

POLAR COORDINATE FARMBOT

FINAL PROJECT REPORT

Interdisciplinary Senior Project 2016-17



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Executive Summary

FarmBot Inc. is a local startup that is advancing precision agriculture through automation and open source technology. The original FarmBot model, FarmBot Genesis, operates over a rectangular area of 3 x 1.5 meters. It plants, waters, weeds and grows produce autonomously using CNC technology. Our project sponsor and inventor of FarmBot, Rory Aronson, tasked our team with developing and testing a polar coordinate farmbot capable of performing on par with the Cartesian farmbot in growing a circular vegetable garden in a user's backyard. A successful project was defined by meeting specific customer requirements and engineering specifications predetermined and discussed with our sponsor. The customer requirements include: a central pivot, accurate planting, scalable farming area, off the shelf parts, and easy customization by the user. Some of the most important polar farmbot engineering specifications include a minimum farmable area of 4.5 m², maximum cost of \$2200, rotational range of at least 360 degrees, and an average velocity of .5 meters per second.

The polar FarmBot was split into several subsystems: arm, base, drivetrain, electronics, and software. Our initial conceptual design was selected with the use of decision matrices to optimize for reliability and simplicity while still fulfilling the customer and engineering requirements.

The final design for the base subsystem includes a concrete bucket with an adapter plate and a 4.5 inch aluminum pipe secured by a bent plate and two u-bolts. The adapter plate sits on three threaded bolts to allow for easy leveling and adjustment. The pipe works in conjunction with the adjustable bearing mounts to sustain the moment exerted on the base by the column and arm. The adjustable bearing mounts also keep the system vertical and centered. Additional stability can be achieved by burying the concrete bucket underground, but regardless, the concrete bucket as the base provides enough stability for use above ground over a raised bed.

The drivetrain subsystem reuses two existing farmbot drivetrains for the movement of the z-axis and r-axis. The center rotation drivetrain system uses a NEMA17 stepper motor coupled with a 51:1 planetary gear to generate additional output torque. The final design of this subsystem has the motor output shaft mate directly with a fixed d-shaped base plate with a turntable in between to allow for rotation. This system was considerably simpler and easier to assemble than other designs. The use of a steel d-shape plate was discovered to be important in minimizing deformation and subsequently any backlash in the rotation. Encoders should also be implemented in future versions to resolve this problem.

The tool bay's final design consists of a circular pattern with six tooling slots. 3D printed clamps allow for the toolbay to be attached to the aluminum pipe. For our prototype, the toolbay was laser cut out of wood, but for future iterations, a stiffer and flatter material would ease the tool removal and replacement operations. Above the pipe and tool bay sits a 3D printed column shroud. The shroud is designed to weatherproof the pipe from water and debris accumulation.

Wiring runs through a rectangular cutout in the tool bay and over the shroud up to the electronic housing that contains the microcontrollers that control the FarmBot movements. Water and air tubing also runs from the base of the FarmBot and into the gantry arm where it is connected to the universal tool mount. The electronics on the FarmBot consist of a Raspberry Pi, which communicates with the FarmBot cloud, and an Arduino MEGA, which runs the RAMPS

motor controller. These two devices on the FarmBot communicate using G-Code, an industry standard for controlling devices such as CNC machines and 3D printers.

The report goes into detail about safety concerns involved with our final design as well as maintenance considerations that the end user would need to follow in order to keep the FarmBot operational. Our team documented all the tools, materials, manufacturing processes and steps taken to fully assemble our prototype. Further documents such as drawings, project schedule, and all other literature can be found in the appendices. Overall our prototype was functional and exceeded our expectations.

Chapter 1: Introduction

The FarmBot Genesis is an automated gardening system, invented by our project sponsor Rory Aronson, and built by his startup, FarmBot. The standard-sized Genesis v1.0 model can be installed on a pre-existing garden box and has the capacity to grow all of a single user's recommended vegetable needs. The device operates using CNC technology similar to a cartesian 3D printer to plant, weed and water vegetables. It is claimed to produce 25% fewer carbon emissions compared to conventional farming techniques and can be combined with solar panels to further decrease its carbon footprint. Through growing produce instead of spending money at the grocery store, the Genesis v1.0 model has a return on investment of three to five years.

Documentation, software and design files pertaining to all FarmBot models are readily available online for educators and the DIY community. Additionally, the operating code is open-source, making it possible for anyone to build, research or develop a commercially automated farming system. Possibilities for modification of FarmBot are endless and can be accomplished with consumer grade 3D printed parts or readily available off-the-shelf parts.

Currently, FarmBot only produces the Genesis model, however Rory Aronson has requested the design and fabrication of a new model. This new FarmBot model will rotate around a central axis and will be based on a polar coordinate system instead of cartesian coordinate system. We are designing this product as an exploration into future possibilities of FarmBot. In the end, our sponsor is looking to see if a polar operating FarmBot is feasible or if it has any advantages over the cartesian FarmBot.

To accomplish this, we plan to iterate and test a number of functional prototypes, with the goal of creating a final prototype ready for production. Simplicity and manufacturability are our sponsor's guiding values, for an end user group that includes educators, makers, and hobbyists who value hackability, scalability and reliability.

1.1 Objectives

In order to create a polar FarmBot that satisfies both our end user and sponsor's needs, our team generated a list of technical requirements for the project, many of which are derived from the existing cartesian FarmBot. To achieve many of these requirements, we utilized existing, generic, off the shelf, or easily user-manufactured parts. We also kept in mind that parts in this category must be designed for manufacturing, such that they could be produced in mass quantities, or on a part by part basis by the individual builder with prototyping tools.

Each user's garden plot is different, so our design needed to scale to fit existing plots or increase in size to provide for larger fields. Backyard farmers or researchers may need a customizable platform upon which they can grow, fertilize and weed in any way they chose. For example, this means that the polar FarmBot needs to have options for the farmer to weed either chemically or physically, and should be able to operate from multiple types of water sources such as elevated rain barrels or pressurized fertigation systems. The customers will also have varying food production requirements, so at minimum, produce yield must be enough to sustain one individual continuously, which has been calculated by our sponsor to be possible with a 4.5 square meter plot.

To satisfy our customer, the FarmBot must be reliable and easily serviceable. Ease of access to internal components such as the Arduino and Raspberry Pi, and the use of standard

fasteners and tools are important to the DIY community. Websites like openbuilds.com, an online retailer and guide for DIY CNC, will provide inspiration for designs this subgroup is accustomed to. Openbuilds.com also provides many components complementary to our FarmBot design.

The main objectives addressed above provide the framework for meeting our project's specific needs. We have quantified more detailed engineering requirements in Table 1 concerning geometry, motion, safety, and operational parameters. We have ranked each requirement with a risk of high, medium, and low directly relating to our priority levels for each item. To meet these requirements, we have compliance methods listed in the far right column. Most of these requirements are based off of the cartesian FarmBot model's specifications, which can be found in Appendix A.

To check that these design requirements help us reach our target consumer, we created a quality functional deployment (QFD) chart. Found in Appendix B, the QFD helps to create a hierarchy of requirement importance to the target customer. We can also use this tool to evaluate how our future design will compare to the current FarmBot. Through the QFD chart, we found that most relevant customer specifications are the length of the rotating arm, accuracy in the equipment, and the stability of the center column.

Category	Parameter Description	Requirements or Target	Tolerance	Risk	Compliance
Geometry	Minimum Radius	1.2m	Min	H	S, I
	Minimum Height clearance above soil	1m	Min	H	S, I
	Farmable Area	4.5m ²	Min	H	S, I
Kinematics	Polar Coordinates	Yes	n/a	H	I
	Angular Velocity	.5 m/s	./- .2 m/s	L	T
	Rotational Range	360 degrees	n/a	L	T
Force	Torque rating from motor	8 N.m	benchmark	L	A
Energy	Power supply	110V or 220V AC	benchmark	L	S
	Motor power draw	1.6 A	benchmark	L	S
Materials	Aluminum	6063 T-5 extrusions	n/a	M	S
	3D Printed Plastics	ABS/PLA	n/a	H	S
Safety	Number of Pinch Points	<10	Max	L	A
Production	3D printable plastics	100% of plastic parts	n/a	H	S
	Off the shelf parts	80% non-plastic components	n/a	H	S
Assembly	Assembly Time	15 hrs	./- 5 hrs	L	T
	Number of Parts	799	benchmark	L	S
Transportation	Shipping Weight	150 lbs (UPS requirement)	Max	M	A
	Shipping Size (L + Girth) Girth=2x(H+W)	165 in (UPS requirement)	Max	M	A
Operation	Motor Resolution	200 steps/rev	Min	M	S
	Overall resolution	2.5 mm	./- 2.5 mm	M	S, A
	Overall resolution: bearings in pipe	<.3mm	./- 2.5 mm	M	S, A
	Overall resolution: arm/bracket deflection	<1mm	./- 2.5 mm	M	S, A
Maintenance	Frequency	once a month	benchmark	L	T
Costs	Cost to Manufacture	\$2,250	Max	M	A
	Price to Customer	\$3,000	Max	M	A
Software	Web API	my.farmbot.io	n/a	H	S
	client hardware	Raspberry Pi 3	n/a	H	S
	motor controller hardware	Arduino MEGA 2560	n/a	H	S
	client application language	Elixir (variant of Erlang)	n/a	H	S
	firmware defelopment language	C++ (or compatible)	n/a	H	S
	client-firmware communication format	G-code	n/a	H	S
	client-firmware communication mode	USB	n/a	H	S

Table 1: Proposed Polar Coordinate Requirements

Chapter 2: Project Background and Description

The original cartesian FarmBot Genesis is a first-of-its-kind device that has only recently entered the market, so by extension the new polar FarmBot has no direct competition. Because of this, the Genesis v1.0, seen in Figure 1, will be our greatest source of inspiration. The current iteration of FarmBot is a logical starting point to collect design requirements for the new polar version.



Figure 1: Original Cartesian FarmBot

After investigating the original Genesis model and working with our sponsor, we determined it advantageous to reuse several design requirements and subassemblies from it for our device. For example, we continued using the z-axis and cross slide subassemblies found on the Genesis v1.0. shown in Figure 2. We also use V-slot aluminum extrusions as the main structural members and make few changes to the electronics. In our new design we look to embody simplicity, manufacturability, scalability, and hackability.

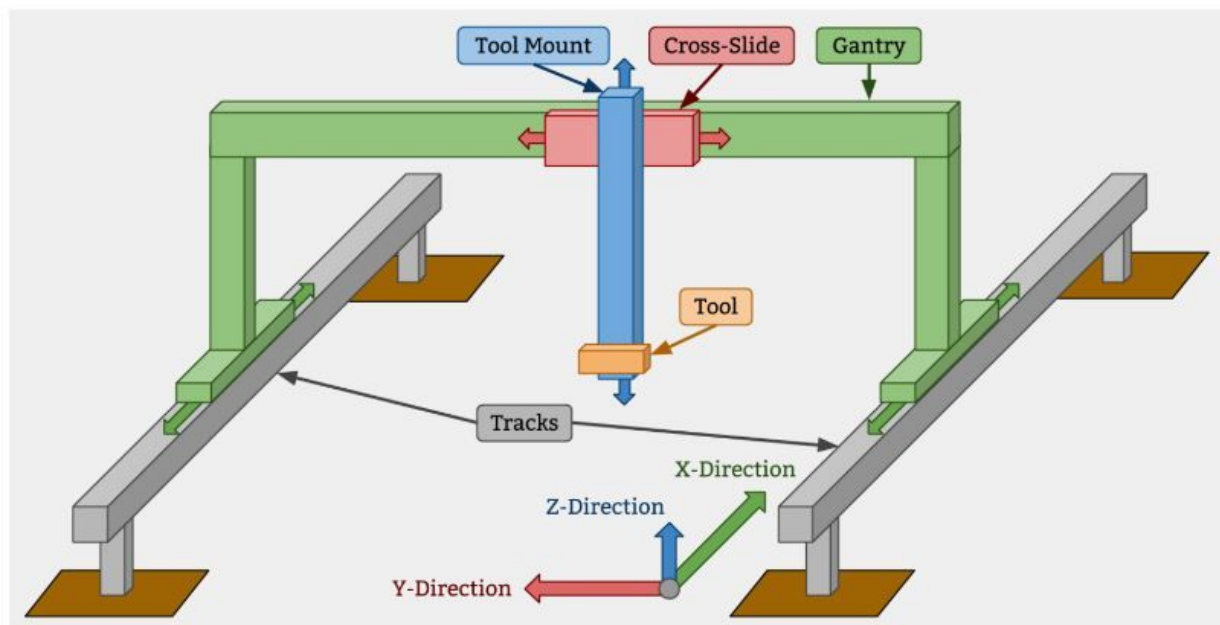


Figure 2: High Level Cartesian FarmBot Design

The current system works like a consumer level 3D printer with stepper motors that allow the tool head to be positioned at particular X, Y, Z coordinates, as shown in the Figure above. Encoders keep track of how far the motors move and can keep track of slippage and stalling. Just like a 3D printer, FarmBot uses G-code to communicate actions to the motor controller (in this case, an Arduino MEGA and a RAMPS shield).

Because there are very few devices similar to a polar coordinate CNC farming device on the market, we utilized the designs of the cartesian FarmBot as much as possible. Fortunately, that original iteration of FarmBot has already been documented meticulously, and there are several functioning models accessible to us. The FarmBot website (farmbot.io) contains a wealth of information on the use, design and assembly of these parts and subsystems, particularly the white paper and documentation sections of the site. Some Other systems, such as rotating ADA pool chair lifts, rotating jib cranes and in-ground flagpole bases have also provided inspiration.

