Hexapods have three general ways that they can walk around. These three walking methods are tripod gait, ripple gait, and wave gait. Tripod gait works by picking up three legs at a time in the shape of a triangle. Whilst the legs are in the air, they move to the new ground position and the cycle repeats for the other three legs. Tripod gait is the fastest of the three gaits, but it is also the least consistent when it comes to walking at a constant velocity. Ripple gait works by moving two legs at a time where the two legs are on opposite sides of the robot and they are not directly across from one another. Wave gait works by only lifting one leg at a time to a new target position, all the while the supporting legs are slowly moving to move the hexapod in the desired direction.

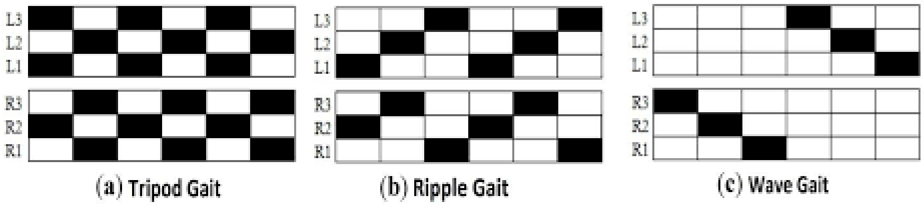


Figure 2: Visual representation of different hexapod gaits

Impressively, there is already another hexapod that prints as it walks called Geoweaver, though there are some distinct differences between that implementation and ours. Geoweaver prints using a hot glue gun, and each leg is driven by two motors, with a non-driven wheel as the end effector. It operates using Firefly, a plugin for Rhinoceros 3D.

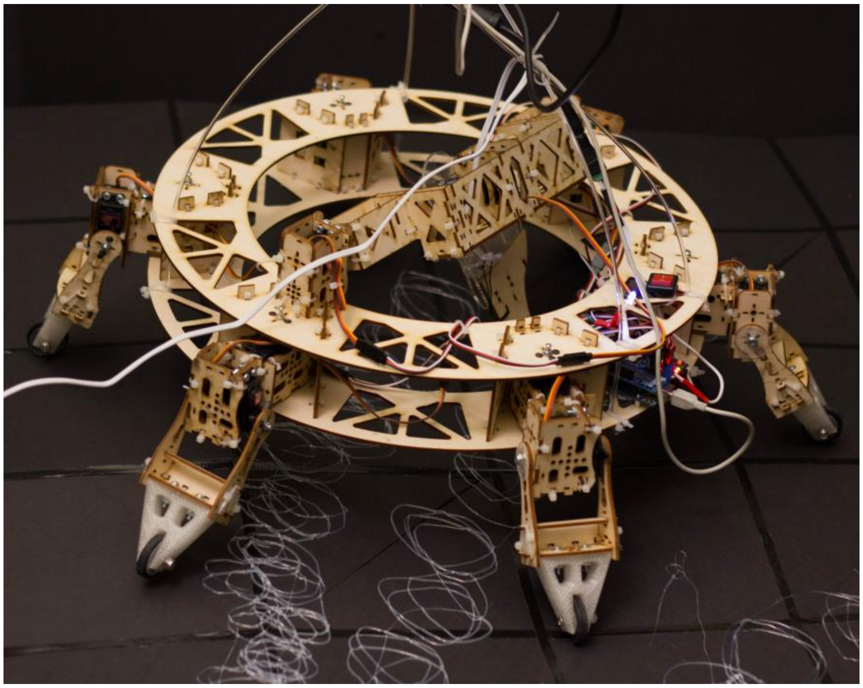


Figure 3: Geoweaver 3-D printing hexapod

3.0 Design and Development

3.1 Qualifying Design

There are two major things that this robot needs to be able to do: walk and print. The print will dictate how the robot needs to walk.

For the robot to be able to “print,” this entails that the robot can move to a specified location and extrude concrete when told to. The same way that a 3d printer moves to different points in space, this robot needs to be able to do the same. As it is still early in the development of this project, the main goal is to be able to print a line of concrete, with additional goals of simple structures.

For the robot to be able to walk and move to specified points, the legs will need to move along the desired trajectory and speed to get the nozzle where it needs to be. This goes for all 18 servo motors controlling movement, all moving in sync with one another.

The decision to have six legs on this robot is quite easy to justify. Hexapods are generally more stable than quadrupeds, where when a quadrupedal robot takes a step, the center of gravity of the robot needs to be within the triangle created by the ends of legs that are still on the ground. A hexapod does not experience this to the same degree, simply by having more legs to distribute the weight more evenly around the robot. Hexapods additionally have the capability of functioning with less than six working legs. If one of the legs were to be damaged on site, it would still be able to walk.

An omnidirectional robot allows us to be able to move the robot from any orientation in any direction without needing to turn (as much). This eliminates a potential issue of our robot printing corners of a wall where on hexapods with a dedicated “front” and “back,” the robot would need to turn about that corner, keeping the extruding nozzle in place as well as avoiding hitting the printed wall with its legs as it's turning.

18 motors each playing a crucial role in the collective stability of construction robot may be difficult to control, however, this system can be controlled by more than just 6 legs. Our robot will include a gyroscopic sensor that will be able to detect if our robot is not level while printing. Additionally, the inclusion of this sensor can also aid in keeping the robot level while traversing over rough terrain. Inclusion of a series of line sensors around the extruding nozzle can also be helpful. Using the contrast of dark concrete (that we might also color black) against the (lightly colored) print bed, the robot can monitor its movement and correct itself as it is printing. Though this check would only work if the first layer of concrete is printed or a black line is pre-drawn.

Where our robot is omnidirectional and inherently has no distinct orientation, the same cannot be said for bricks. Most standard bricks come in the shape of a rectangle and they can only be laid down in one orientation. Depending on the implemented solution, the robot may need to reposition itself in order to lay down bricks following printing concrete. Regardless of the implementation, orientation of the bricks as they are being laid down is something that needs to be addressed when designing the mechanism.

Lastly, what was most paramount with this project is how these different functions are able to come together. If the robot moves too slow, there will be too much concrete per unit line. If the robot moves too fast, there will not be enough concrete per unit line. Having these two sync up is imperative to the print quality of the structure or part.

3.2 Robot Design

3.2.1 Leg Design

As the robot needs to be able to print structures out of concrete, this entails that the robot be able to print at different heights. This means that the legs need to have enough clearance between their linkages so as to have enough flexibility for different printing positions.

One of the first things that needed to be fixed was the design of link 2 (L2). The previous iteration of the link was angled at 90 degrees and offset by 15mm (Figure 4). This would result in an increased torque load on the second motor. The goal was to be similar to typical hexapods that are being manufactured where all the links with exception of the link touching the ground are in-line with each other. To fix this, L2 was redesigned to be straight, similar to an H-bracket (Figure 5).

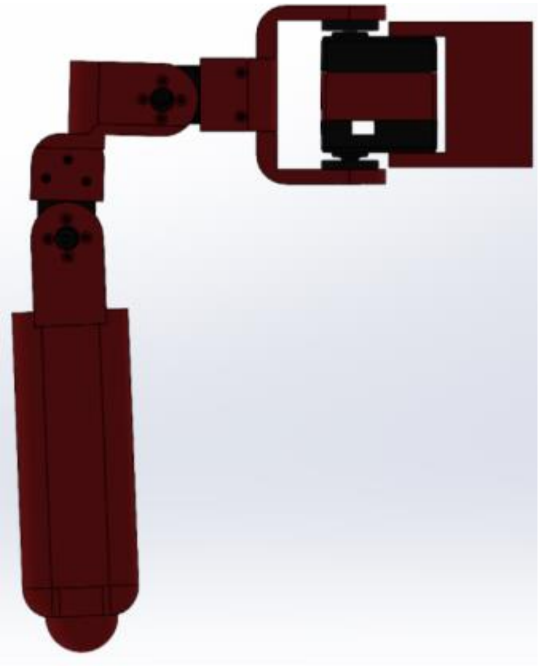


Figure 4: Original Leg Design

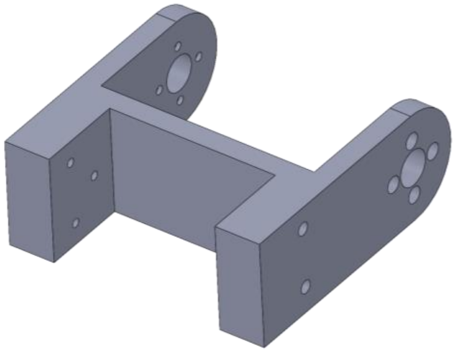


Figure 5: Updated Design of L2

The link that needed the most work in terms of its redesign was link 3 (L3). From the design requirements, the decision was made to bring the leg back into one singular piece instead of two separated pieces connected by a plate. A decision was also made to hollow the final leg design out in order to reduce the weight of the leg. Different iterations of the design were made throughout the term and adjusted according to suggestions given on how to improve the design of the leg. One of these iterations was a more curved design that attached to the motor from the side so that all points of attachment to the motor were in line with each other (Figure 6). However, a leg design that was more angled that attached vertically to the motor was chosen as the final design as the calculations for the forward and inverse kinematics for the robot were simpler if the point of the leg that was touching the ground was in line with the point where the leg attached to the motor (Figure 7).

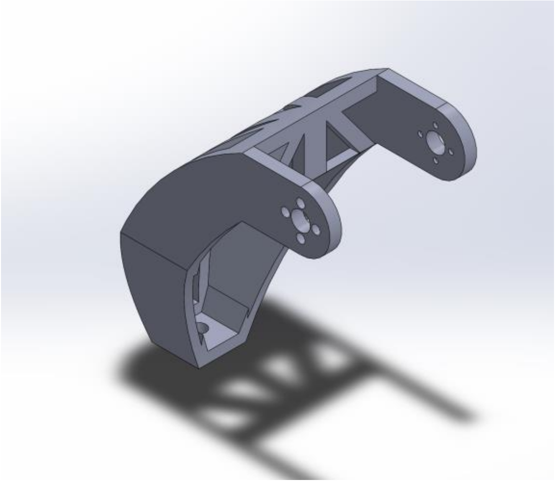


Figure 6: Previous Iteration of L3

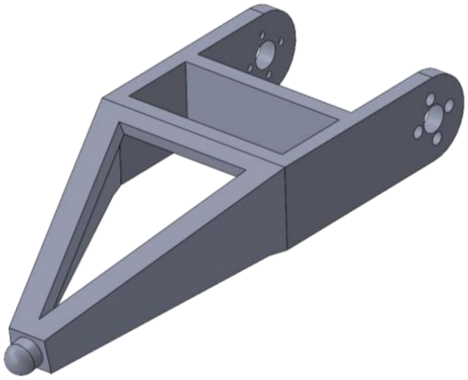


Figure 7: Design of L3

Instead of a modular design for the endpoint of the leg, it was decided that a single ball endpoint was needed for the leg. This was because both of the modular endpoints being developed would have a ball as its tip so whether the rest of the endpoint was spherical or pyramidal did not matter. A fully spherical endpoint was chosen because it gave the most surface area for the leg in case of accidental slippage of the leg. Once the leg was made, the tip of the leg was dipped in a rubberized material to increase the friction at the contact point the leg makes with the ground and reduce the chance of the leg slipping while walking.