In addition, various external resources exist for developing software and machine instruction sets for the polar applications. Both the cartesian and polar versions will use the same software, thus Nerves Project (nerves-project.org) and Elixir (elixir-lang.org) will be relevant sources of information. Also, both the cartesian and polar versions will make use of G-code (an industry-standard numerical control programming language) for tool positioning. Because G-code is standardized, we can refer to its specification (see NISTIR 6556 and ISO 6983-1:2009) when modifying any relevant software.

With the operating Genesis v1.0 and CAD files, as well as several commercial products and numerous relevant internet resources, we believe we have the tools necessary to fully meet our project and customer requirements.

Chapter 3: Design Development

3.1 Conceptual Design and Selection

With our background research and customer requirements in mind, we formulated dozens of conceptual design ideas, subsystem by subsystem. We narrowed this large pool of ideas by creating mock-ups, running simple calculations and comparing them to our design requirements.

We entered our top concept choices into decision matrices shown below, and each team member rated how well the designs matched our requirements specific to that system. Appendix C, D, and E contain our more detailed decision matrices for reference. The concepts were compared to one chosen design that acted as a datum and were rated as worse (-), better (+) or the same (s) in meeting the requirements. This process did not pinpoint our final subsystem designs, but rather identified the strengths and weaknesses of each design and drove our inspiration for the final concepts.

Various arm system designs (Tables 2 and 3), which function as a support and track for the cross-slide and z-axis, were analyzed and evaluated through a design matrix shown. Most of the arm designs were different answers to two main questions. The first was whether the arm should span the radius or diameter of the circular garden plot. This determined how much the device would have to rotate before all points on the circle could be reached (360 degrees for the radial arm and 180 degrees for the diametral arm.) The second was whether the arm should be supported on its far end, with a wheel or track, or be a cantilever beam solely supported at the center column. In any case, the system needed to be robust, hit all points on the circle, retain precision and be easy to assemble and source.

Considering these attributes, our initial datum design of choice, a diametral arm with an offset, c-shaped column, scored rather low although it was innovative and could hit all points on the circle with ease. This design used parts that were expensive and hard to find or manufacture, and strayed from one of our guiding objectives of simplicity. Realizing that the job could be easily completed with a much simpler design, we decided to use a radial, cantilever arm. This decision was further validated with finite element analysis that showed minimal deflection of the arm under expected loads, providing the accuracy and reliability we require.

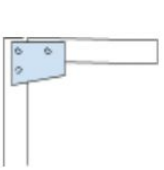
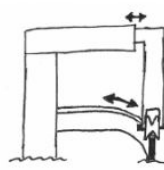
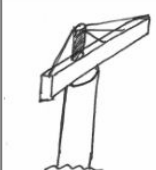
				
Simple Radial Arm with metal support bracket	Radial arm with wheel	Radial arm with groove and track	Radial arm with wheel and flexible track	Radial arm with cable support

Table 2: Arm Conceptual Design (1/2)

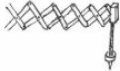
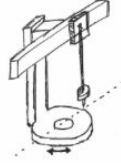
					
Cantilevered radial arm with counterweight	Radial scissor arm	Full arm with perimeter track	Full arm with perimeter wheels	Full arm with offset column	Full arm with moving counterweight

Table 3: Arm Conceptual Design (2/2)

As for our base design, it needed to be reliable and easily installed, adjustable, and integrated with the rest of the device. We divided the base design into two main parts: base platform (concrete, soil screw, etc.) and base to column attachment. In our search for a reliable and strong base platform we considered concrete, fence post spikes, soil screws and buried flat plates. These ideas were analyzed according to our customer requirements in a decision matrix found in Appendix C. We received mixed results from the analysis. Our team found it difficult to come to consensus on what system would be easiest to vertically align and install while still providing long term reliability. Again, simplicity guided us to choose concrete, given that it is a cheap, commonly used and robust material. From here we looked at possible base to column attachments, seen in Table 5, which interface the FarmBot device and the base platform.

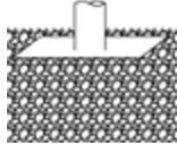
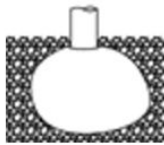
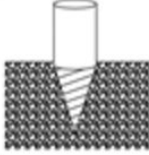
				
Concrete	Footed Plate	Ballast Bag	Soil Screw	Fence Post Spike

Table 4: Base Platform Conceptual Designs

For the base to column attachment we considered set screws, simple bolted brackets, and directly setting the column into concrete/soil. These ideas and others were analyzed in a decision matrix found in Appendix E. The most important qualities that emerged were reliability, adjustability, and ease of installation. With these qualities in mind, we determined that no single design in our matrix was best. Instead we combined multiple aspects into one design, as described in detail in the concept subsystems section of our report. Table 4 shows the base designs that contributed to our final concept design.

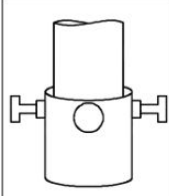
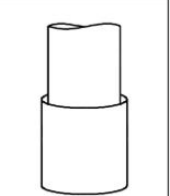
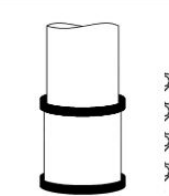
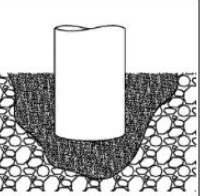
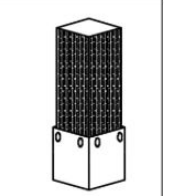
				
Christmas Tree Style Base	Threaded Collar	Pressed Into Bearings/ Collar	Directly set in concrete/ soil	Bolted to Metal Bracket

Table 5: Base to Column Conceptual Designs

Our drivetrain was constrained by the final concept designs of the arm, column, and base systems. This is because the interface between the column and base dictates how a motor might rotate the arm about the vertical axis. One design decision was determining whether the rotating mechanism was going to be on the top or the bottom of the column. However, after the decision was made to use v-slot extrusions for the column and radial arm and the attachment point was a bracket, having the rotation mechanism on the top would be much more difficult. From here, the design process was more organic. Ideas were drawn up with different methods of motor mounting and gearing system at different locations. Designs also changed as we found different types of motors available online. The final drivetrain concept is detailed further below.

Chapter 4: Description of Final Design

4.1: Overview

Our final conceptual design fulfills customer requirements of accuracy, reliability, ease of assembly, maintenance, part sourcing and customization. The device rotates on top of a central concrete base, which acts as a stable platform. It utilizes aluminum v-slot extrusions for the structure of the center column and the gantry arm, which also act as platforms for attaching elements such as the electronics box and cross slide. V-slot extrusions are already in use on the original cartesian FarmBot and have proven easy to source, assemble and modify. Furthermore, they provide adequate stiffness and strength for our applications. In addition to the extrusions, our design reuses the existing cartesian cross slide and z-axis (with their corresponding drivetrains) and electronics. The proposed software makes minimal changes to the original cartesian FarmBot code while still providing quick and accurate control of the device. Our designs for the arm attachment, base, drivetrain and software and electronics subsystems are further detailed below with the assembled subsystems shown in Figure 3.

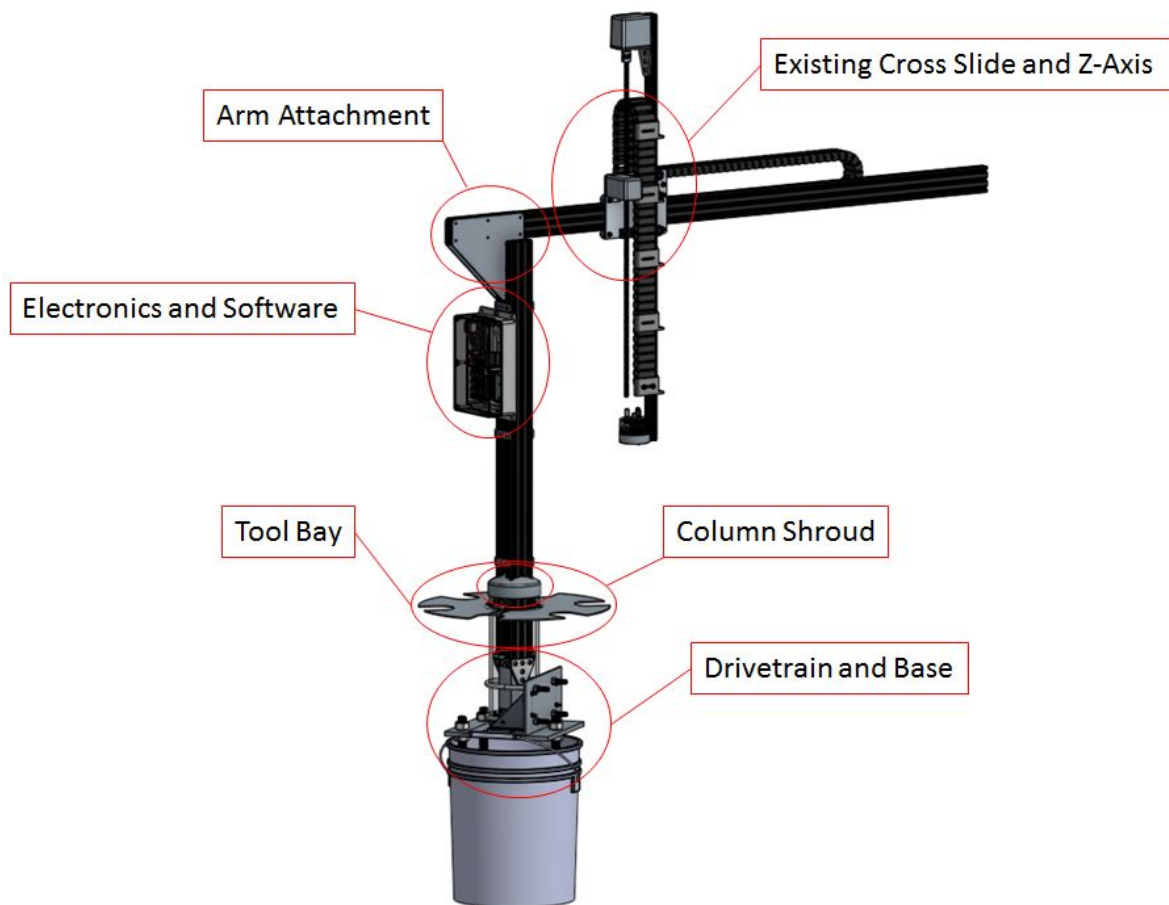


Figure 3: Overall Conceptual Design

4.2 Final Mechanical Subsystems Design

4.2.1 Base

The base system for the polar version of FarmBot is necessary to anchor the column to the ground with a stable foundation for the complete system. It must support and counteract the weight and moment of the cross-slide and gantry. This design requires ease of assembly, easily-sourced parts, and reliability for the user. Additionally, the column must remain in a vertical position such that accuracy of the system is maintained within 5mm of resolution at the tip of the tool. It was with these parameters that we arrived at our final design.

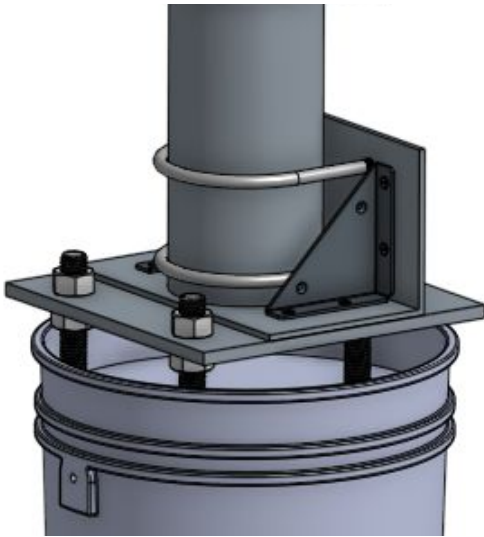


Figure 4a: Base to Column Attachment

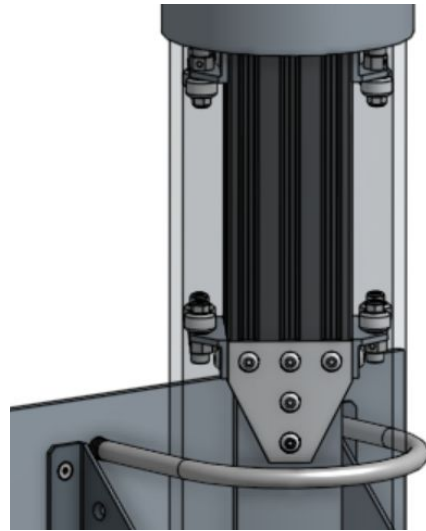


Figure 4b: Interior View of Column

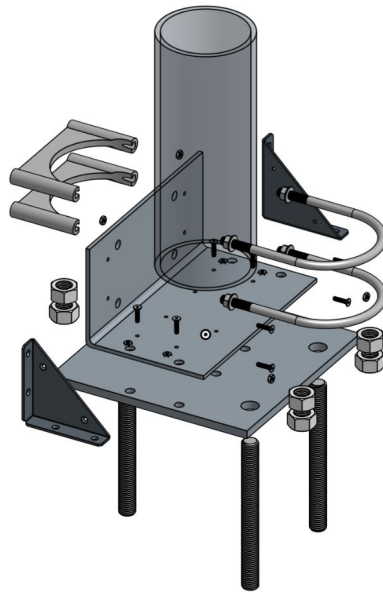


Figure 4c: Exploded View of Base

The final design is a concrete base with an adapter plate and 4.5-inch pipe attached to it by two u-bolts, as seen in Figure 4a. This design came about after deciding that the column would be made from two 60x20mm extrusions. The rotating arm would be directly attached at the top, meaning that the entire column would rotate. The aluminum pipe allows for the column to interface with the base, and it allows the column to brace itself on the inside of the pipe via two sets of roller bearings that track along the inside surface of the pipe. As seen in Figure 4b, the column contains bearing brackets which span the extrusions, allowing the column to rotate within the pipe similar to the load-bearing rotation of a jib crane. The two sets of bearings are designed to take the moment load induced by the weight of the z-axis and cross slide cantilevered on the arm. The vertical load is taken by a small turntable contained in the drivetrain, further detailed below.

Our team decided on concrete for the base because it is readily available, easy to use and allows for the user to set it themselves. This component will not be provided, but is up to the user to source. Concrete is heavy and gives a rigid base for the system to support the moment of the cross slide and gantry. With the base set in a 5-gallon bucket, it is not necessary to pour a new base and support bracket set-up if the device is to be moved. It can be set into the ground, in a raised bed, or potentially even above ground with a shorter column, providing the customer with flexibility of installation for different environments.

Adjustability of the base system is in the flat base plate that holds the 4.5-inch pipe. Adjusting the nuts that secure the base plate to the threaded bolts allows the user to level and relevel the system as necessary. An L-bracket with two 90-degree braces allow the pipe to be secured to the base. The pipe is attached to the L-bracket by a pair of U-bolts. This base plate is then anchored into the concrete by the three threaded bolts, as shown in the exploded view Figure 4c. Furthermore, it is possible that our end software can allow for a calibration round to eliminate vertical misalignment of the z-axis to the contour of the farmable plot.

All of these parts are found off the shelf (OTS), except for the base plate adaptor and the

L-bracket. This base plate is a flat piece of 10mm aluminum that can be fabricated by drilling holes of various diameters in the specified locations. The L-bracket will be manufactured using a standard 90-degree press brake and the holes drilled accordingly. Further analysis is required to analyze the strength of the concrete bolts, as well as the base plate interacting with the entire system.

Overall, the base system satisfies the key customer requirements and engineering specifications. Dependable vertical alignment is easily achieved with these OTS and easily-sourced parts.

4.2.2 Adjustable Bearing Mounts

The adjustable bearing mounts (drawings found in Appendix F.3) are responsible for keeping the column tightly centered and vertical inside the base support pipe. The bearings are rigidly mounted to the column and ride on the inside face of the pipe, supporting the load of the overhung weight of the arm. The adjustable bearing mounts design requires ease of assembly, available parts, and reliability for the user. Additionally, they must keep the column rigid in a vertical position to maintain a system accuracy of 5mm. The ease of assembly requirement was particularly hard to achieve because the adjustable bearing mounts are housed inside the base support pipe.

For assembly, the user must first mount the aluminum brackets to the column extrusions in predetermined locations, then mount the bearings onto the aluminum brackets via the eccentric spacers. The eccentric spacer is the mechanism that allows the user to adjust the bearings to fit snugly against the pipe. The m5 socket head screws that hold the bearings onto the mount have a head diameter of 8.5mm, while the eccentric spacers require a 10mm wrench to tighten. This allows the assembler to use a 10mm socket wrench to adjust the bearings even after it is inside the base support pipe as seen in Figure 5a. Loosening of the eccentric spacers during operation was a concern in design of this subassembly. Based on the anticipated friction provided between the eccentric spacer and the aluminum bracket, the force required on a single bearing to rotate the eccentric spacers out of position was calculated to be above 2300 lbs (full calculation found in Appendix G).

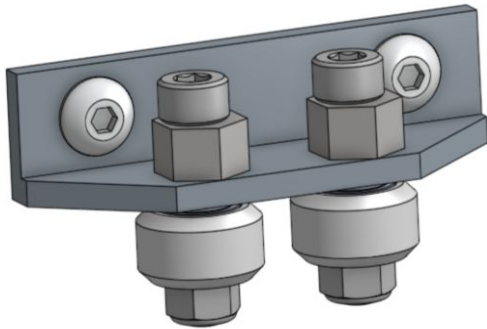


Figure 5a: Adjustable Bearing Mount Assembly

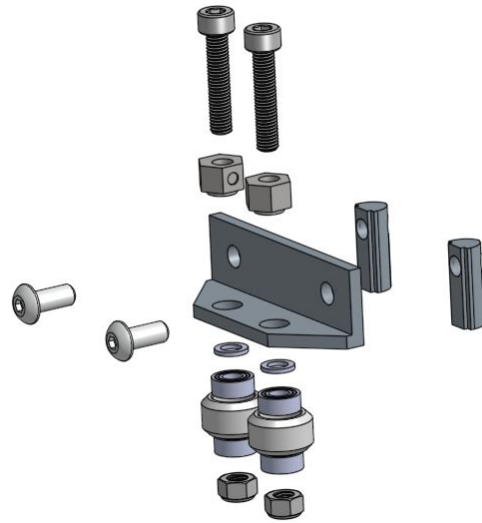


Figure 5b: Exploded View

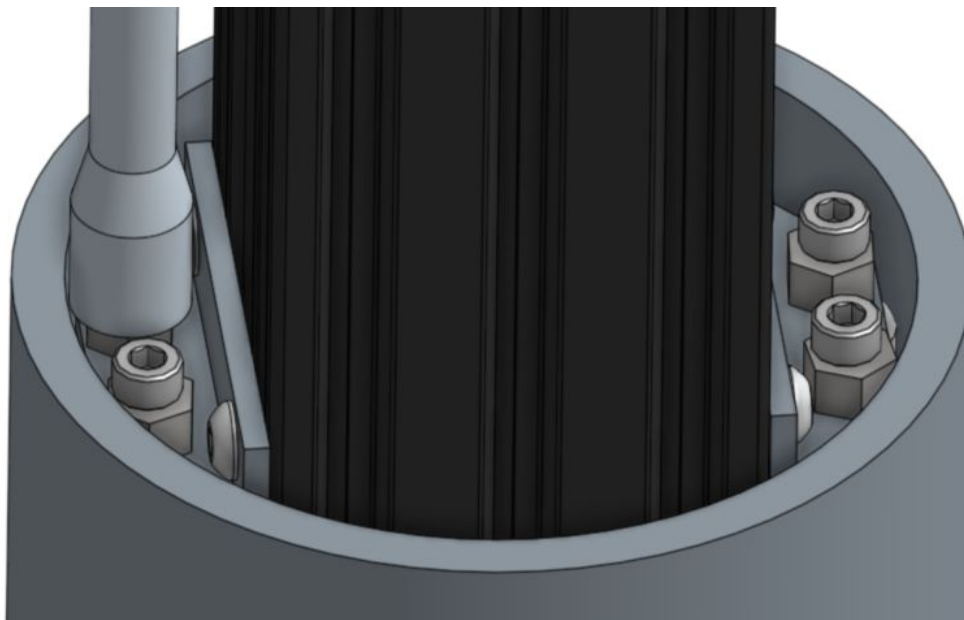


Figure 5c: Socket Head Adjusting the Bearings After Assembly

Analysis was done on the deflection of the Adjustable Bearing Mount Assemblies to determine if they would adhere to the precision requirement of 5 mm under normal operating loads expected at 67 lb per bearing. FEA analysis was done on the aluminum bracket to determine the degree of angular deflection as well as on the bearing retaining bolt to determine the linear amount of deflection. Both of these values were used to calculate the resulting total linear deflection of the bearings to be .0867 mm, which amplified over a one meter column becomes 1.5mm of deflection.

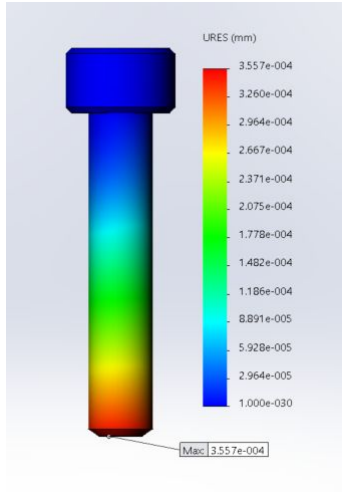


Figure 5d: Bolt Deflection FEA

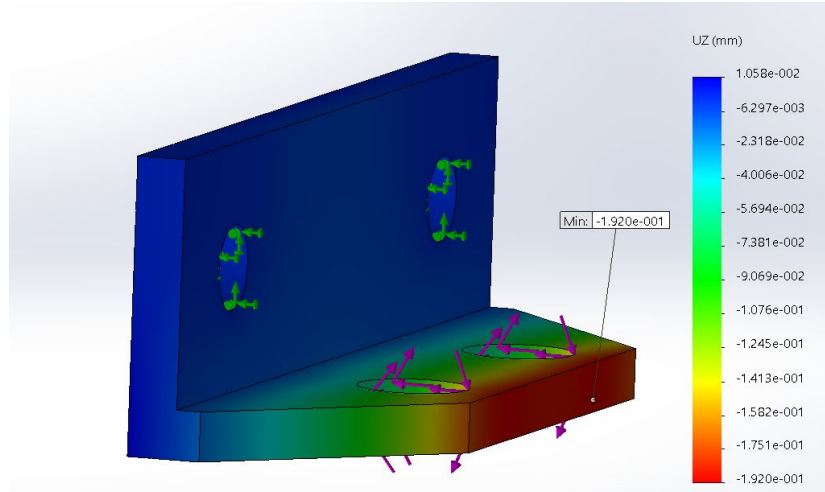


Figure 5e: Bracket Deflection FEA

Stress analysis was also done on the aluminum brackets to ensure that their failure strength is above our expected maximum loading. This maximum loading is not expected to occur during standard operation but rather in accidental cases such as if something were to fall on the arm, or perhaps a child were to try to swing on it. The maximum loading designed for puts a 282 lbs on each bearing. Hand calculations were done to ensure that the 6061 aluminum bracket could withstand this force. The calculations resulted in a safety factor of 2.15.

4.2.3 Drivetrain

The drivetrain subsystem drives the movements of the 3 axes on the polar farmbot: (1) center column rotation, (2) cross slide movement along the y-axis, and (3) movement of the z-axis. Of these 3 drivesystems, both (2) and (3) can be reused from the previous cartesian farmbot system, meaning the re-design will only be required for (1), the rotation of the center column. By re-using the two existing drivetrains, it eases both mass production manufacturing and customer support on our sponsor's end.

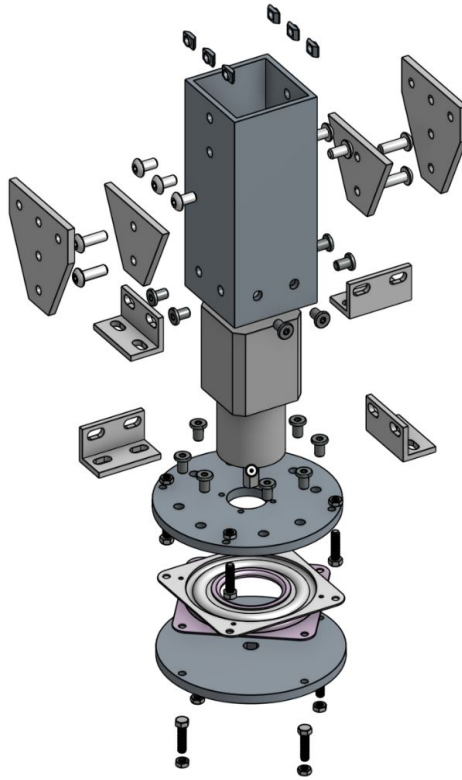


Figure 6a : Exploded View of the Drivetrain system

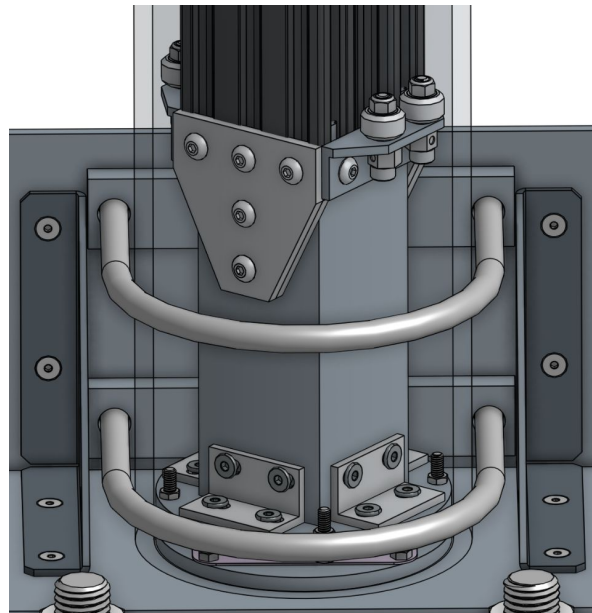


Figure 6b: Drivetrain Housing

The final drivetrain design for the center rotation is a compact system that is secured directly between the base system and column. The entire drivetrain is also fit within the 4" ID Al pipe as seen in Figure 6b. The most relevant customer requirements for the drivetrain included

ease of assembly, manufacturable, use of OTS components, accuracy, and reliability -- we felt that this concept was able to fulfill these requirements well. The reasoning behind this design was to isolate the loads on the motor such that it would only be subject to torsion required to rotate the column and arm. All additional loads would be supported by external loads around the motor. In Figure 6b, it can be seen that the adjustable bearing mounts sit directly above of the drivetrain, transferring any moment caused by the radial arm and the column not being perfectly plumb, to be directly into the pipe, rather than through the drivetrain. It can also be seen that the entire column and arm assembly will be fastened directly on top of the drivetrain motor housing rectangular tube. This motor housing's purpose is to transfer all axial load from above down to the motor plate, turntable, base plate, and into the base system, with no load directly on the motor.