While the previous iteration of the leg design worked and allowed the robot to walk, it needed some slight modifications to better suit the needs of the project. One of the things that needed to be changed on the leg is that the part of the leg that attached to the motor was not wide enough, causing the leg to bend which could cause the leg to break . Something else that was noted on the leg was that the leg could not move around its full range of motion due to the sides of the leg hitting L2. To resolve this issue, the entirety of L3 was widened and the motor attachments were extended to allow for L3 to pass around L2, allowing for full range of motion for the leg. Since the leg would be less stable due to it becoming wider and remaining hollow, extra supports were added to the final leg design to keep structural integrity (Figure 8).

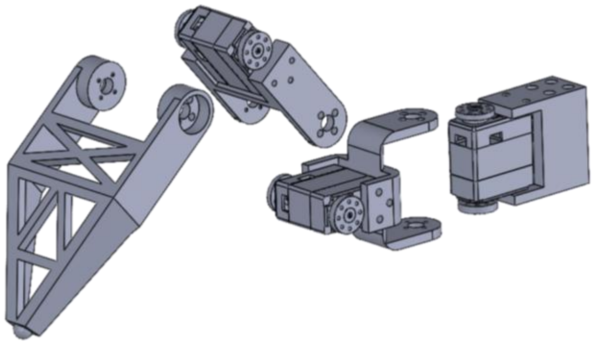


Figure 8: Final Leg of Robot

3.2.2 Concrete Extruder

The amount of concrete that the robot can carry depends on the motors and how much torque they can supply while still offering stability to the robot. Given that the goal for the current implementation is simple structures the 5 supporting legs can support, it is a matter of how much of that weight isn’t concrete. This includes the microcontroller, motor controller, body and leg weight, the printing and brick laying mechanisms, and anything else that will go on the robot. The remaining weight can be concrete. Then it is a matter of deciding how thick each layer and wall should be, and what the required ratio of water to cement powder is needed to sustain such a requirement. Then we will have an idea of just how much cement the robot is capable of carrying and operating with.

Printing concrete from layer to layer may have some restrictions. All purpose quick drying concrete has a working time of one hour. Given how slow the hexapod will walk using wave gait, it can be a safe assumption that by the time it is done with the first layer, it can move on to the next layer, though this can depend on the type of print, water content, layer height, and nozzle size. However, it should be noted that the print needs to be completed before the working time of the cement is up.

While there are examples of robots that can extrude cement, they do not operate in a similar way that the hexapod does. For the most part, robots that have a concrete extrusion mechanism either act like a 3D printer and move around a set frame and lay concrete similar to how an FDM printer extrudes plastic (Figure 9), or is designed as a robot arm with wheels at its bases to drive around and lay concrete. While the robot design is not similar to what is being developed, how the concrete extruded can work within the parameters of the robot and ultimately what was decided to be pursued as the extrusion mechanism. This mechanism has a tank that holds the concrete itself, and has a self contained swirler that rotates to flow the concrete at a given speed by the controller (Figure 10).

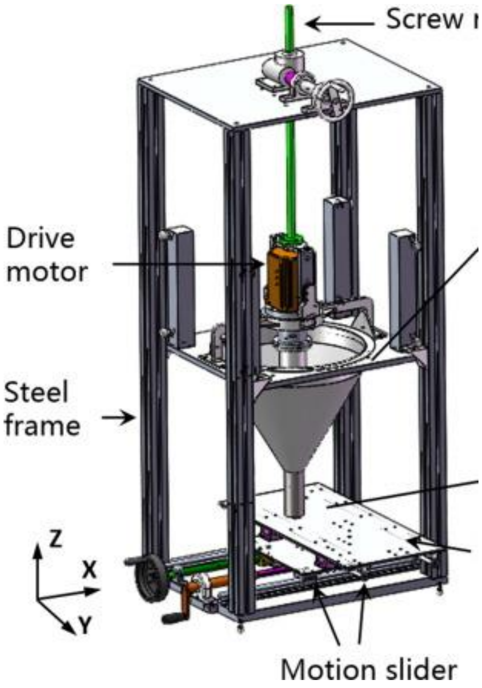


Figure 9: FDM Style Concrete Extrusion

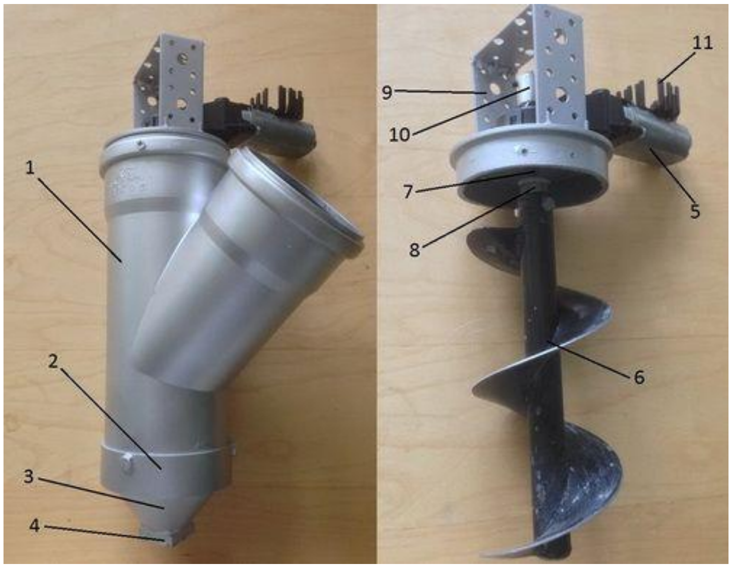


Figure 10: Concrete Extruder with a Swirler

For the tank that holds the concrete, special consideration needed to be held for the size of the tank and how it would fit into the center of the robot. One of the original ideas discussed for the tank was to have it take up the entire center of the robot and be cylindrically shaped and have a separate nozzle piece under the robot. But after further discussions, it was decided that the tank should be smaller than the diameter of the top and bottom plates. This is because the weight of concrete would add a lot of weight to the robot that could cause the legs to not hold up the weight and collapse. So the decision was made to reduce the diameter of the tank so the robot could not carry more weight than it could handle. It was also decided that the nozzle and the tank would be one solid piece to reduce the chance of concrete leaking. To do this the hole at the center of the bottom plate needs to be expanded to allow the lip of the tank to sit on the inside face of the bottom plate (Figure 11 and 12).

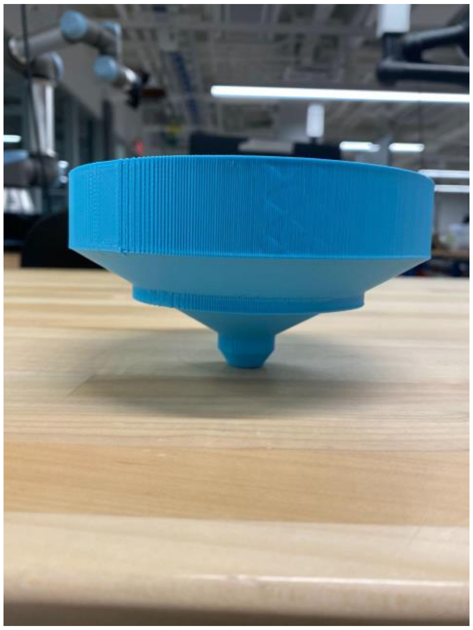


Figure 11: Front View of Concrete Tank

Figure 12: Top View of Concrete Tank

For the swirler that extrudes the concrete, a design similar to other swirlers was decided. The radial distance of the spiral was increased to prevent any of the concrete from pooling at the bottom of the tank, which would make the rate of extrusion not equal at all times which would lead to a failure in the printing of whatever is being made. The spiral does not go all the way down so that the concrete can collect at the nozzle and have an even rate of flow as it is extruded. The top of the swirler is in line with the top of the tank in order to control all of the concrete held within it (Figure 13 and 14). For the actuation of the swirler in order to make it spin to extrude the concrete, the motor driving it must be close to the top of the swirler. A thought that was discussed was possible expanding the center of the swirler and connected to the actuated part of the motor, with the motor resting on the top plate.

Figure 13: Concrete Swirler

Figure 14: Concrete Swirler Inside of the Concrete Tank

Following the first iteration of the concrete extruder, a proper mounting system for the swirler and the motor were created and tested both by hand and motor driven.

During motor driven testing, it was found that the tank and the swirler were too wide as well for the extrusion hole at the bottom of the tank. As a result, when loaded with concrete, the swirler would scrape in the inside of the tank if ever driven off axis. This, combined with the fact that the axle was too thin at a diameter of 5cm, resulted in the swirler breaking when driven by a motor. Additionally, There were additionally some gear meshing issues with the mounting platform, where during motor driven testing, occasionally there would be some flexing.

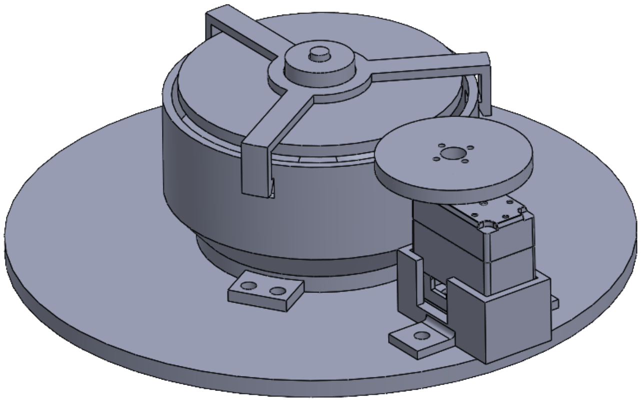


Figure 15: CAD model of rev2 concrete extruder system

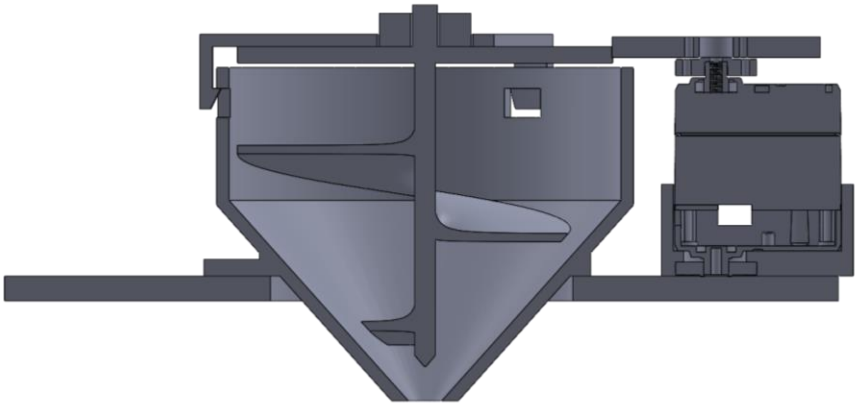


Figure 16: Cross section of rev2 of concrete extruder

Figure 17: Hand driven trial of rev2

Figure 18: Aftermath of motor driven trial of rev2

Revision 3 tried a different method of extrusion, though while still taking some design notes from past revisions. Revision 3 uses a pusher system, similar to that of a clay extruder used for ceramic 3d printing. The motor is now attached to the tank. Although this makes adjustments in motor position for gear alignment more difficult, it allows for a more robust power transmission. Misalignment of the threaded rod within the tank was additionally a concern from the last revision, so this iteration of swirler mount has two bearings on either end to prevent unnecessary bending and misalignment. Quick swap mounting tabs were also added to the tank, allowing for smoother transitioning between testing trials.