The motor, as shown in Figure 6a, is the heart of the drivetrain and creates the rotational torque. It is a NEMA17 that is coupled directly into a 51:1 planetary gear, which can be purchased off-the-shelf online. The rotation of the entire system is possible through the use of a turntable, sandwiched between a base plate and motor plate. The base plate is fixed directly with the base system and has a D-shaped hole that can couple with the D-shaped motor shaft. The motor and motor housing are fixed on top of the motor plate. So when rotating the entire system, the motor shaft will be fixed in the base plate, resulting in the motor, motor plate, and subsequently the entire system to rotate above the turntable.

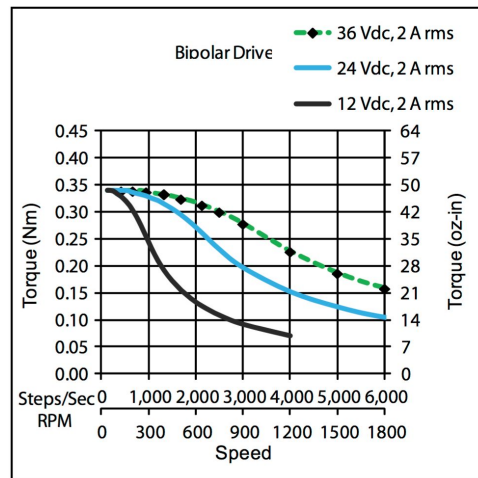


Figure 7a: NEMA 17 Speed-Torque Curve

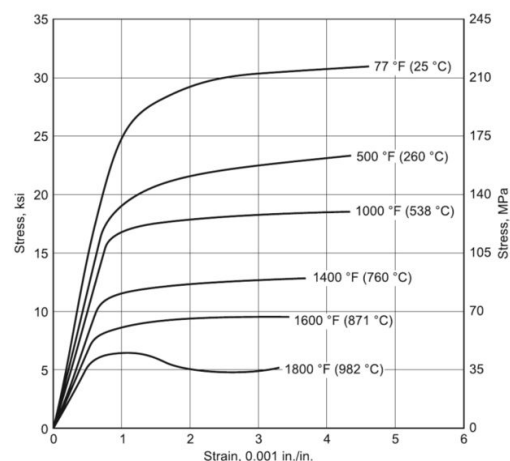


Figure 7b: Stress-strain Curve of Steel

To confirm that this design would be able to meet the design requirements, we performed multiple calculations. The two main driving requirements, was to be able to rotate at a minimum of 0.5m/s at the end of the arm and to be able to maintain an overall resolution of 5mm at the tool head. To confirm these designs, we utilized the motor torque curve (Figure 7a) of the standard NEMA17 motor and applied the gear reduction and efficiency rating to find the motor output torque was roughly 8N-m. Using the 0.5m/s requirement, we were able to derive the angular acceleration of 0.33 rad/s^2 and also use take the mass moment of inertia of the column, radial arm, and z-axis to find the required torque, which was $\sim 0.6 \text{ N-m}$. The frictional force of the system wasn't taken into account because it could potentially vary from how vertical the entire system was, but there was already quite a large safety factor from the large motor output torque. Another concern was possibility of the motor shaft breaking under the load. A stress analysis on

the shaft was performed based on the amount of torque applied by the system and it was found to be roughly ~ 11 MPa, which is far below the yield strength of steel as seen in Figure 7b. To solve for the resolution, we took the motor step count along with the gear reduction to find a step angle of 0.067° which translates to 1.75mm at the end of the arm. As a sanity check, we also calculated the angular deflection on the motor shaft to see if there would be any significant effect on resolution and we determined that the deflection of 0.0034° or 0.089mm at the end of the arm could be deemed negligible.

Overall, this design was able to fulfill all of our customer requirements particularly being easy to assemble and predominantly using only off-the-shelf components. The components that did require a level of manufacturing: motor plate, base plate, motor housing, all had relatively simple manufacturing operations. The only concern was the broaching process to achieve the D-shaped hole for mating between the base plate and motor shaft; however, from a mass production standpoint to our sponsor, tooling is very inexpensive and it could perhaps be a component sold directly from the Farmbot website. It is also worth noting that if it is discovered after testing that additional torque is required, a 50:1 planetary reduction can easily swapped with the current 27:1 reduction and the only additional adjustment would be to extend the motor housing.

4.2.4 Tool Bay

The tool bay (Figure 8, drawings found in Appendix F.7) stores tool heads (seeders, weeders, watering etc) and seed trays while not in use. It is bolted to a 3D printed clamp which connects it to the base cylinder. The circular pattern is designed for ease of location by the universal tool mount on the z-axis. A rectangular slot is cut in one side of the sheet to allow for routing of electronics wiring, vacuum tubing and water.

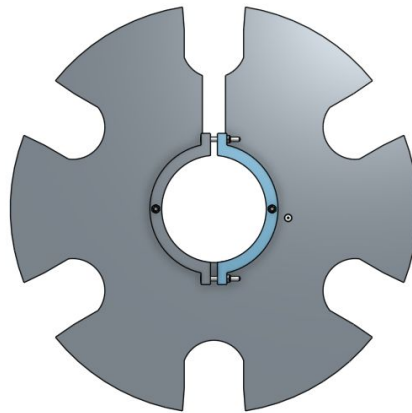


Figure 8: Tool Bay Plate

4.2.5 Weatherproofing

Given that FarmBot devices face a wide range of environmental conditions, weatherproofing is integral to maintaining reliable function. All electronics are sealed in plastic enclosures, structural components are made of corrosion resistant aluminum, and all bearings are sealed. However, the cylinder housing the rotational drivetrain is especially susceptible to gathering water or dirt. To address this, a 3D printed plastic shroud (Figure 10, drawings found in Appendix F.8) will be placed over the center column to cover the open face of the cylinder from rain and other contaminants. The interface between the shroud and the column will be sealed with silicone sealant that is quick-drying and flexible. This sealant will also be used to seal the bottom end of the pipe. In addition, to prevent water from collecting in the cylinder through the open ends of the v-slot extrusions, end caps (Figure 9) will be added.



Figure 9: End Caps

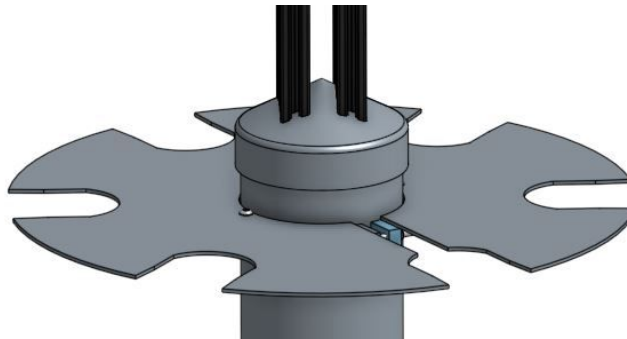


Figure 10: Column Shroud

4.2.6 Column

The central column (Figure 11a) is the backbone of the FarmBot device. It is constructed from two 20 x 60 x 1000mm v-slot extrusions connected by six, three hole brackets and spaced by cut pieces of 20 x 20mm v-slot extrusion. The v-slot system was chosen for compatibility with existing parts carried over from the Cartesian FarmBot as well as common CNC and 3D printing components. It interfaces with the base cylinder through the bearing bracket and is bolted with t-bolts to the gantry arm through two flat plates.



Figure 11a : Column

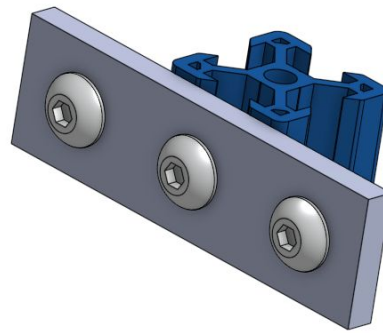


Figure 11b: Column Spacer and Bracket

4.2.7 Tubing and Wiring

The FarmBot device requires water, power and air to run. 18 gauge electrical wire runs to the electrical box, which houses the brains of the device, the vacuum pump, and the three stepper motors located on the cross slide, z-axis and inside the base cylinder. ¼" clear PVC tubing carries water from a garden hose to the universal tool mount for the watering attachment. Water flow is actuated by a solenoid valve inline with the tubing and electrically connected to the Arduino. Air is supplied to the seeder tool head by the another length of PVC tubing originating at vacuum pump, also powered by the Arduino. The following diagram (Figure 12) illustrates the general cable and tubing routing.

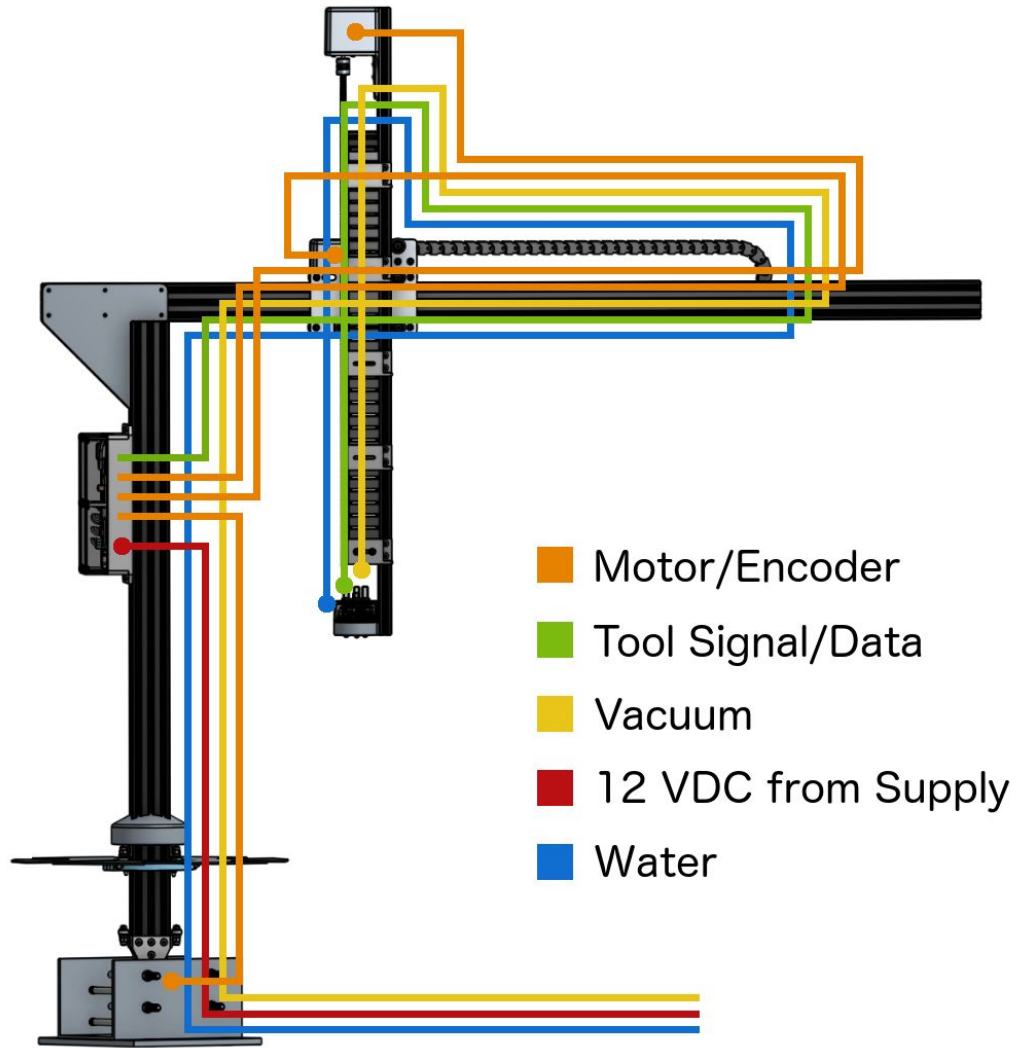


Figure 12: Tubing and Wiring Diagram

Specifically, tubing and wiring for the electronics box and tool mount is routed up the base cylinder, through the rectangular slot in the tool bay and into the center of the column. They are managed by cable carriers (made of individual plastic links) that move with the cross slide and z-axis. The wiring for the rotational stepper motor is routed up over the lip of the cylinder, below the cylinder shroud, and down through the rectangular motor housing. A gap was left between the inner diameter of the shroud and the outer diameter of the pipe to accommodate the motor wiring. Appropriate slack has been added to the tubing and wiring to accommodate the rotational movement of the device.

Note: towards the end of the project, a change to the routing design was made to accommodate mounting the vacuum on the end of the z-axis near the tool mount. This reduces the air tubing required, but also appears to reduce the reliability of the seeding tool. The new vacuum has a tendency to clog with dirt and debris, while the original was more tolerant. In this new configuration, the air tubing spans only a few inches from the vacuum to the tool mount.