However, this design did not work. During testing, it seemed as if the difference in input versus output cross sectional area seemed too high to allow for concrete to extrude out the bottom. The pusher inside the tank is not flat bottomed as well, which may have also contributed to the extruder's inability to extrude. When tested using a motor, it was found that the water was just being squeezed out of the concrete mixture rather than a proper extrusion.

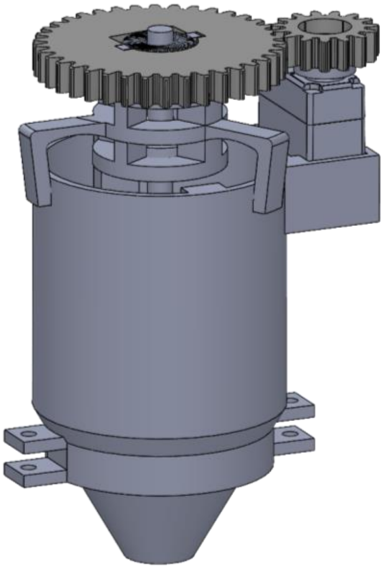


Figure 19: CAD model of rev3 pusher design

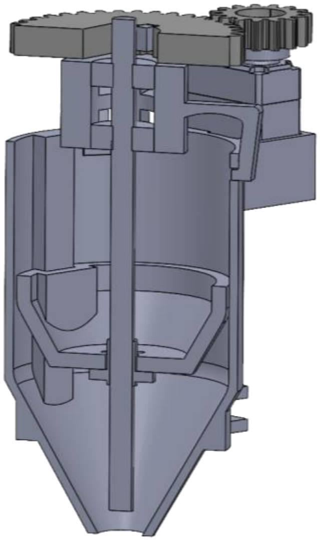


Figure 20: cross section of rev3 pusher design

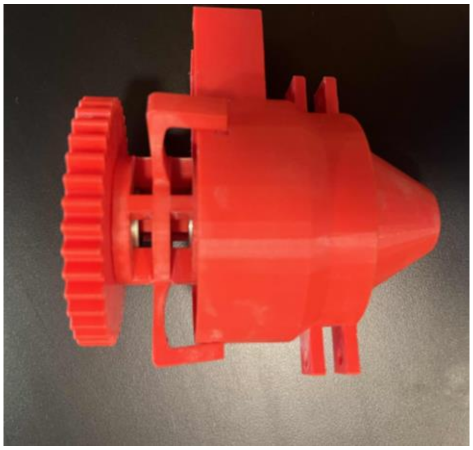


Figure 21: Model of rev4

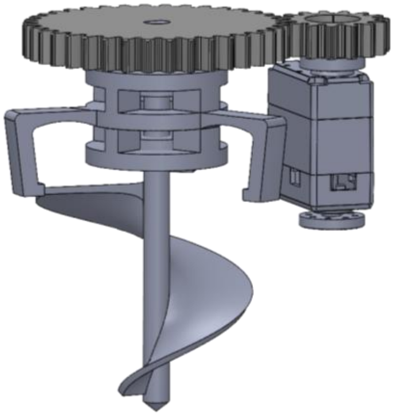


Figure 22: Inside view of rev4

For the fourth revision of the concrete extruder, it was decided to pursue the swirler design again. The improvements from the third revision were taken in the form of the swirler mount, gears, and a shorter tank. The large change for revision 4 was the concrete swirler. For this iteration, the revolution density was decreased so as to reduce the vertical stress on the swirler. This was done following the damage from the testing of revision 2 where the swirl portion broke upwards. Additionally, the axle was made thicker at 8 mm. However, during testing, it was found that there was too much shifting of the swirler during use. This again resulted in excessive scraping of the swirler against the inside of the tank, which broke or deformed the swirlers.

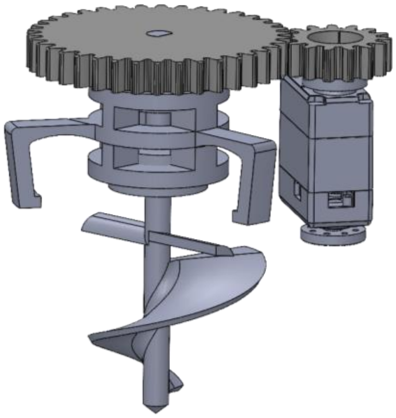


Figure 23: New swirler rev5

From the last revisions of the swirler, there was a strong need to reduce deformation and shearing of the axle and swirl portion. This was done in many ways so as to create a design that would remain strong under motor driven testing.

For the new model of swirler, aerators were added to keep the concrete from setting too much and to put ease on the swirl portion. Additionally the radius of the swirl potion was made smaller to combat scraping on the inside of the tank when concrete is added. The swirl portion length was also decreased from x to x to reduce the projected area that the swirl portion would be in contact with the concrete. This combined with increasing the revolution density and adding a chamfer, allow for a design that is able to withstand being motor driven and extrude concrete. The final version of the tank remained the same size but instead of a circular nozzle it had a rectangular nozzle shape. This was done so that the concrete extruded would be a rectangular shape to match the shape of the bricks to help with brick cohesion to the concrete

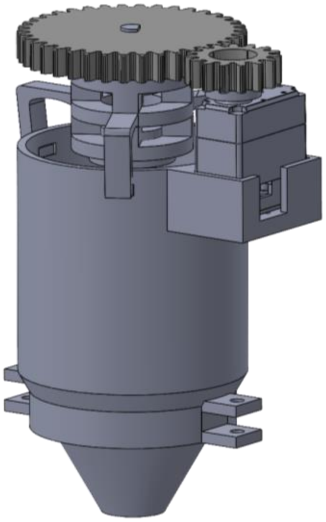


Figure 24: CAD model of rev6

Figure 25: inside of rev6

3.2.3 Brick Placing Mechanism

For the brick laying mechanism, it was decided to make the mechanism similar to a PEZ Dispenser, where the actuator when moved forces the candy to slide out. For our mechanism, a motor attached to the bottom face of the bottom plate would actuate the movement of the brick. A PEZ dispenser type mechanism was chosen because of its vertical stacking storage allowing it to be closer to the ground, which will be discussed more in Section 5.1.5.3.

During the initial design concept for the bricks and how they would be laid on top of the concrete, the shape of the brick needed to be discussed and thought through first. The shape of the bricks was between a perfect cube or a rectangular shape more akin to how actual bricks look. The main advantage to using a cubical brick for the construction system is that the orientation of the mechanism laying the bricks does not matter as long as it is in line with the concrete being extruded. The main advantage of the rectangular bricks is that it allows for a larger number of bricks to be stored, which allows the robot to run for longer amounts of time without needing to stop to get more bricks stored in its system. It was decided to move forward with a rectangular brick design over the cube ones because even though the robot is omni-directional, it will only move forward one way, and if the brick laying mechanism is placed directly behind the nozzle of concrete extrusion, the orientation does not matter for the rectangular bricks either. The bricks chosen have a dimension of 4.5x9x18 mm which allows us to store a large amount of bricks as well as the brick being thin enough to perfectly sit on the extruded concrete.

Once the size and shape of the bricks were decided, the next decision needed to be made was what kind of storage system would hold the bricks. The two designs that had the most promise were a radial storage system and a stacking storage system. The advantage to having a radial storage system is that the bricks could be placed at any position needed. But the cost of this is that to push each brick out you would need an equally long spring to wrap around the storage device and have enough tension to push each brick out. Another disadvantage of this type of storage is that to operate properly would need to be right under the bottom plate. So to place the brick the robot would need to move the legs in such a way that the robot is leaning forward or else the brick may rotate as it falls and not land on top of the concrete as intended. This is why a simpler stacking storage system was chosen to hold the bricks (Figure 26).

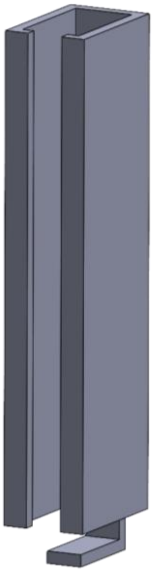


Figure 26: Brick Laying Storage Apparatus

For the actuation of the mechanism either a stepper motor moving back and forth similar to how a PEZ dispenser operates or two motor rollers on either side of the brick storage were to be chosen. The advantage of the motor rollers is that an even force is applied to both sides of the brick allowing for its placement to be smooth and landing perfectly on the concrete, compared to the stepper motor which has a chance of pushing the brick out at an undesirable angle. The stepper motor design was chosen however due to its simplicity and considering the size of the bricks, the motor rollers would need to be very small and would end up being more complex than is needed to lay the bricks. The mitigation taken to make sure the stepper motor design does not rotate the bricks is to have it very low to the ground to prevent the bricks from having enough time to move in an undesirable way.

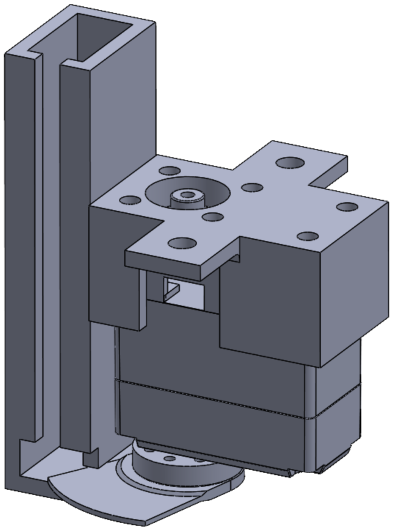


Figure 27: CAD model of rev2

The new iteration of the brick laying mechanism used a solid paddle to push the bricks out instead of using motor driven belts as was previously planned. This is due to the size of belts that could be used being too large to work with the size of bricks selected.

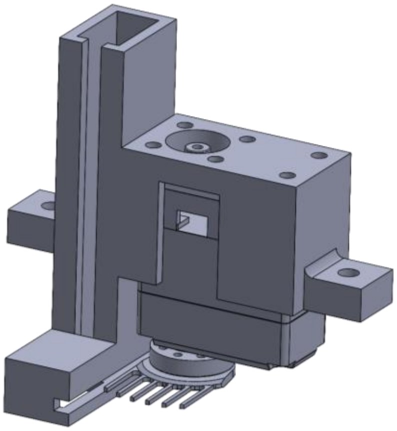


Figure 28: CAD model of rev3 with compliant 3d printed pusher

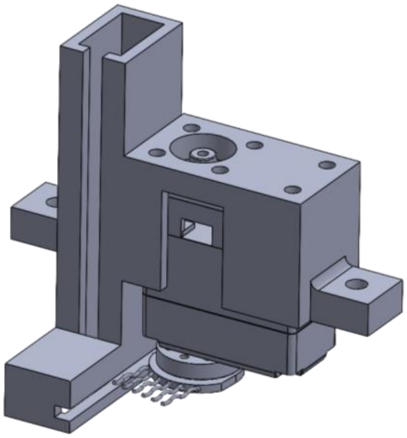


Figure 29: CAD model of rev3 with compliant pusher made from plastic broom bristles

For the next revision of the brick placer, a guide was added to aid in the alignment of bricks.
A more compliant pusher was also added in the event that a part or brick were to come out of place, the damage sustained to the motor and other parts would be minimal.
However, the guide does not perform consistently in aligning bricks, and the bricks fall unevenly once pushed out of the storage tank.