4.2.8 Arm System

The design requirements for this subassembly are consistent with that of the entire polar FarmBot: simplicity, ease of assembly, manufacturability, DIY friendly and low cost. The arm system is responsible for providing the length of track on which the end effector will move radially on the cross-slide and vertically on the z-axis to reach plants as far as 1.2 meters from the central axis and 1.0 meters above the ground. We used the main beam of the gantry on the FarmBot Genesis v1.0 as our initial inspiration for the arm system because the function is nearly identical. The major design difference between the main gantry beam on the Genesis v1.0 and the polar concept (Figure 13) is that the arm is only supported at one end, acting as a cantilever beam rather than a simple span.

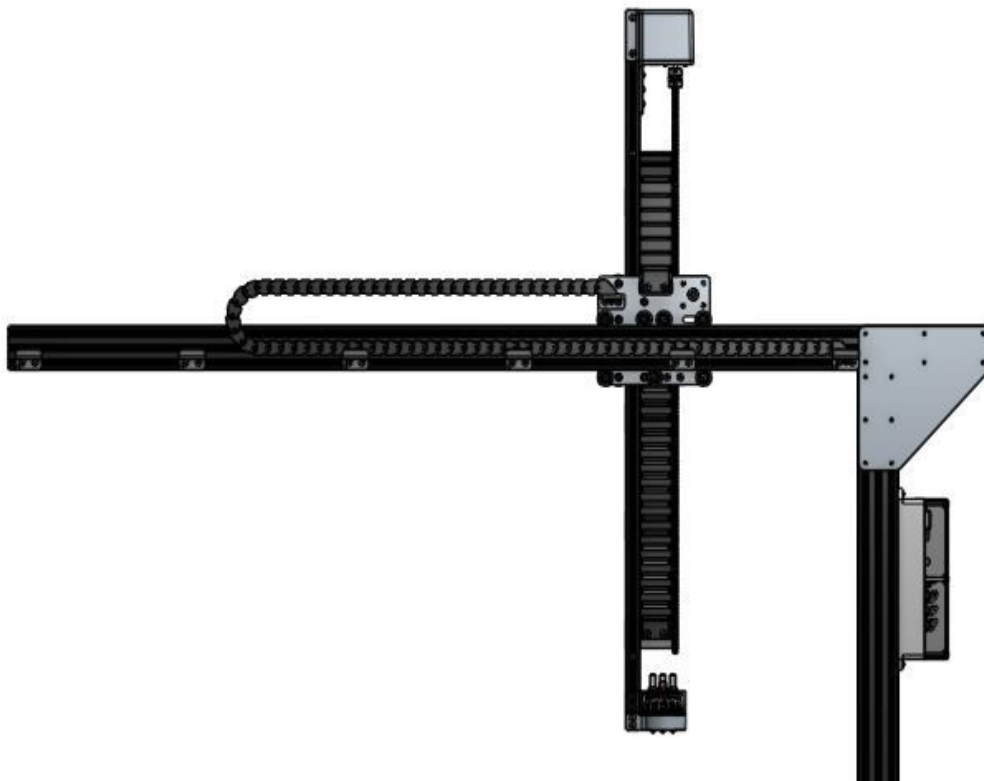


Figure 13: Gantry Arm

This drew our concerns to the higher amount of stress that will occur near the joint of the arm and column, due to the moment created from the weight of the extrusion and the moving cross-slide and z-axis assemblies. This was something that the Genesis v1.0 parts were not intentionally designed for. Another concern we identified was the potential for deflection at the end of the arm member. With these concerns in mind we continued to evaluate parts on the Genesis v1.0 for manufacturability, simplicity and cost purposes.

The same 20mm x 60mm x 1500mm 6061 Alloy Aluminum V- slot extrusions used as a gantry beam on the Genesis v1.0 model are also used in our design. As mentioned previously, the arm and the column are connected by a custom, although very simple, 5mm flat aluminum plate via T-bolts (Figure 14c), a common and strong type of connection seen in DIY 3D printer

designs. We moved away from the OTS brackets found on the cartesian FarmBot to a custom bracket in order to ensure the rigidity of the arm-column connection and reduce deflection of the arm.

Minimal deflection is integral to accurate and precise operation of the entire FarmBot system. The extrusion, cross-slide and z-axis are relatively lightweight and the moment created by these loads is calculated to be just under 50 N.m when the z-axis and cross-slide are both stationary at the outmost position possible along the arm. Unexpected loading, such as if the user leaned on the arm for support while harvesting their vegetables was taken into consideration as well. For this reason, we instituted a minimum strength requirement that the arm should support a downward force of 50 lbs at 1.0 meters from the central axis, equivalent to a moment of approximately 200 N.m.

To confirm that the V-slot extrusion will be sufficient as the main structural member, a finite element analysis (Figure 14a) was done using the loads from the weight of the extrusion, cross-slide and z-axis. The goal of this analysis was to determine the deflection at the of the 1500mm long, 6061 aluminum alloy V-slot extrusion under normal operating loads, so the unexpected loading of 200 N.m. was not included. The results of the analysis determined that the deflection of the extrusion is well under the maximum imprecision requirement of 5 mm, and can be considered negligible for the scope of the design.

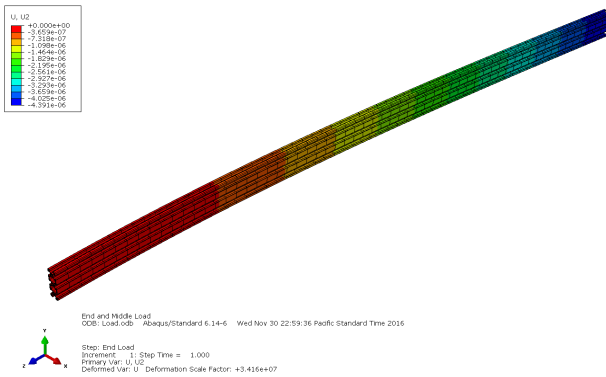


Figure 14a: FEA Analysis of Arm

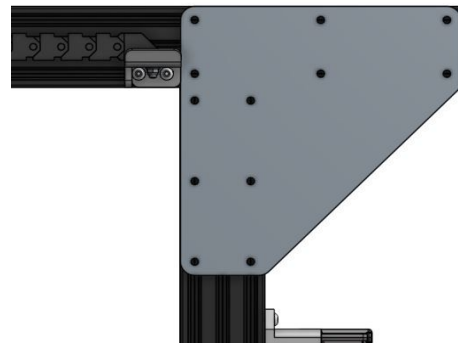


Figure 14b: Arm Bracket



Figure 14c: T-Bolt

The aluminum plate bracket (14b) is also of some concern, as any deflection here will result in a reduction of precision amplified by the distance that the cross slide is operating at. For example, if the linear pattern of bolt holes in the aluminum plate bracket deflects as much as 1° , and the end effector is operating at the maximum radius of 1.2 meters, there will be an imprecision of 20mm in the z-axis direction. In order to insure that this does not happen with our

design we have increased the effective cross-sectional area in the second iteration of design. Because these parts are inexpensive and easily accessible, we can order them and construct the subassembly for physical testing.

4.3 Cost Estimate and Supplier Summary

The cost estimate for building our prototype is mainly derived from the original cartesian FarmBot's bill of materials (BOM), as our devices share much of the same hardware. The main differences between the two BOMs result from new components, some purchased and others specially manufactured, in the rotational drivetrain, base, tool bay and column. The following table (Table 6) summarizes our expected costs.

Subsystem	Cost
Column	\$173.69
Gantry Arm	\$112.98
Cross Slide	\$259.87
Z Axis	\$227.93
Cables and Tubing	\$44.65
Universal Tool Mount	\$123.97
Electronics Box	\$256.53
Tool Bay	\$155.79
Rotational Drivetrain	158.04
Linear Drivetrain	\$140.00
Base/Base Connection	\$124.96
Adjustable Bearing Mount	\$77.42
Total Cost	\$1,875.05

Table 6: Expected Costs

Our expected cost of \$1875 is well below our max cost of \$2250 to manufacture our FarmBot. A comprehensive BOM detailing each part used in the device, its cost, quantity and supplier can be found in Appendix H. The following table (Table 7) summarizes where we will be sourcing parts and how many unique parts we will be purchasing. Many of these parts are already in our sponsor's inventory and will not need to be ordered. Otherwise, all of these suppliers have shipping times of a week or less.

Supplier	Part Count (# of SKU's)
McMaster Carr	34
Open Builds	24
Shapeways	10
House Built	9
Amazon	6
Peaksight	5
Home Depot	4
Adafruit	3
Inventibes	2
SparkFun	2
UltiMachine	2
Big Blue Saw	2
Sainsmart	2
OMC-Stepper Online	1
Alibaba	1
Apex Magnets	1
US Digital	1
Total	109

Table 7: Supplier Summary

If put into production, the manufacturing cost will be reduced to around \$900, in-line with the cost reduction seen when our sponsor moved from prototype to Chinese based production.

4.4 Safety Concerns

The following table details the potential safety hazards we've identified for FarmBot and our precautions to minimize those hazards. An extended safety checklist can be found in Appendix I.

Hazard	Description	Assesment and Precautionary Action
Environmental exposure	Device will be located outdoors and may face a wide range of environmental factors.	Medium risk - Device will be made of corrosion resistant aluminum and plastics. Areas that could trap water or debris will be enclosed.
Moving mass	Approximately 10 pounds (cross slide and z-axis) will be moving at .5 m/s at full extension.	Low risk - It is a small mass rotating at a low velocity. User warning will be included.
Electrical shock	Connected to a standard 110 volt connection.	Low risk - All electronic components will be inside in a waterproof plastic enclosure and grounded.
Pinch points	Cross slide and z-axis movement create potential pinch points, and drivetrain components could catch hair or clothing.	Medium risk - Drivetrain will be enclosed. Other pinch points are at low speed and low force. User warning will also be included.
Falling and striking user	Moment caused by cross slide and z-axis, as well as by wind or human interference causes potential for device tipping and striking user.	Low risk - Minimize tipping potential with base design. Currently, the concrete base with hardware weighs around 120 lbs and will be buried to provide extra resistance to tipping
Abnormal effort	Pouring concrete, assembly of device may be strenuous	Low risk - Proper instructions and warnings will be included

Table 8: Safety Concerns

4.5 Maintenance Considerations

The following table (Table 9) outlines the typical maintenance tasks necessary to keep the polar FarmBot in operation. Much of the Polar FarmBot maintenance is the same as for the Genesis version, however this section has been updated to reflect any new designs. Detailed instructions for carrying out these maintenance tasks can be found on the FarmBot website here: <http://genesis.farmbot.io/docs/maintenance-guide>

<u>Issue</u>	<u>Maintenance Action</u>	<u>Inspection Frequency</u>
Debris buildup	Wipe down FarmBot exterior with a damp sponge or cloth	Monthly
Loose screws	Tighten loose screws; apply loctite if necessary	Monthly
Shifted spacers	Reset and tighten the eccentric spacers that fix the wheels to the cross-slide, z-axis, and column bearing mounts	Every 3 months
Loose belt	Loosen and reattach the belt clip plate to the cross-slide so that the belt has no slack	Every 3 months
General part damage	Replace the damaged parts	Monthly
Worn leadscrew block	Replace the lead screw block	Yearly
Leadscrew buildup	Wipe down leadscrew with a damp sponge or cloth	Yearly
Magnetic debris	Remove the metallic flakes on the magnets of the universal tool mount and the magnets on the individual tools	Every 3 months
Seeder debris	Run warm water through the injector tip	Every 3 months
Watering nozzle debris	Soak in hot water and vinegar mixture for a few hours	Every 6 months

Table 9: Maintenance Tasks

Chapter 5: Hardware/Software Design and Development

5.1 Hardware Design

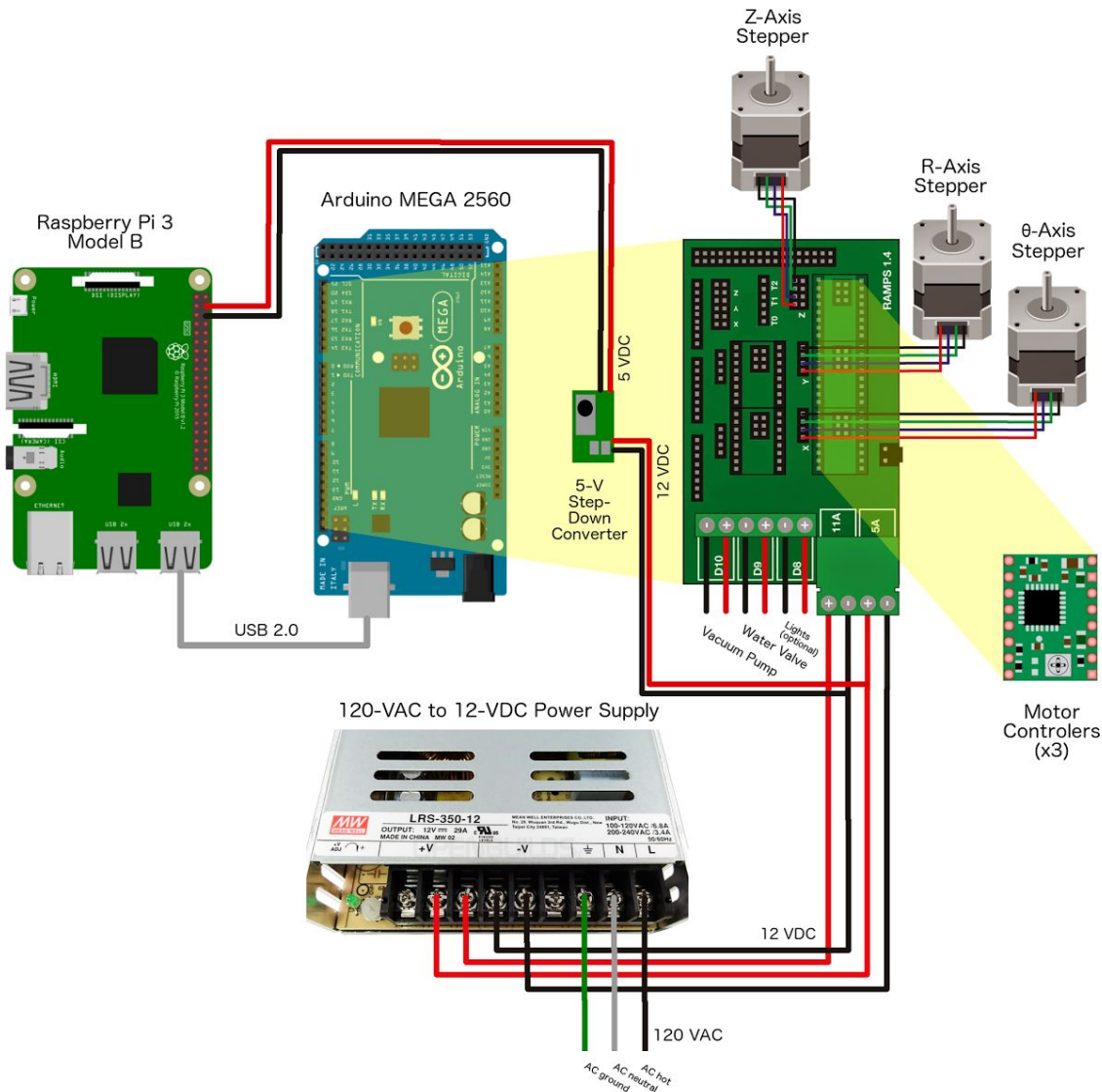


Figure 15: Wiring Diagram

The wiring diagram included above, (Figure 15), includes the major electronics components used in our design. The diagram shows the interconnection of the components, including a Raspberry Pi, Arduino, RAMPS shield, stepper motors, motor controllers, power supply, and step-down converter. The power supply converts 120V from an electrical outlet to 12V DC for powering the RAMPS shield. The power supply also powers a step-down converter which converts the 12V DC to 5V DC for powering the Raspberry Pi.

The pins on the RAMPS shield correspond to sockets on the Arduino, so the shield can be plugged into the Arduino; in the same way, the motor controllers plug into the sockets on the

RAMPS shield as shown in the diagram. The stepper motors plug into the stepper ports on the RAMPS shield. Note that while the Z-axis stepper motor plugs into the Z-axis port, the R-axis and θ -axis motors plug into the Y- and X-axis ports respectively. Lastly, the Pi and Arduino communicate via a USB 2.0 cable.

Shown on the RAMPS are the connections for the water solenoid and the vacuum pump as well. These two devices operate on the 12 V from the power supply, and the ramps acts as a relay, shielding the rest of the electronics from electromagnetic noise generated by these high-inductance devices. Additionally, the tool mount leads connect to the pins on the opposite side of the board. In future designs, motor encoders will also be attached there as well.

There were no significant issues with the hardware design. Because of connectivity issues, and while waiting on FarmBot to overhaul the web interface to provide controls for polar FarmBot, the Raspberry Pi was fairly obsolete. The current web app cannot control the polar FarmBot due to a mix of connectivity issues (which are the result to bugs in the web api and FarmBot OS on the Raspberry Pi), version discrepancies (FarmBot started making changes to the firmware and fixing said bugs after we made a copy of it and started adding polar code), and lacking functionality in the web app (even if it could connect, all input and output would have to be done in rectangular coordinates). While these are software issues, they forced us to improvise. For example, the USB cable that is supposed to go to the Raspberry Pi was rerouted directly to the controlling laptop.

5.2 Software Design

Throughout the design process, our team focused on reusing the rectangular FarmBot's existing hardware and software, and on minimizing the differences between the new polar and existing rectangular code. These specific focuses supported our overall goal of a functional and stable system characterized by simplicity, scalability, and hackability. Our hardware/software subsystem design embodies our goals of architecture reuse and minimal code changes, and it is detailed in the remainder of this section.

To begin, our design process started with an analysis of the existing hardware and software components of the rectangular system. We spent time investigating each component, analyzing which could be reused and which needed to be modified. Below, Diagram 1 identifies the major hardware and software components involved in our analysis.

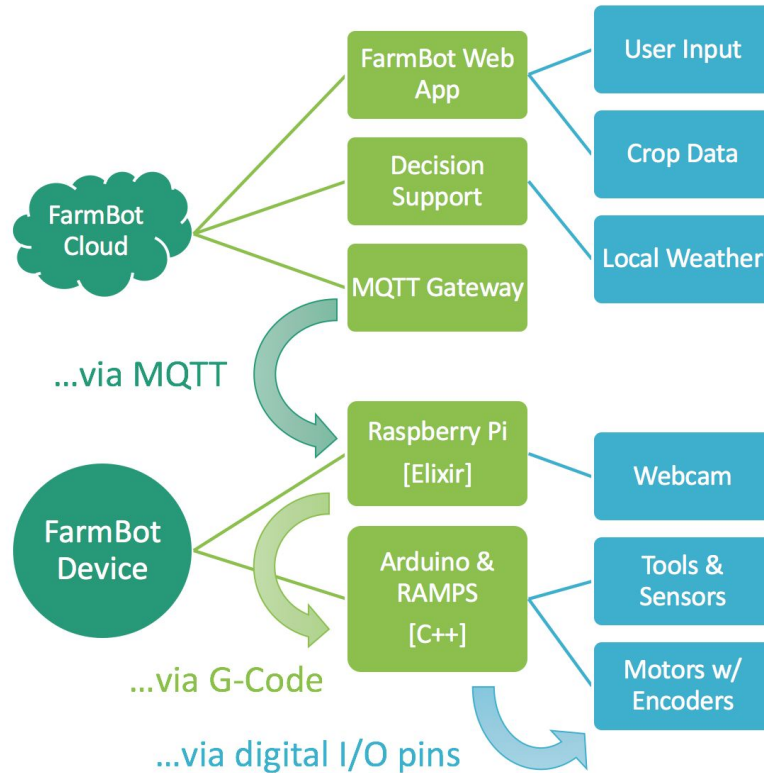


Figure 16: Major Hardware and Software Components

As a general overview, the FarmBot system consists of two major subsystems, the FarmBot cloud and the FarmBot device. The FarmBot cloud handles nearly all user interaction from input of garden specifications, to scheduling tasks, to displaying sensor data and camera video streams. The FarmBot device does the actual farming automatically, taking care of everything from seeding to watering to harvesting. The commands and configurations input by the user to the FarmBot cloud are sent to the FarmBot device through MQTT protocol, which connects the MQTT gateway to the Raspberry Pi. The Pi then produces G-Code (an industry standard typically used in CNC device control) and sends the G-Code to the Arduino. The Arduino is equipped with a RAMPS motor controller shield which drives the stepper motors via digital I/O pins.

After researching how the current FarmBot system works, discussing customer requirements with our sponsor, and reading through and testing the code of various software components, we determined that it would be possible (and recommended) to reuse the entire FarmBot cloud, without requiring any changes to the existing cloud subsystem. That being said, it would be recommended to alter the user interface to handle polar functionality in the Web API GUI, but this can be left to the developers at FarmBot to update as they see fit with no usability impact to our new polar version design.

That leaves two possible locations to introduce our polar coordinate functionality. The first option would be to send polar G-Code from the Pi to the Arduino, and the second would be to receive rectangular G-Code instructions as usual and modify the motor control firmware on the Arduino. Through investigation of the firmware source code, we discovered that G-Code

instruction processing was coded for each instruction individually, thus, if we were to send new polar G-Code, there would be no code (handlers) written to handle these. Because of this (in conjunction with the fact that changing the hardware and the positions of the motors will require changes to the Arduino motor control firmware anyway), it was decided to introduce all polar coordinate functionality in the motor control firmware. Doing so fulfilled our goals of hardware and software reuse and minimization of code changes. As seen Diagram 2, our changes affected only the two minimally required systems.

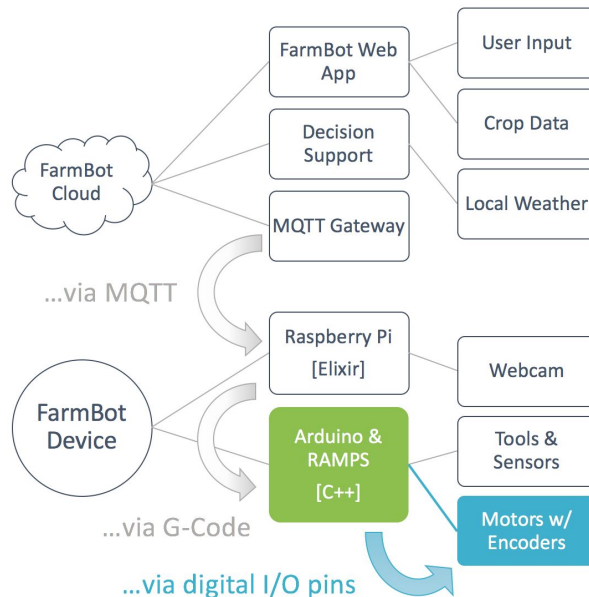


Figure 17: Affected Systems

There are four steps that the Arduino firmware carries out that would be potential spots to make the necessary code changes. The Arduino receives raw binary data from the Raspberry Pi over a USB connection, the raw data is processed as text and interpreted as rectangular G-Code, a handler is executed for each G-Code command received, and the motor controller sends I/O signals to the RAMPS motor shield to control the stepper motors. These steps and examples of the data and code involved in each step are illustrated in Figure 18.

1. 01000111001100000011000100100000010110
00001100010011000100100000010110010011
00100011000100100000010110100011001100
11000100100000010100110011000000110101
2. G01 X11 Y21 Z31 S05
3. moveToCoords (11, 21, 31, 5, 5, 5);
4. axisX = 11, xMaxSpd = 5
axisY = 21, yMaxSpd = 5
axisZ = 31, zMaxSpd = 5



Figure 18: Arduino Steps

As shown in the figure above, the raw binary data sent from the Raspberry Pi (or computer in our case) to the Arduino (#1) is interpreted as G-Code (#2). All of the G-Code handlers (#3) are written in C++ code, which is a series of commands and signals to the motors (#4). In light of this, changing the handlers is the best approach for implementing a polar system. Adjusting the handlers will allow us to optionally convert each rectangular point into a polar point, and then appropriate signals can be sent to the motors. An illustration of the types of changes we made is below in Diagram 4. (Note, the illustration is simplified, but it demonstrates our approach.)

Original:

```
move_x(delta) {
    motor_x = x + delta;
}
```

Proposed:

```
move_x(delta) {
    if (rectangular)
        motor_x = x + delta;
    if (polar) {
        motor_r =  $\sqrt{(x + \text{delta})^2 + y^2}$ 
        motor_theta =  $\tan^{-1}(y/x + \text{delta})$ 
    }
}
```

Figure 19: Pseudo Code of Approach

5.3 Software Development

In order to ensure the software development process could be completed on time and in an efficient manner, the following measures were taken. First, code for the current farmbot is already available as open-source software on GitHub. The “FarmBot/farmbot-arduino-firmware” repository on GitHub was duplicated as a ‘forked repository’ to avoid interfering with development of the cartesian version (though the new code can ultimately be merged together). Continuing development on GitHub allowed (and will continue to allow in the future) incremental code changes to be documented and tracked, in addition to the added comments in the source files where code has been modified. Since the code was developed incrementally and tested constantly, bugs were addressed as they were created (for example, the negative axes edge case that was detected and fixed). Despite these benefits, however, maintaining two separate code versions led to frequent compatibility issues between the Arduino and the Raspberry Pi. Because we branched off the original code line, we could no longer benefit from updates and bug fixes that FarmBot was making to the code we started with.

Our original plan for system testing was to use the FarmBot web app to send cartesian-point instructions to the FarmBot and verify that motors move to correct the positions (within acceptable tolerances). In theory this was a good plan. In reality, whenever the FarmBot was turned on, it never showed up in the web interface (“FarmBot Disconnected”, and “Unable to send command.”) Note that we did not design the web interface or the connection software. Our solution to this was to develop a standalone user interface that could send G-Code from a

computer directly to the Arduino. This solution is viable because the Arduino sees no difference in the G-Code, and it cannot distinguish whether the commands are being sent by the computer or the Raspberry Pi. In the future, when the web API is updated to work with polar FarmBots and our changes can be merged with the newest firmware, no changes will need to be made to the polar code; the web API just needs to send the G-Code as usual and the polar firmware in the Arduino will respond accordingly.

5.4 GUI Development

The figure below shows the latest iteration of the GUI. It allows the user to control the FarmBot by entering either traditional rectangular coordinates or polar coordinates. It also provides position adjustment buttons for adjustment relative to the current position. Below that, the GUI outputs the current position in both coordinate systems.