The final iteration of the brick placer changed to try and address the issue of the bricks not adhering to the concrete when placed. Instead of having a rotating paddle that would push the bricks out, the motor was placed further behind the storage cartridge and used links to and a paddle to push the bricks out in a linear motion. On the other side of the storage tank was a pusher mechanism that in the opposite cycle of motion of the brick pusher would move downwards. This was implemented so that as it moves past the bricks, the pusher will depress the bricks further into the concrete to help adhere the bricks to the concrete.

Figure 30: Final Iteration of the Brick Placer Mechanism

3.3 Software

3.3.1 Hexapod Definition

When working with the hexapod, some definitions must be made in order to control the robot. This is done within the realm of leg assignment and orientation assignment. Each leg has three joints and three segments. The segments are the coxa, femur, and tibia. The joints are the hip, knee, and ankle, each also respectfully known as the alpha, beta, and gamma angles.

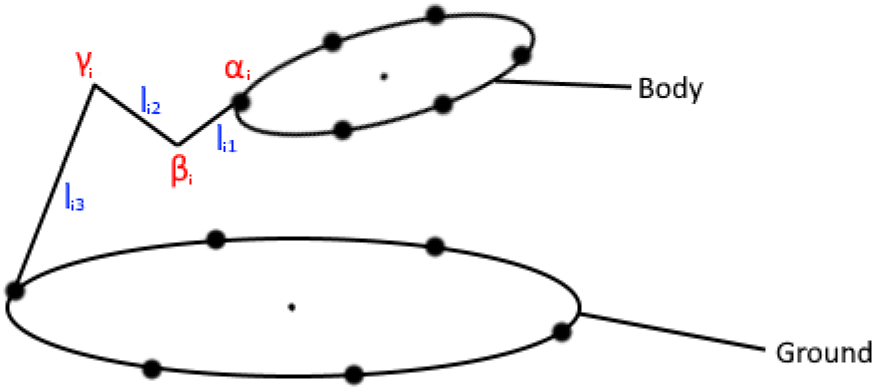


Figure 31: Hexapod leg joints and leg segments

Leg assignment is important as it allows for forward movement to be corrected. As the entire robot is a circle, forward movement of the hip motors means that only half of the motors would be rotating in the forward direction of the robot. This is able to be corrected in the assignment of leg numbers, where the direction of rotation can be multiplied by -1^n, where n is the assigned leg number (Equation 1).

The hip joints of the robot additionally need to be assigned properly. Wherein both forward and inverse kinematics, knowing where in space the hip joints are is imperative. The hip joint values, known as s_i values, are an array of 3 values for x, y, and z position in space with respect to the main body of the robot. In the matrices below, r is the radius of the main body from center to hip joint, and B is the angle between each of the legs. For this robot, r is 185 mm and B is 60 degrees.

$$s_1 = \begin{bmatrix} r\cos\left(\frac{B}{2}\right) \\ r\sin\left(\frac{B}{2}\right) \\ 0 \end{bmatrix}$$

$$s_2 = \begin{bmatrix} -r\sin\left(\frac{\pi}{6} - \frac{B}{2}\right) \\ r\cos\left(\frac{\pi}{6} - \frac{B}{2}\right) \\ 0 \end{bmatrix}$$

$$s_3 = \begin{bmatrix} -r\sin\left(\frac{\pi}{6} + \frac{B}{2}\right) \\ r\cos\left(\frac{\pi}{6} + \frac{B}{2}\right) \\ 0 \end{bmatrix}$$

$$s_4 = \begin{bmatrix} -r\cos\left(\frac{\pi}{3} - \frac{B}{2}\right) \\ -r\sin\left(\frac{\pi}{3} - \frac{B}{2}\right) \\ 0 \end{bmatrix}$$

$$s_5 = \begin{bmatrix} -r\cos\left(\frac{\pi}{3} + \frac{B}{2}\right) \\ -r\sin\left(\frac{\pi}{3} + \frac{B}{2}\right) \\ 0 \end{bmatrix}$$

$$s_6 = \begin{bmatrix} r\cos\left(\frac{B}{2}\right) \\ -r\sin\left(\frac{B}{2}\right) \\ 0 \end{bmatrix}$$

Equation 1: s_i matrices

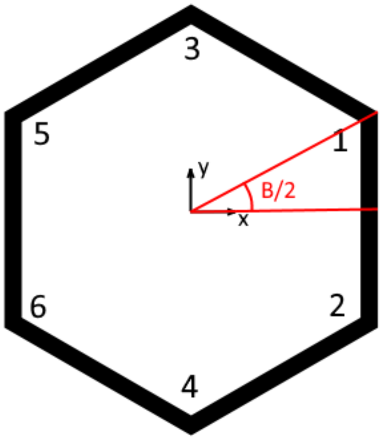


Figure 32: Leg and orientation assignment on the hexapod body (top down view)

When calculating the positions for each of the hip joints, a reference point needs to be chosen. In this case, s_1 is located at 30 degrees, or $B/2$.

However, these s_i values are not enough on their own, and for most forms of calculation, a transformation matrix R must be applied to the s_i values. For this transformation matrix, three angles are used as input to denote the rotation of the main body in this case. These angles are called euler angles. For a rotation matrix to work properly, it is important that the order of angles is maintained. For the case of this robot, the order is XYZ.

$$R_x(a) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(a) & -\sin(a) \\ 0 & \sin(a) & \cos(a) \end{bmatrix}$$

$$R_y(b) = \begin{bmatrix} \cos(b) & 0 & \sin(b) \\ 0 & 1 & 0 \\ -\sin(b) & 0 & \cos(b) \end{bmatrix}$$

$$R_z(c) = \begin{bmatrix} \cos(c) & -\sin(c) & 0 \\ \sin(c) & \cos(c) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R = R_x(a) \cdot R_y(b) \cdot R_z(c)$$

Equation 2: R transformation matrices

3.3.2 Parallel Robot Inverse Kinematics

Hexapods are very similar to parallel robots, where there is a top platform that can be translated and rotated through space as a result of legs running from the bottom platform to the top platform. In this case of the hexapod acting as a parallel robot, the end effectors are in contact with the ground and do not move. Having this hexapod be able to function as a parallel robot is imperative as this robot is required to be able to walk at any height within its range of motion to print multiple layers of concrete.

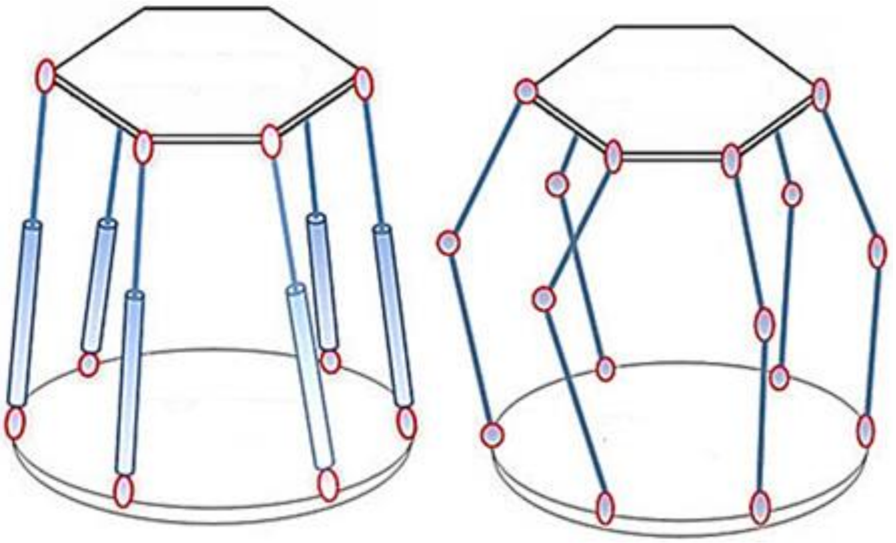


Figure 33: Parallel robot (left) and hexapod (right)

The way that this iteration of inverse kinematics works is that a target position is passed into the robot in the form of $\vec{O}$ and euler angles. Then using these inputs and the end effector positions, angles for each joint on each can be calculated using a series of four loop closures. These loop closures represent new values that need to be found in finding the joint angle values.

First Loop Closure:

The first loop closure is used to calculate the alpha values for each of the legs. Using equation 3, under the assumption that $\vec{O}$ and $\overrightarrow{u_i}$ are given, $\overrightarrow{l_i}$ can be calculated. However, this yields angles that are with respect to the ground. The angles that need to be passed in to the motors need to be with respect to each leg. This can be done by adding or subtracting the angle of the hip joint with respect to the ground.

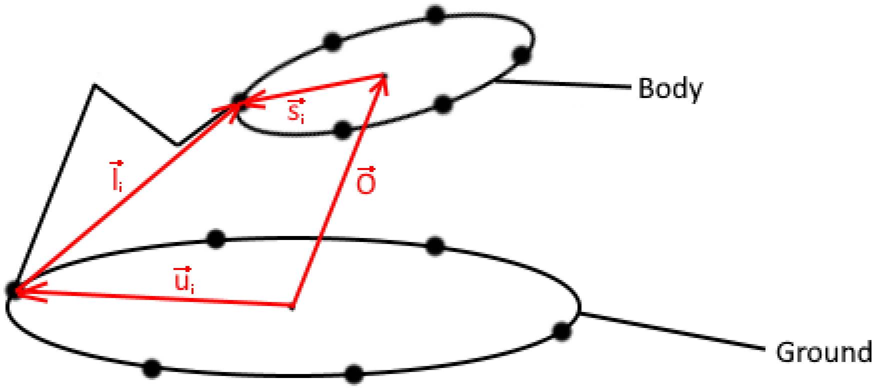


Figure 34: Visual representation of first loop closure

$$\vec{l_i} = \vec{O} + R\vec{s_i} - \vec{u_i}$$

Equation 3: $\vec{l_\imath}$ equation

- $\vec{l_\imath}$ is the vector from the hip joint to the end effector for each leg.
- $\vec{O}$ is the vector from the origin on the ground to the center of the body of the robot. This is also our target position for the body of the hexapod.
- s_i is the vector from the center of the body to the hip joint with respect to the body
- R is a rotation matrix applied to the s_i values so that they can be with respect to the ground.
- $\vec{u_\imath}$ is the vector from the origin on the ground to the end effector

$$\vec{l_i} = \begin{bmatrix} l_{ix} \\ l_{iy} \\ l_{iz} \end{bmatrix}$$

Equation 4: $\vec{l_\imath}$ matrix

$$a_i = \arctan\left(\frac{l_{iy}}{l_{ix}}\right)$$

Equation 5: α angle calculation using l_i values

Second Loop Closure:

Using the alpha angles from the first loop closure, $\overrightarrow{s_{\iota 2}}$ values can be collected for the next loop closure.

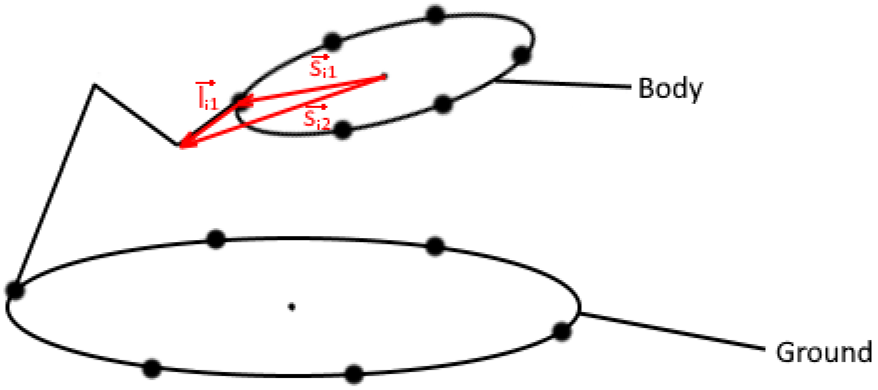


Figure 35: Visual representation of second loop closure

$$\vec{s_{i2}} = \begin{bmatrix} s_{i1x} + (-1)^i l_{i1} \cos(a_i) \\ s_{i1y} + (-1)^i l_{i1} \sin(a_i) \\ s_{i1z} \end{bmatrix}$$

Equation 6: $\overrightarrow{s_{\iota 2}}$ matrix

Third Loop Closure:

For the third loop closure, the previously calculated $\overrightarrow{s_{i2}}$ values are inserted in equation 3 to calculate a new set of l'_i values to isolate the bottom triangle that is created in the fourth loop closure.

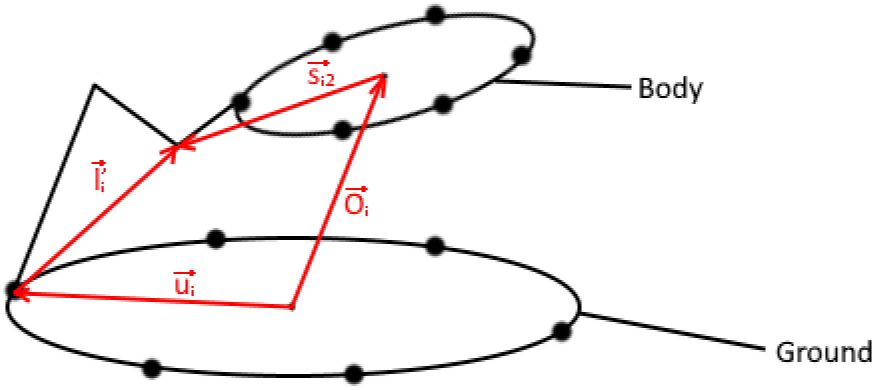


Figure 36: Visual representation of third loop closure

$$\vec{l'_i} = \vec{O} + R\vec{s_{i2}} - \vec{u_i}$$

Equation 7: $\overrightarrow{l'_i}$ equation

Fourth Loop Closure:

In the fourth loop closure, a plethora of values are used to calculate β and γ. This works by using the law of cosines to solve for gamma.

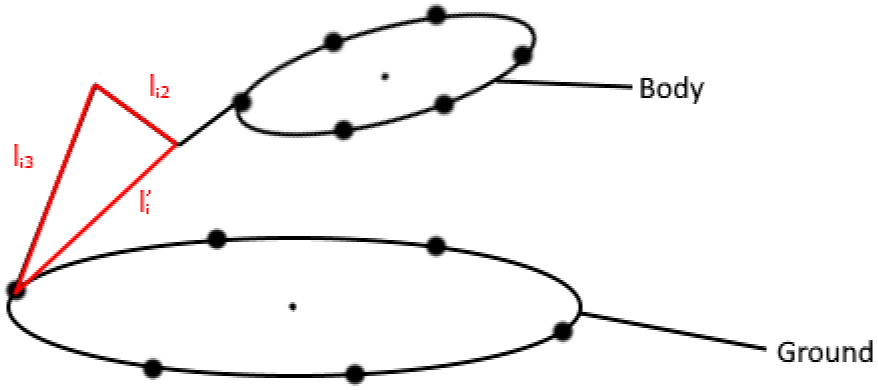


Figure 37: Visual representation of fourth loop closure

$$\beta_i = \arccos\left[\frac{l_{i2} + l_i'^2 - l_{i3}^2}{2 l_i l_i'}\right] - (\rho_i + \phi_i)$$

Equation 8: β_i equation

$$\rho_i = \arctan\left[\frac{l'_{iz}}{\sqrt{l'^2_{ix} + l'^2_{iy}}}\right]$$

Equation 9: ρ_i equation

$$\phi_i = \arcsin\left[\frac{l'_{iz} - l_{iz}}{l_{i1}}\right]$$

Equation 10: ϕ_i equation

$$\gamma_i = \pi - \arccos\left[\frac{l_{i2}^2 + l_{i3}^2 - l_i'^2}{2 l_{i2} l_{i3}}\right]$$

Equation 11: γ_i equation

3.3.3 Forward Kinematics

The end effector positions should be known at all times. A way that this can be done is through the use of forward kinematics. In the previous case of the parallel robot, the end effectors are not moving. This means that the end effector positions only need to be calculated once. However, in more complicated cases where the robot is moving, this end effector calculation will need to happen more often.

The first thing that needs to be done is to figure out where the hip joint is with respect to the ground. This can be done by applying the transformation matrix to the hip joint values $\vec{s_i}$ and adding $\vec{O}$ to it, where $\vec{O}$ is the current cartesian position of the hexapod body.

Once the position of the hips are known, then using the leg lengths and joint angles, the positions of the end effectors of the legs can be calculated.

However, this is in the case of the main body being parallel with the ground. In the event that the main body of the robot is rotated at all, that rotation must be taken into account when calculating the position of the end effector. This tilt angle can be found by using the euler angles to calculate what the tilt angle is for each of the hip joints.

3.3.4 Walking

For the hexapod to walk, the end effectors of the legs need to move in a certain manner. For this case of walking, a wave gait is being used, though the following trajectory can be used for any type of standard gait.

Trajectory points for walking are generated based on the home position of the robot, where height and length steps are input to define geometries. This is done by initially finding the position of the end effector with respect to each leg origin using either forward kinematics based on the leg joint angles or by using a CAD model. As this is done with respect to each leg's base or alpha joint, all of the home position values are the same. Once this home position is known modifiers based on length and height step can be used to generate the trajectory points.

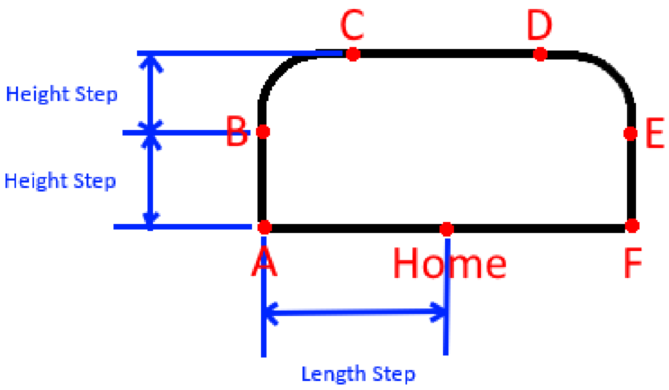
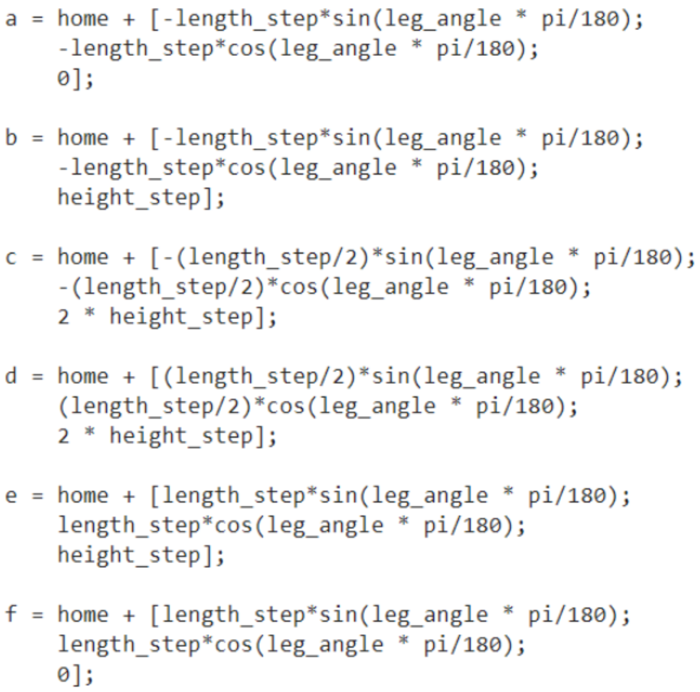


Figure 38: Trajectory of leg end effector



```
a = home + [-length_step*sin(leg_angle * pi/180);
    -length_step*cos(leg_angle * pi/180);
    0];

b = home + [-length_step*sin(leg_angle * pi/180);
    -length_step*cos(leg_angle * pi/180);
    height_step];

c = home + [-(length_step/2)*sin(leg_angle * pi/180);
    -(length_step/2)*cos(leg_angle * pi/180);
    2 * height_step];

d = home + [(length_step/2)*sin(leg_angle * pi/180);
    (length_step/2)*cos(leg_angle * pi/180);
    2 * height_step];

e = home + [length_step*sin(leg_angle * pi/180);
    length_step*cos(leg_angle * pi/180);
    height_step];

f = home + [length_step*sin(leg_angle * pi/180);
    length_step*cos(leg_angle * pi/180);
    0];
```

Figure 39: Trajectory point calculations in Matlab

However, the issue with this approach is that the orientation of the legs are different with respect to the body of the robot. For the robot to walk properly, all the legs must be moving in the same direction. To remedy this, the matrix of trajectories is multiplied by an angle modifier specific to each leg so that the legs can all move in the same direction. This allows the robot to be able to walk at any height (in its range of motion) in any direction.