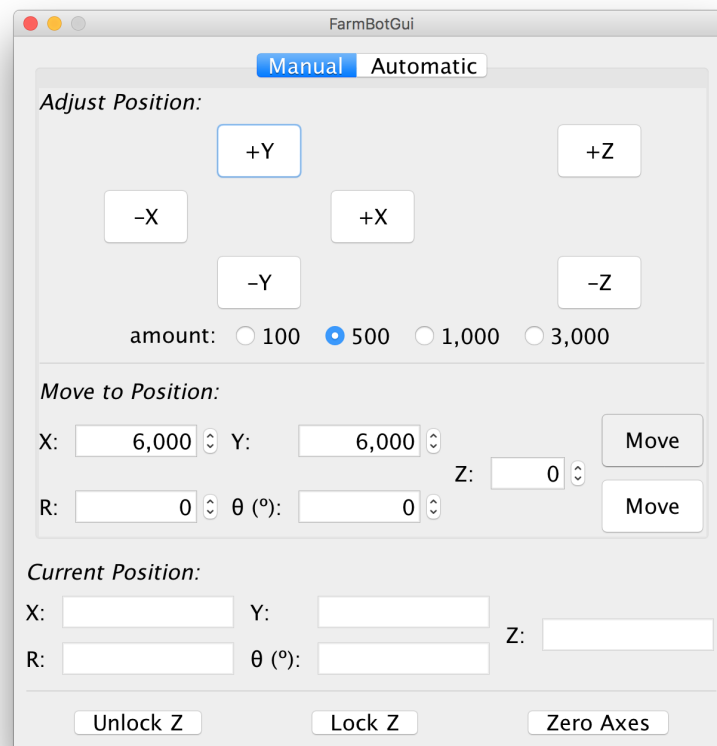


Figure 20a: FarmBot GUI, Manual Mode

Note the 6000 step offset in the GUI above. The offset is the result of converting between the two coordinate systems.

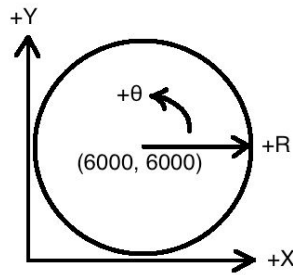


Figure 20b: Both Coordinate Systems

In the figure below, the second tab of the GUI is shown. This allows the user to input a series of commands which the FarmBot will execute in order (and optionally loop through repeatedly.)

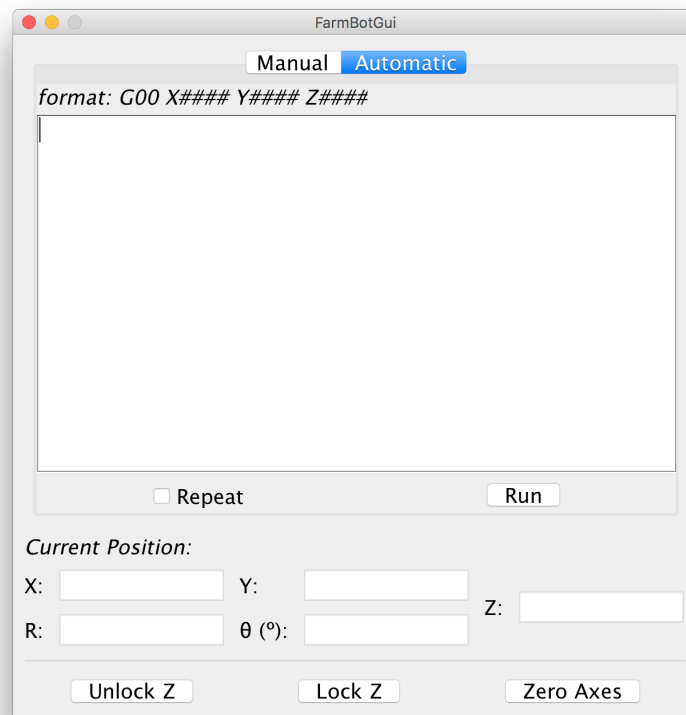


Figure 20c: Farmbot GUI, Script Window

While necessary for us at the time, this user interface that we developed for testing, will likely become obsolete in the future. At the time, since we were unable to reliably use the Web API for controlling our prototype, we needed a user interface to easily test commands, perform functions such as unlocking the z-axis, and execute looping scripts of instructions. This GUI served that purpose.

5.5 Unit Testing

Below is a list of unit tests that we ran in order to ensure the rectangular to polar conversions were being calculated correctly. All of the tests pass, and the tests checked edge cases, so we are confident that the added polar code functions as expected. We did notice unexpected behavior at times during the system testing, but we were unable to identify the source of this unexpected behavior.

TOLERANCE = 3 steps

==== POLAR -> RECT tests ====

```
test 1: polar(0, 0) -> rect(0, 0), result: (0, 0) [PASS]
test 2: polar(4242, 0) -> rect(4242, 0), result: (4242, 0) [PASS]
test 3: polar(4242, 180) -> rect(-4242, 0), result: (-4241, 2) [PASS]
test 4: polar(4242, 270) -> rect(0, -4242), result: (0, -4242) [PASS]
test 5: polar(4242, 90) -> rect(0, 4242), result: (1, 4241) [PASS]
test 6: polar(6000, 0) -> rect(6000, 0), result: (6000, 0) [PASS]
test 7: polar(6000, 135) -> rect(-4242, 4242), result: (-4242, 4243) [PASS]
test 8: polar(6000, 180) -> rect(-6000, 0), result: (-5999, 3) [PASS]
test 9: polar(6000, 225) -> rect(-4242, -4242), result: (-4244, -4241) [PASS]
test 10: polar(6000, 270) -> rect(0, -6000), result: (-1, -6000) [PASS]
test 11: polar(6000, 315) -> rect(4242, -4242), result: (4242, -4242) [PASS]
test 12: polar(6000, 45) -> rect(4242, 4242), result: (4244, 4240) [PASS]
test 13: polar(6000, 90) -> rect(0, 6000), result: (1, 5999) [PASS]
```

==== RECT -> POLAR tests ====

```
test 1: rect(0, 0) -> polar(0, 0), result: (0, 0) [PASS]
test 2: rect(4242, 0) -> polar(4242, 0), result: (4242, 0) [PASS]
test 3: rect(-4242, 0) -> polar(4242, 180), result: (4242, 179) [PASS]
test 4: rect(0, -4242) -> polar(4242, 270), result: (4242, 269) [PASS]
test 5: rect(0, 4242) -> polar(4242, 90), result: (4242, 89) [PASS]
test 6: rect(6000, 0) -> polar(6000, 0), result: (6000, 0) [PASS]
test 7: rect(-4242, 4242) -> polar(6000, 135), result: (5999, 134) [PASS]
test 8: rect(-6000, 0) -> polar(6000, 180), result: (6000, 179) [PASS]
test 9: rect(-4242, -4242) -> polar(6000, 225), result: (5999, 224) [PASS]
test 10: rect(0, -6000) -> polar(6000, 270), result: (6000, 269) [PASS]
test 11: rect(4242, -4242) -> polar(6000, 315), result: (5999, 315) [PASS]
test 12: rect(4242, 4242) -> polar(6000, 45), result: (5999, 44) [PASS]
test 13: rect(0, 6000) -> polar(6000, 90), result: (6000, 89) [PASS]
```

5.6 System Testing

The following is our script for system-level testing. It allowed us to input a series of points and verify whether the system functioned as expected.

```
G0 X6000 Y6000 Z0
G0 X6160 Y6000 Z12950
G0 X6600 Y6000 Z12950
G0 X10500 Y6000 Z15000
F44 P9 V1 W0 T1000 M0
G0 X5250 Y7298 Z15000
F44 P9 V1 W0 T1000 M0
G0 X5250 Y7298 Z12975
G0 X5913 Y6130 Z12975
G0 X5842 Y5992 Z12000
G0 X5842 Y5992 Z12975
G0 X5402 Y5969 Z12975
G0 X5300 Y6000 Z10000
G0 X5876 Y5745 Z10000
F41 P10 V1 M0
G0 X5876 Y5745 Z11700
G0 X5876 Y5745 Z10000
G0 X6000 Y3500 Z10000
G0 X6000 Y3500 Z15150
F41 P10 V0 M0
G0 X6000 Y3500 Z12975
G0 X5300 Y6000 Z12975
G0 X5840 Y6000 Z12975
G0 X5840 Y6000 Z10000
G0 X5921 Y6137 Z10000
G0 X5921 Y6137 Z12975
G0 X5652 Y6605 Z12975
G0 X6600 Y6000 Z12950
G0 X6160 Y6000 Z12950
G0 X6000 Y6000 Z0
```

Chapter 6: Manufacturing and Testing Processes

6.1 Manufacturing and Assembly

The following table (Table 10) summarizes our expected manufacturing process for custom “house-built” parts. These processes are further discussed below.

Part	Manufacturing Process	Where	Time to Complete
Shroud	3D Printed	Sponsor Formlabs Form 1	4 hrs
Tool Bay Plate	Lasercut	IME Lab Haas Lasercutter	1 hrs
Column Clamp	3D Printed	Sponsor Formlabs Form 1	4 hrs
Eccentric Spacer Bracket	Bandsaw, Milled	BRAE Lab Bridgeport Mill, Bandsaw	2 hrs
Drivetrain Base Plate	Milled	IME CNC Lab Haas Mill	3 hrs
Top Drivetrain Motor Plate	Milled	IME CNC Lab Haas Mill	2 hrs
Arm Connection Plate	Milled, Drill Press	BRAE Lab Bridgeport Mill	2 hrs
Drivetrain Motor Housing	Bandsaw, Drill	BRAE Lab Bandsaw, Bridgeport Mill	1 hr
Base Plate	Milled, Drill Press	BRAE Lab Bridgeport Mill	2 hrs
Base Channel	Plasma Cut, Bending, Drill press	BRAE Lab Hydraulic Press Brake, Plasma Cutter	3 hrs

Table 10: Manufacturing Summary

All custom manufactured parts will be completed by the end of the quarter, 3/14 for integration into subassemblies, so that we can proceed with testing and any resulting redesign.

6.1.a: 3D Printed Components

The clamp (Figure 21a) connecting the tool bay to the column and the column weatherproofing shroud (Figure 21b) will be 3D printed. Both the clamp and column weatherproofing shroud can be printed at our sponsor's in-house Formlabs Form 1 stereolithography printer out of methacrylate photopolymer resin. Both parts will be available the next day after we place our order. Before ordering, CAD files will need to be converted to STL files.

When this device goes into production, all plastic parts will be injection molded by chinese suppliers that our sponsor has developed a relationship with.

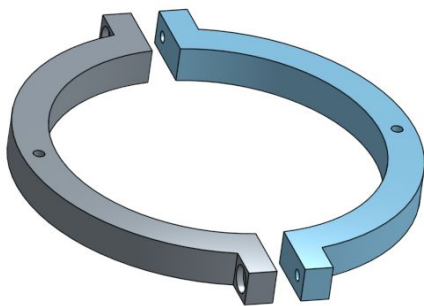


Figure 21a: Tool Bay Clamp

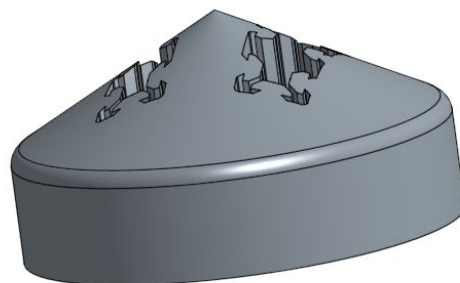


Figure 21b: Column Shroud

6.1.b: Machined Components (drivetrain plate, eccentric spacer bracket, arm connection plate)

Six components will need to be machined. The eccentric spacer bracket and rotational drivetrain motor housing will be cut on the BRAE lab band saw. The two custom motor plates will be drilled on the IME lab CNC mill, due to the large number of operations required, and the simpler parts, (base plate, eccentric spacer bracket and arm connection bracket) will be drilled on Bridgeport Mills in the BRAE lab.

The drivetrain base plate will be broached with a D-shaped cutter in order to interface with the stepper motor shaft

6.1.c Laser and Plasma Cut Components

The tool bay plate (Figure 21) will be laser-cut out of 1/10" steel plate with the HAAS laser-cutter in the IME department CNC lab. This is the easiest method of manufacturing this part given its complex geometry and the equipment at our disposal. In addition, for purposes of prototyping, this process has a much shorter lead time than purchasing a part from a vendor.

The base l-channel will be cut into its rough shape with the BRAE lab plasma cutter, as it is a structural component that is too thick to lasercut. It will also be bent to 90 degrees by the hydraulic press brake in the BRAE lab.

Eventually, after prototyping, the tool bay plate and base l-channel will be waterjet cut from more weather resistant aluminum plates by a supplier like Big Blue Saw (<http://www.bigbluesaw.com/>), or our sponsor's suppliers in China.

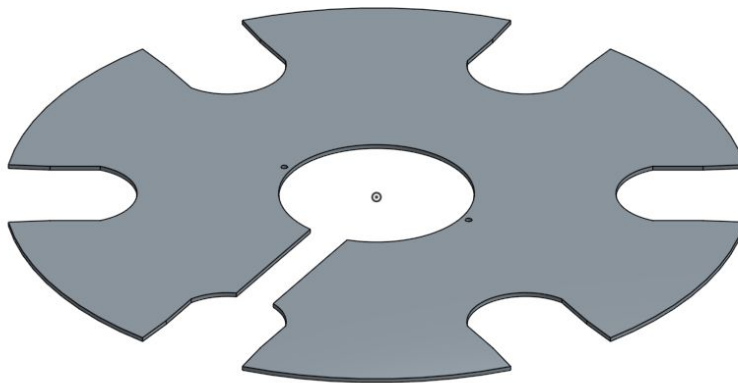


Figure 22: Tool Bay Plate

6.1.d: Assembly Tools

The following table (Table 11) details the tools required for assembly of the FarmBot device. As per our customer requirement of being DIY friendly, all the tools required to assemble the device can be acquired at a local hardware store or online through retailers like Amazon.