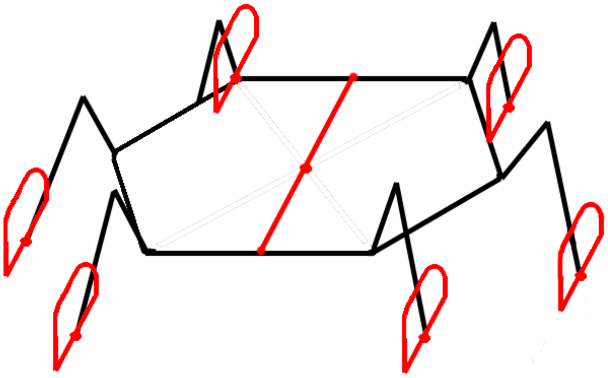
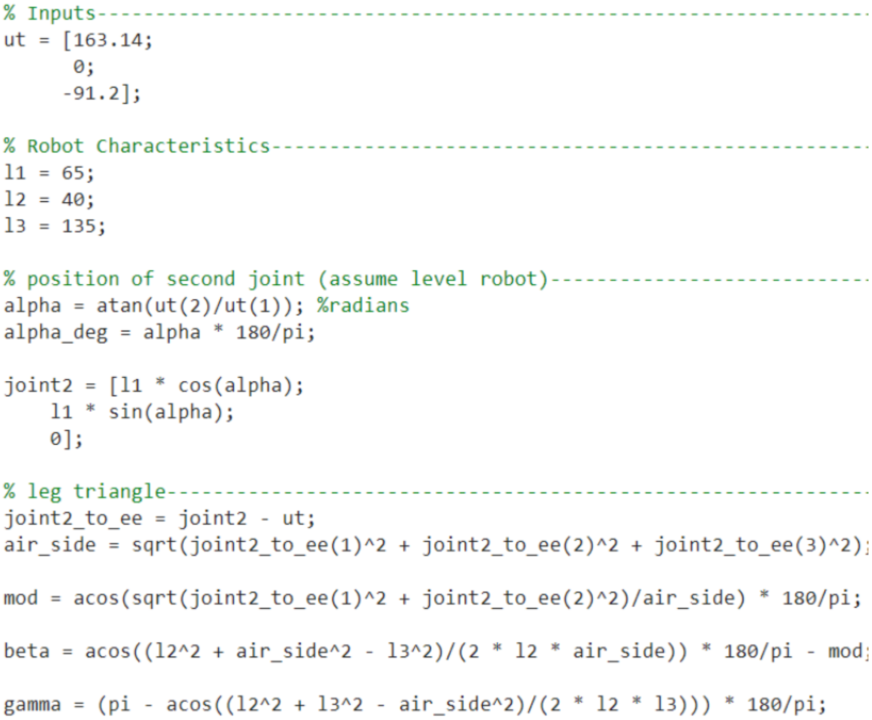


Figure 40: visualization of leg trajectories

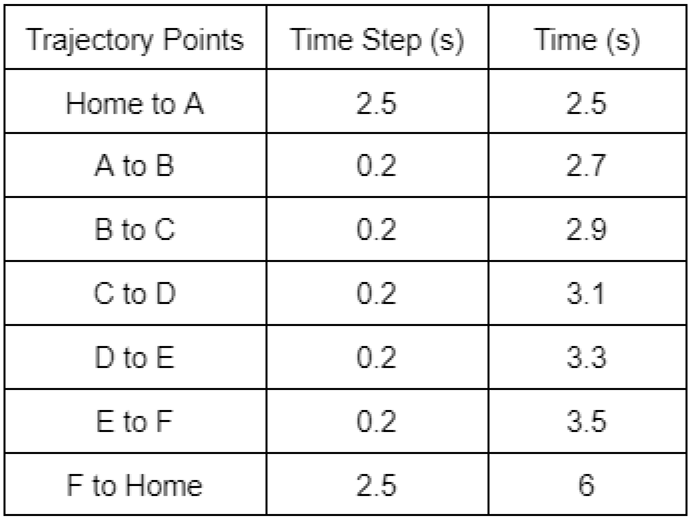
Once leg specific trajectory points are generated, the next step is making the legs move to these points. This is done using inverse kinematics very similar to that of parallel robot inverse kinematics described in Section 5.2.2, though with the body staying parallel to the ground.



```
% Inputs-----------------------------------------------------------------
ut = [163.14;
      0;
     -91.2];

% Robot Characteristics---------------------------------------------------
l1 = 65;
l2 = 40;
l3 = 135;

% position of second joint (assume level robot)---------------------------
alpha = atan(ut(2)/ut(1)); %radians
alpha_deg = alpha * 180/pi;

joint2 = [l1 * cos(alpha);
    l1 * sin(alpha);
    0];

% leg triangle------------------------------------------------------------
joint2_to_ee = joint2 - ut;
air_side = sqrt(joint2_to_ee(1)^2 + joint2_to_ee(2)^2 + joint2_to_ee(3)^2);

mod = acos(sqrt(joint2_to_ee(1)^2 + joint2_to_ee(2)^2)/air_side) * 180/pi;

beta = acos((l2^2 + air_side^2 - l3^2)/(2 * l2 * air_side)) * 180/pi - mod;

gamma = (pi - acos((l2^2 + l3^2 - air_side^2)/(2 * l2 * l3))) * 180/pi;
```

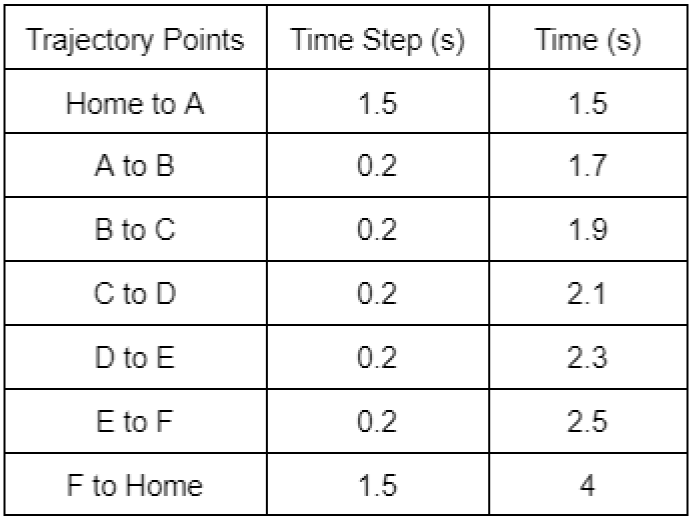
Figure 41: Inverse kinematics of single leg with sample input

After each of the legs can move to specified trajectory points, the next step is synchronization of legs for walking. For wave gait specifically, only one leg is in the air at a time, where when one leg touches down, another goes up. As this happens, the remaining 5 legs are moving the robot at a constant speed to actually move the robot. This means that the uptime of the leg needs to be a fifth of its downtime as there are six legs on the robot. Similarly, a quadruped walking in wave gait would need leg uptime to be a third of its downtime.



Trajectory Points	Time Step (s)	Time (s)
Home to A	2.5	2.5
A to B	0.2	2.7
B to C	0.2	2.9
C to D	0.2	3.1
D to E	0.2	3.3
E to F	0.2	3.5
F to Home	2.5	6

Figure 42: synchronization chart for 6 legged wave gait



Trajectory Points	Time Step (s)	Time (s)
Home to A	1.5	1.5
A to B	0.2	1.7
B to C	0.2	1.9
C to D	0.2	2.1
D to E	0.2	2.3
E to F	0.2	2.5
F to Home	1.5	4

Figure 43: synchronization chart for 4 legged wave gait

As the hexapod can gyrate given positional and rotational inputs, the robot can move to certain poses prior to walking for printing and maneuvering purposes. This is called takeoff walking, similar to that of a plane, where the robot is moving prior to walking. The only difference in the walking of the robot is that instead of starting and ending a leg cycle on the home position, the cycle starts and ends on either A or F depending on the leg. This is due to the fact that the hexapod is starting its walk not from home position but from the initial gyration pose.

4.0 System Testing and Results

Large points of contention in testing the systems came in the form or general movement or locomotion and materials testing. Movement tests came in the form of gyration and walking tests, while materials testing consisted more of trial and error to see if new designs were suitable under load.

4.1 Movement Testing

Gyration testing consisted of sending the robot to different poses to see the type of movement that was capable within its range of motion. This means that even though the robot can move to a certain position, depending on the rotation as well, some points would be outside of the range of motions when coupled with specific angled poses. After testing, it was found that the robot could comfortably move about 10 centimeters in all directions with any euler angle less than about 7 degrees.

Once the range of motion of the robot's gyration capabilities were found, it was next to figure out how slowly the robot can move to a given pose. As the rate of 3d printing is generally slow, it is important to see that the robot be able to move from point to point slowly without any stuttering, as stability is paramount when printing. By sending the robot from one pose to another 10 centimeters away over the course of five seconds, the robot is able to move steadily enough where the print quality is passable. Below is a test print showing this specific protocol.

Figure 44: Steady Print Test

Walking was tested by how well the robot was able to consistently move in one direction at a steady velocity. This testing was done by filming the robot walk over a measured distance and seeing how fast the robot would walk on average. For a length step of 10 centimeters with time steps identical to that of Figure 42, the robot was able to walk at a rate of about 6 centimeters every 3 seconds, or about 19 mm/s. However, the more important aspect is that this is a consistent 19 mm/s, as that allows for best print quality whilst walking.

4.2 Materials Testing and Synchronization

The working ratio of concrete powder to water ended up being around 350g of concrete to about 80g of water. This mixture was able to yield concrete that was still able to flow through the concrete extruder, while still being firm enough to hold its place once it is extruded. However, this working ratio needed to be adjusted for every trial based on how well the concrete powder was sifted from the larger sediment.

Two different types of tests were done for robot printing. The first one was printing a straight line. This was done in both gyration and walking. For the gyration line testing, no bricks were laid down on account of the design limitations of the brick placer. For the walking testing, a longer line is able to be drawn, so bricks were placed on top of the concrete for this testing.

Gyration line testing was adequate, so long as the concrete extruder was primed ahead of time so concrete would come out at the right time. Walking line testing was more temperamental as the concrete extruder and brick placer had to be in the same line of motion, otherwise some bricks would miss and fall off. This also came to be an issue if the robot became unlevel for any reason, the brick placer could very easily interfere with the print quality due to clearance. Due to this, the success rate for printing a line and laying bricks on top was rather low.

Figure 45: Successful Walking Line Print Test Result

The second test was to print a simple four-sided structure. Structure printing was simplified to a 10x10 centimeter square stacked at one to three layers high. Using these parameters and controlling print speed, extrusion speed, and other factors, the robot was able to print this basic structure (Figure 44).

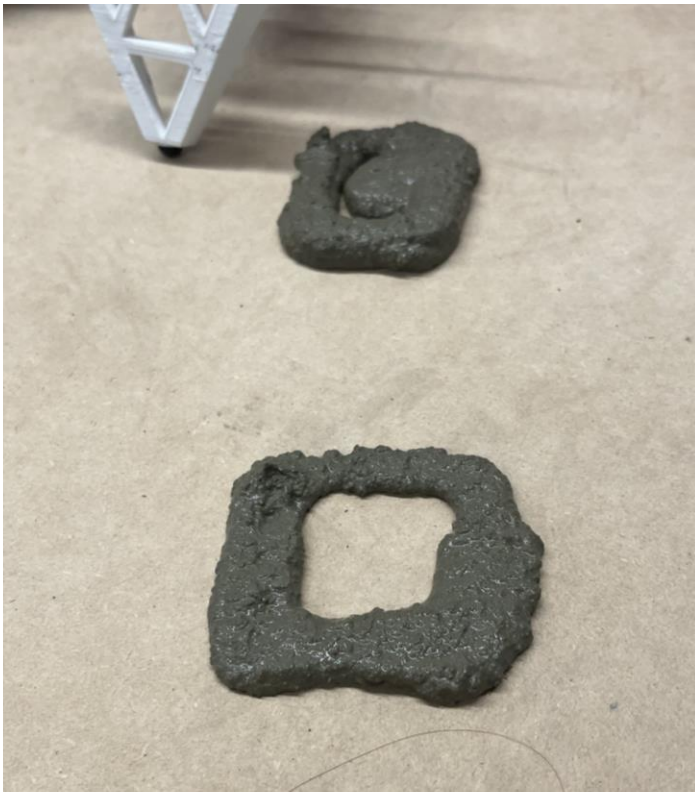


Figure 46: 1 Layer Square Test Prints

Figure 47: 3 Layer Square Test Prints

Under these tests, the main metrics for success were accuracy and consistency. It was imperative that the robot be able to consistently move to exactly where it was needed, when it was needed.

5.0 Conclusion and Recommendations

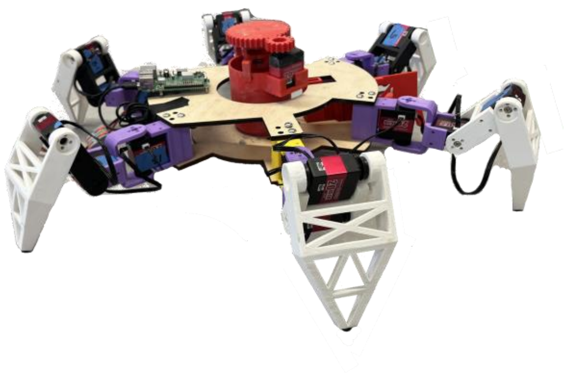


Figure 48: Final Version of Robot

The robot was able to move, walk, and print with not just one but two materials. The key conclusions that were drawn from this project is that FDM style printing by that of a hexapod is very possible and that there is more to be discovered here. This hexapod is one of the first of its kind by being able to walk and move around and print at the same time in an ordered manner.

Recommendations for future work include: spatial awareness, gyroscopic sensor and additional leg joint for on–the-fly terrain mapping, g-code implementation, and a separate, pressurized concrete tank. These changes allow for the scope of this project to reach much farther than in its current iteration. However, there are still testing changes that could be made to this robot to make testing and setup much easier and straightforward. This may include making the concrete extruder mix the material for you or creating a test rig to make working on the robot less inconveniencing.

A big part of working on this project was learning the proper math just to be able to make the hexapod move in the intended manner. As this is rather advanced, this is something that took more time than originally intended, which also halted the development of the rest of the robot. As this is something so ingrained in the nature of this robot, it is recommended that future groups still familiarize themselves with this math and system so as to have a better holistic view over the entirety of the project.

What this project is able to establish is that this is just the beginning of additive manufacturing robots, and whether it be for the purpose of housing or even self-repair, this is capable of changing the way that we view manufacturing as a society.

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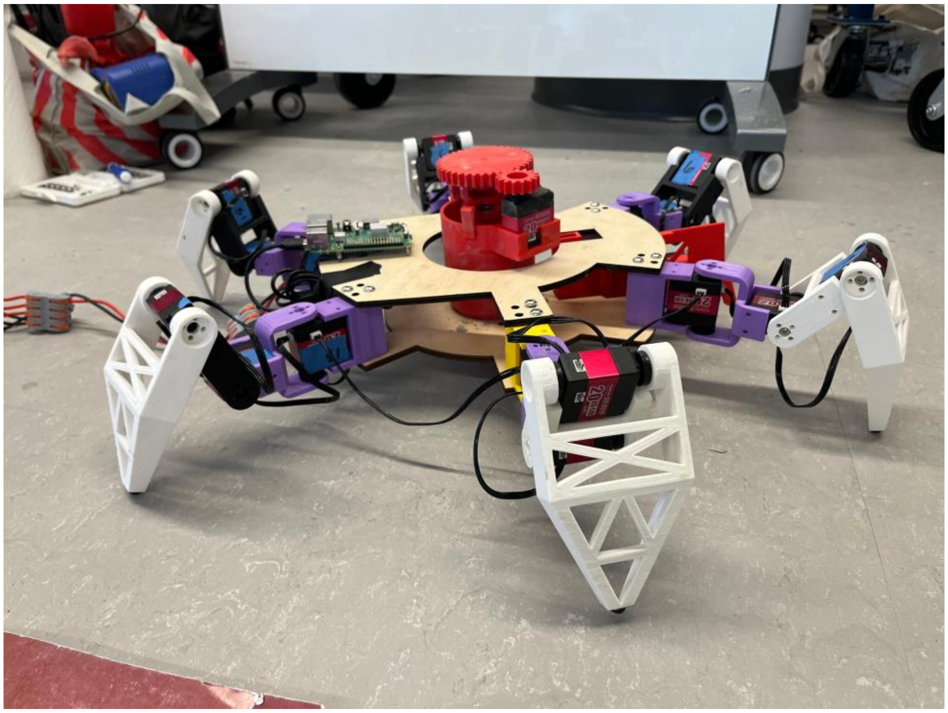
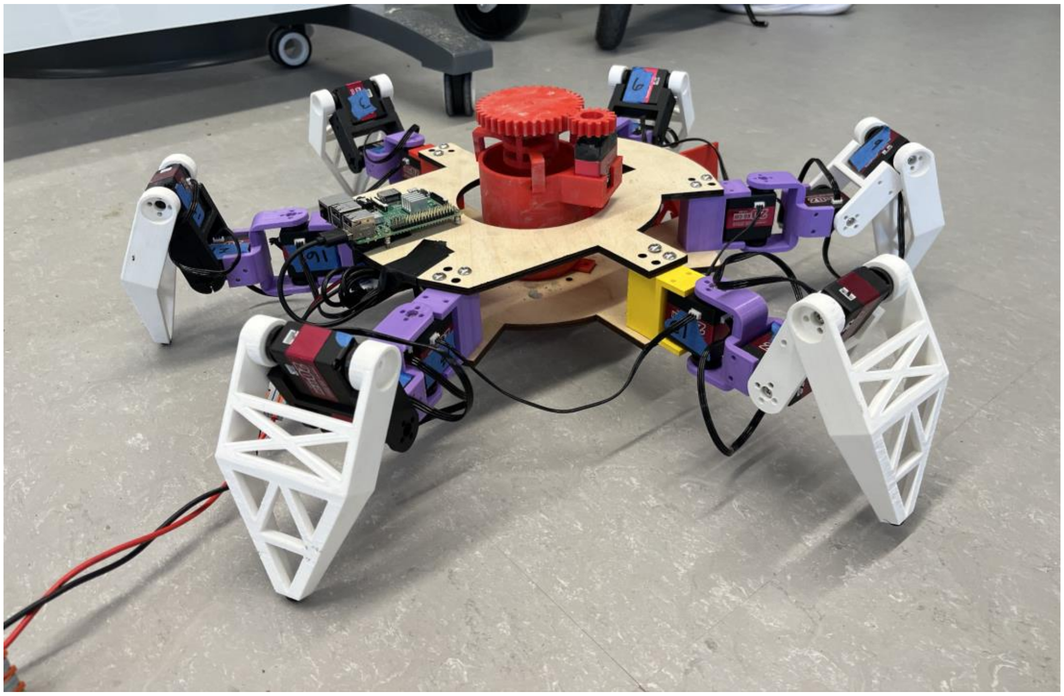
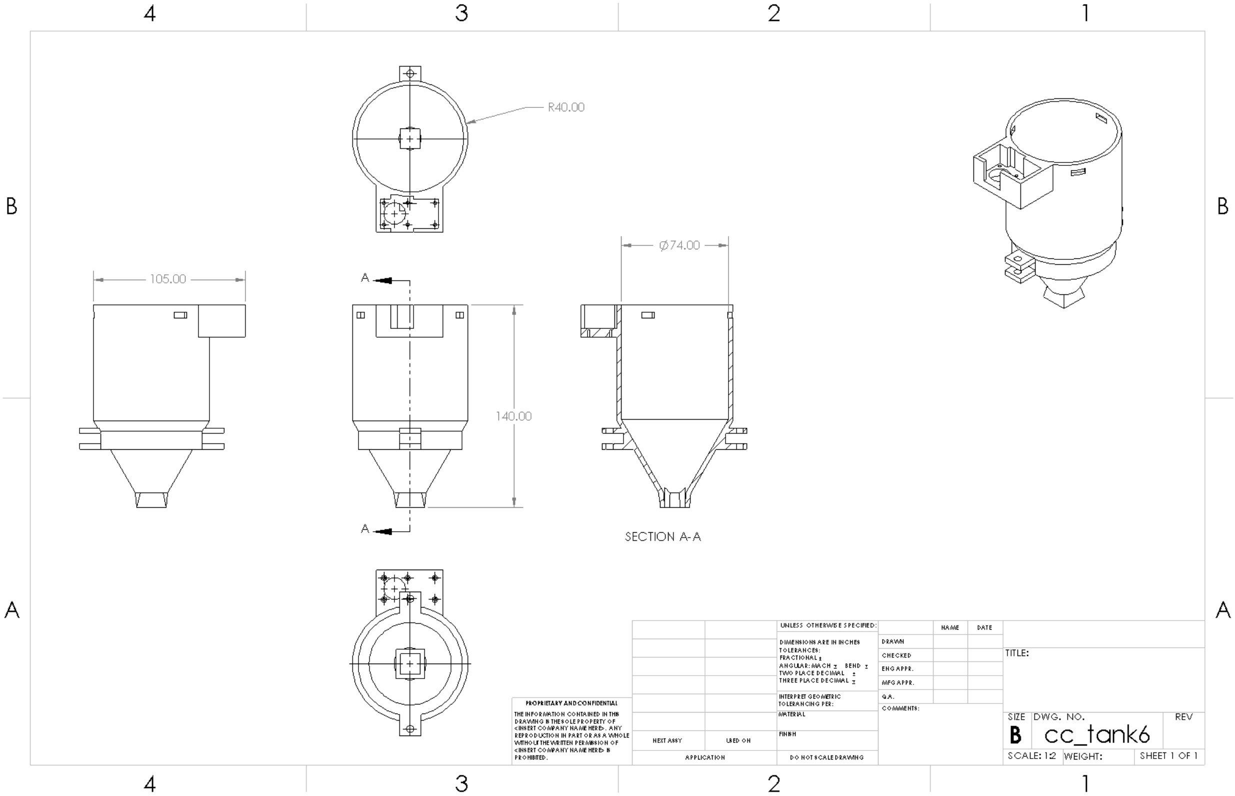
Appendices

A Final Robot Pictures





B CAD Drawings of Parts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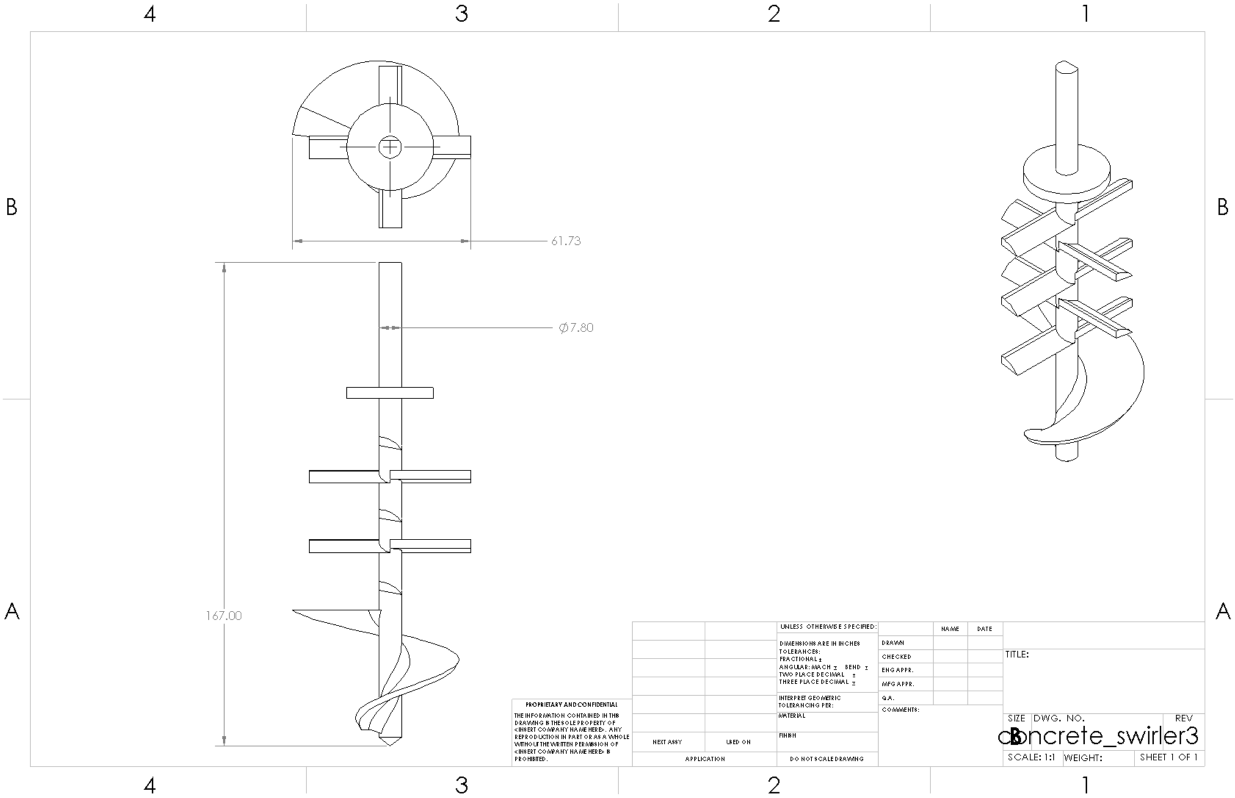
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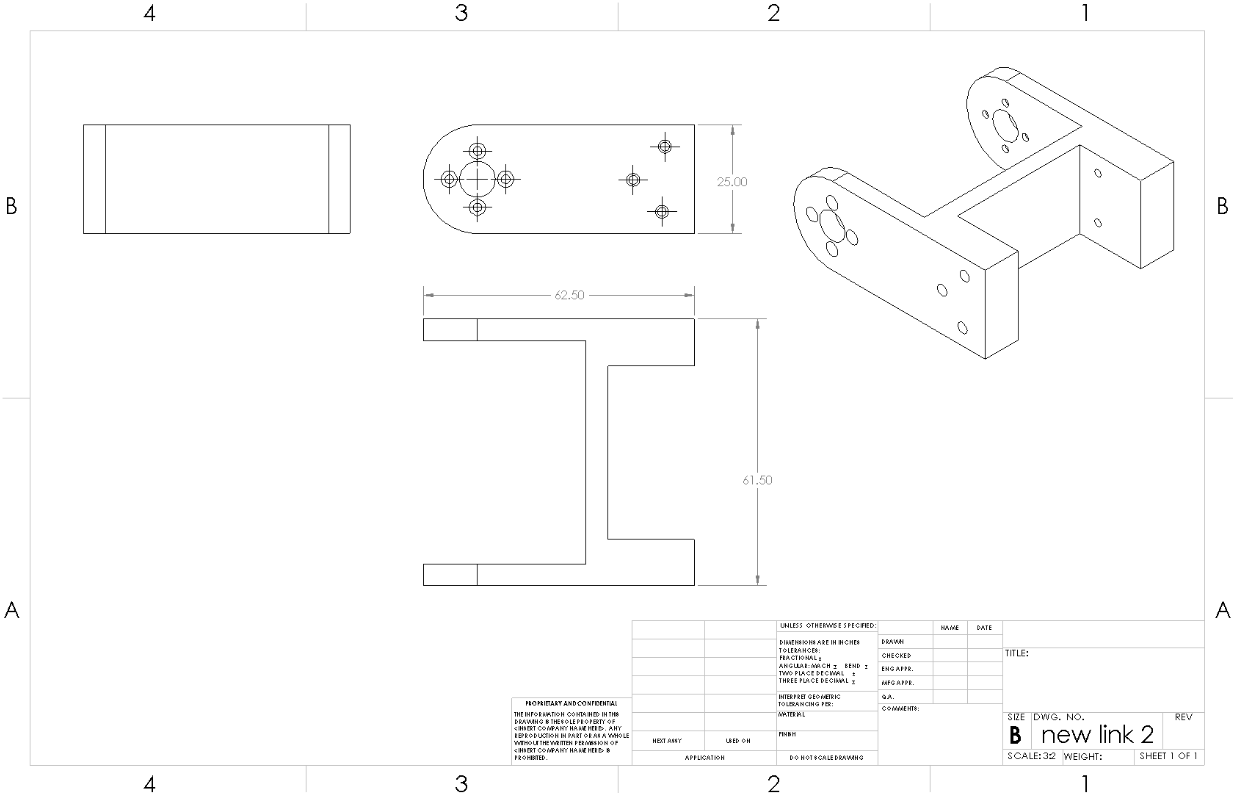
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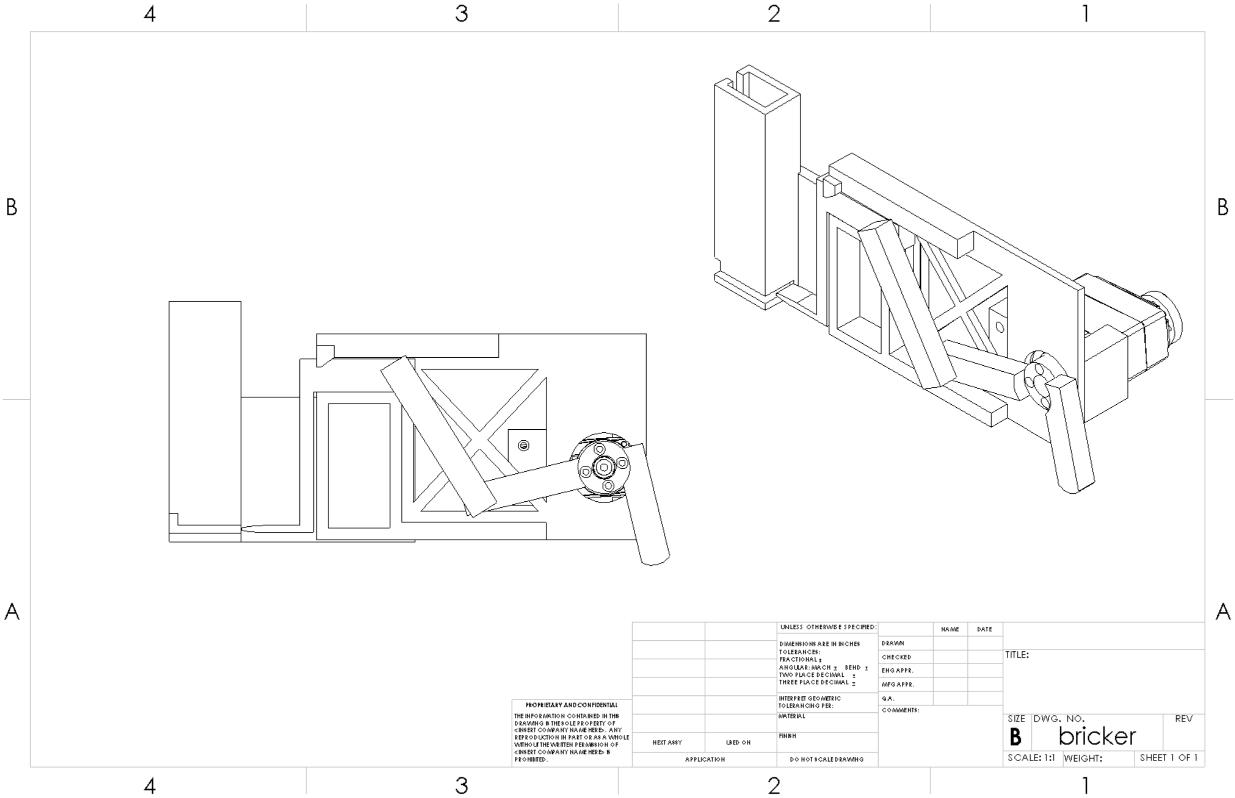
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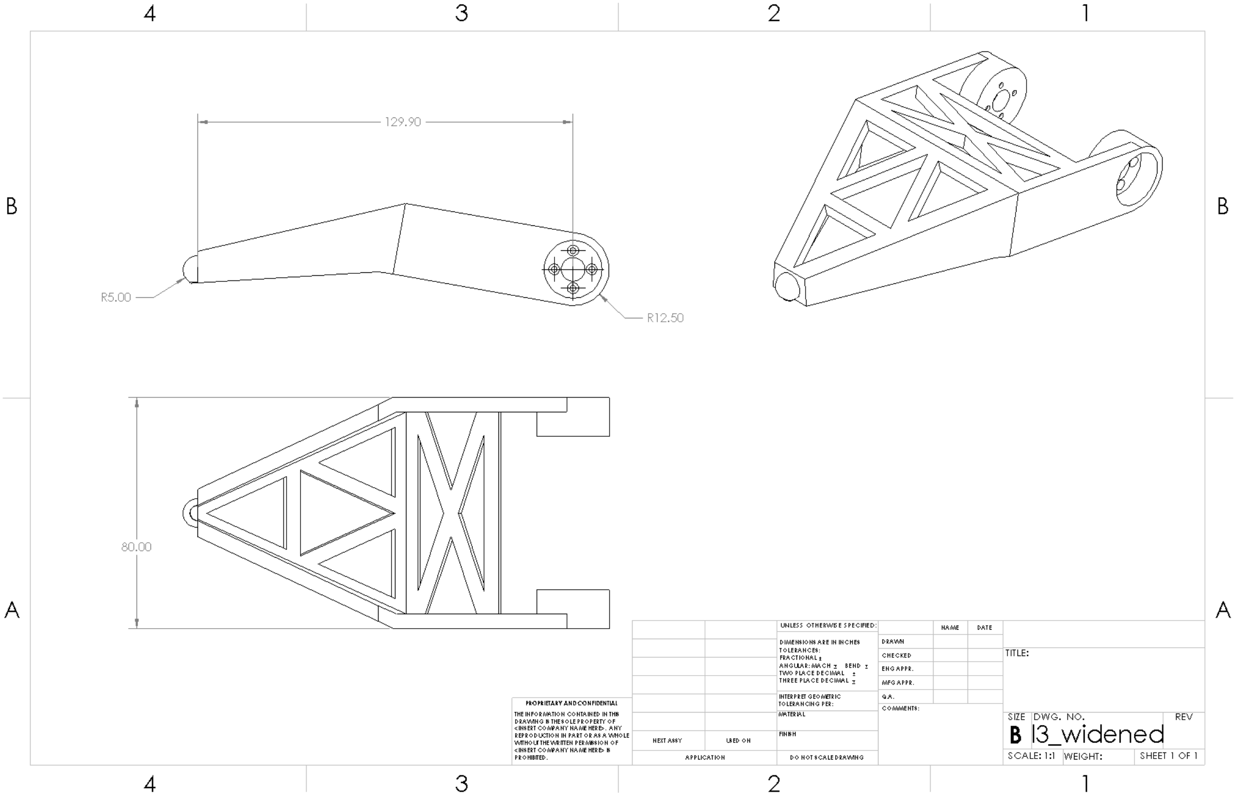

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