Tools Needed for Assembly	Supplier: Amazon/Home Depot
Crossslide	Number 2 phillips screwdriver or electric drill with a number 2 phillips driver bit
Z-Axis	3mm hex (allen) wrench
Z-Axis	2mm hex (allen) wrench
Universal Tool Mount	2mm hex (allen) driver
Universal Tool Mount	3mm hex (allen) driver
Universal Tool Mount	6mm wrench
Universal Tool Mount	8mm wrench
Universal Tool Mount	Exacto blade
Universal Tool Mount	Wire strippers
Electronics Box	3mm hex (allen) driver
Electronics Box	2.5mm hex (allen) driver
Electronics Box	2mm hex (allen) driver
Electronics Box	1.5mm hex (allen) driver
Electronics Box	Small flat-bladed screwdriver
Electronics Box	Wire strippers
Tool Bay	Drill with a #2 phillips driver bit or a #2 phillips screwdriver
Camera	3mm hex (allen) driver
Tools: Seed, Soil, Weeder, Water	2mm hex (allen) driver
Tools: Seed, Soil, Weeder, Water	3mm hex (allen) driver
Tools: Seed, Soil, Weeder, Water	6mm wrench
Tools: Seed, Soil, Weeder, Water	8mm wrench
Tools: Seed, Soil, Weeder, Water	Wire strippers
Tools: Seed, Soil, Weeder, Water	Scissors

Table 11: Tools Needed for Assembly

6.1.e: Special Assembly Considerations

Step by step assembly instructions for the cross slide, z-axis, electronics box, cables and tubing and the universal tool mount can be found at the following locations:

- Cross Slide: <http://genesis.farmbot.io/docs/cross-slide>
- Z-Axis: <http://genesis.farmbot.io/docs/z-axis>
- Electronics Box: <http://genesis.farmbot.io/docs/electronics>
- Cables and Tubing: <http://genesis.farmbot.io/docs/cables-and-tubing>
- Universal Tool Mount: <http://genesis.farmbot.io/docs/universal-tool-mount>

Drawings of custom parts used in assemblies can be found in Appendix F.

Overall Assembly of Polar Farmbot:

Base Adapter to Concrete:

1. The 5 gallon bucket can be placed in the ground or filled above ground.
2. Follow the Quikrete instructions to mix concrete within the 5 gallon bucket.
3. Assemble the adapter plate and the three threaded bolts with their nuts, leaving about ½ inch of bolt above the top nut. Using the base adapter plate with the threaded bolts

already installed, align the plate and set the bolts several inches into the concrete right after the pour.

4. Using a level and the lag bolt nuts, ensure the adapter plate is completely level and the lag bolts are as vertical as possible.
5. Wait for the concrete to cure.

Creating the Column:

1. Using two 20mm x 60mm x 1000mm extrusions, sandwich 20mm x 20mm cut extrusions and tighten them together using the M5 screws with the 3-hole bracket.
2. Six (3 on each side) of these 20mm x 20mm pieces should run down the entire length of the column. This will keep the two 1000mm extrusions properly spaced and also increase the overall rigidity.
3. Slide the shroud onto the column from the bottom such that it sits below the bottommost 3-hole bracket.

Drivetrain to Base:

1. Attach motor plate onto the motor using 4x M3 button head screws.
2. Attach turntable onto motor plate using 1/4" wrench on 4x 8-32 threaded steel hex head bolts/nuts.
3. Align the D-slot in the drivetrain base plate to motor shaft.
4. Slide the shaft into the D- slot and attach the drivetrain base plate and Angle U-bolt bracket to the turntable using 1/4" wrench on 4x 8-32 threaded steel hex head bolts/nuts.
5. Align motor housing and L-brackets in position and fasten together with M5 screws.
6. Align column extrusions to the top of drivetrain system and fasten together with T-joining plates. This will involve M5 screws threading into nuts for the motor housing and t-nuts for the column. (It is recommended to work on the assembly laying down on a table).
7. Assemble the 4 adjustable bearing mount subassemblies, referencing the exploded view in Figure 5b.
8. Attach the two lower adjustable bearing mounts to the bottom of the column extrusions so that the bottom face of the spring loaded T-nuts are flush the bottom of the extrusions.
9. The adjustable bearing mounts can be fully tightened to the column at this time, but the eccentric spacers will be adjusted later so do not over-tighten the bearing retaining bolt.
10. The desired torque of the bearing retaining bolt can be tested by checking if the eccentric spacers are still able to be adjusted by a 10mm socket without excessive effort.
11. Rotate the eccentric spacers so that the bearings are biased inward towards the column.
12. Slide the pipe over the entire drivetrain assembly.
13. Using a 10mm socket on a 6" or larger extension, rotate the eccentric spacers incrementally on each side so the bearings ride up against the inside wall of the pipe.
14. To have room for inserting the socket, remove the bottommost 3-hole bracket and slide the shroud out of the way.
15. Once you get the pipe seated firmly, attached the remaining 2 adjustable bearing mounts so that the hex button head screws are just above the outside of the pipe and accessible by allen wrench. Tighten down these fully at this location.

16. Using the 10mm socket again, rotate the eccentric spacers incrementally on each side so the bearings ride up against the inside wall of the pipe.
17. Once the eccentric spacers are all tightened, lower the shroud back down above the pipe and re-insert the previously removed 3-hole bracket in step 14.

Base + Drivetrain + Column to Base Adapter:

1. Align the drivetrain base plate to the appropriate holes along the U-bolt channel and fasten the two together using the previous 4x hex head bolts
2. Ensure the adapter plate on the lag bolts are still level after the concrete has cured.
3. Remove the base adapter from the lag bolts and align the adapter plate to the U-bolt channel. Fasten them together with the U-bolt channel with the appropriate bolts
4. Align the Base Corner Brackets to the U-bolt Channel. The vertical bolts will go through the corner bracket, U-bolt channel, and the adapter plate. The horizontal bolts will only go through the corner bracket and U-bolt channel.
5. Using the U-bolt and U-bolt clamps, tightly secure the pipe to the U-bolt channel.
6. Place the entire combined system onto the lag bolt and tighten.

Cross Slide + Z-axis to Column:

1. Securely attach the radial arm (20x60x1500mm extrusion) and onto the column using the two aluminum plate bracket. Ensure all the appropriate bolts are secured before moving onto the next steps. There should be 12 M5 screws for each brackets.
2. Take the assembled z-axis and cross slide assemble the two together
3. Take the previously assembled z-axis and cross slide assembly and slide these onto the radial arm.

Electronics Box and Tubing/Wiring:

1. Attach the pre-assembled electronics box onto the column using the 2x M5 screws.
2. Follow the Tubing/Wiring diagram in Figure 12 to route the cables.
3. Note that as the wiring/tubing is brought up the column from the base, the bundle should slide through the slot on the tool bay.
4. Leave an appropriate amount of slack in the wiring/tubing right above the tool bay prior to bring them through the center of the column.
5. The wiring from the electronics box to the drivetrain should follow along the bundle and create a J-loop as it enters the drivetrain from under the shroud and down through the center of the column into the motor housing.

Finishing Touches:

1. Place end caps on the end of the column. This step is crucial for preventing water from running down the center of the extrusions.
2. Using the silicone sealant, seal all openings that would allow water to drip within the pipe.

6.2 Product Realization

6.2.a Manufacturing Processes Employed

In creating our device, we generally followed the above manufacturing and assembly plan. Many of the brackets and plates were cut, bent, and drilled in the BRAE lab and 3-D printed parts were made at the Makerspace. However, a number of important deviations from our manufacturing plan were made. They are as follows:

- All aluminum plates for the drivetrain, base and gantry were fully or partially waterjet cut instead of cnc milled. Given that these plates will be eventually waterjet cut if this device goes into production, we decided to test the process on our prototype. We found that the supplier, Big Blue Saw, provided acceptable, high tolerance parts for our device.
- The drivetrain base plate was switched from an aluminum plate to a thicker steel one (also waterjet cut). The original aluminum plate was wearing prematurely and introducing backlash into our device. The steel plates did not have as accurate of a cut (probably due to increased thickness), preventing them from interfacing cleanly with the motor shaft. This required us to file down the d-hole in order to attach the motor.
- The toolbay plate material was changed from steel to wood, as the IME CNC laser cutter did not have an adequate platform for cutting our size part, and we had access to a wood laser cutter at the Makerspace. We used $\frac{1}{4}$ " plywood for our plate. We needed to run the program multiple times in order to fully cut through the wood. In addition, $\frac{1}{4}$ " plywood was slightly too thick for our tools to slide onto, so we needed to sand it down.
- The column shroud was 3-D printed as planned, but did not have enough inner allowance to slide freely on the central column. It had to be forcibly slid onto the column with a heatgun and mallet. Given this, the design should be changed for future use.

6.2.b Prototype vs. Planned Design

Our final prototype that we displayed at the exposition was in most aspects identical to our planned design. Small differences came about due to available materials or a timeline that determined the quickest way to have a working model. Our prototype differs from our planned design in a few key ways.

The differences are listed below:

- Toolbay
  - Instead of wood, sheet metal or thin plate metal was planned to be used for structure. We had a laser cutter available to fabricate a wooden piece.
- Encoders
  - We had originally proposed encoders on our z-axis and r-axis to track location, but this was extra work and an iteration for further prototypes.

- Electronics box wires
  - Our electronics were connected with longer cables or smaller sections spliced together. We had poor cable management, so there should be a better way of enclosing the free wires for safety.

6.2.c Recommendations for future manufacturing of your design

The vast majority of our parts were off the shelf and can be easily acquired by future customers. However, a number of key parts were custom manufactured by our team or specially ordered from suppliers. These parts cannot be easily manufactured by the average user and therefore should be provided by FarmBot as part of a kit or for sale individually through the website. All plates should be waterjet cut, including the tool bay, and the 3D printed parts should be injection molded.

6.2.d Cost estimation for future production

At the current stage, mass production cost is difficult to predict because many designs and material use would be different from what is currently being used on the prototype. The existing polar farmbot is still in the prototyping phase and has many revisions before it is production scale ready. Some examples of this could be brackets that are currently aluminum but instead could be made of injection molded plastic. The cost of waterjet parts will also drastically reduce under mass production, when right now, the waterjet components cost from a prototyping shop for a single farmbot costs ~\$120. In terms of a very rough estimate, the cost of manufacturing this prototype costs ~\$1940.00 so the production cost can be expected to be roughly ~\$550 based on how the cost of the cartesian farmbot went down from \$2,200 in prototyping to ~\$600 in scaled production.

6.3 Testing and Design Verification Plan and Report

A comprehensive design verification plan and report (DVP&R), detailing our engineering requirements and how we plan to test and verify that we are meeting them, can be found in Appendix J . The following table (Table 12) summarizes a selection of especially important tests for the functionality of our device.

Test Plan Summary				
Requirement	Spec	Test Description	# of Trials	Acceptance Criteria
Velocity	0.5 m/s +/- .2 m/s	Calculate velocity at outermost position on the radial arm, and x and z axes by measuring time to move over a set path	20	Tool head achieves .5 m/s +/- .2 m/s every trial
Overall Resolution	2.5 mm +/- 2.5 mm	Send tool head to pre-determined position and measure actual vs. measured position	20	Difference between measured and actual position is less than 2.5mm +/- 2.5mm 18/20 trials
Rotational Range	360 degrees +/- 5 degrees	Complete two full rotations of device, one clockwise and one counterclockwise	5	Achieves 360 degrees, stops at 360 degrees and reverses direction every trial
Farmable Area	4.5m ² min.	Run device to max and minimum positions. Use these measurements to calculate farmable area	5	Area of plot > 4.5m ² every trial
Maintenance Frequency	once a month	Continually run the device on an accelerated schedule that simulates a months worth of usage (50 hours). After test period check against maintenance instructions	1	Device runs continuously for test period without any necessary maintenance

Table 12: Test Plan Summary

6.3.a Test Equipment

Only basic measurement tools are required perform the tests detailed in the DVP&R. A measuring tape, stopwatch, and a postal scale will be sufficient to test the functionality and performance of our device. A computer hooked up to the FarmBot web app will be necessary to run test code (and the device in general).

6.3.b Test Results Summary

Test Results Summary Table				
Test Name	Test Description	Required Spec	Actual Spec	PASS/FAIL
Velocity	Tool velocity at outermost radial position	.5 m/s +/- .2 ms	.5 m/s	PASS
Software	Conversion Unit Tests	N/A	N/A	PASS
Software	Tool Retrieval Functional Test	N/A	N/A	PASS
Arm	FEA Analysis confirmed that there is no bending in the arm	< 5mm deflection	.8mm	PASS
Accuracy	Tool head retrieves the tools successfully	9/10 times	9/10 times	PASS
Accuracy	Tool head returns the tools successfully	9/10 times	5/10 times	FAIL
Rotation	Complete one rotation without stalling	180, -180	180, -180	PASS
Area	Achieve full farmable area	4.5 m ²	4.5 m ²	PASS
Tubing	Water flow through tubes	10/10 times	10/10 times	PASS
Seeding	Seeder tool picks up seed	9/10 times	1/10 times	FAIL

Table 13: Test Results Summary

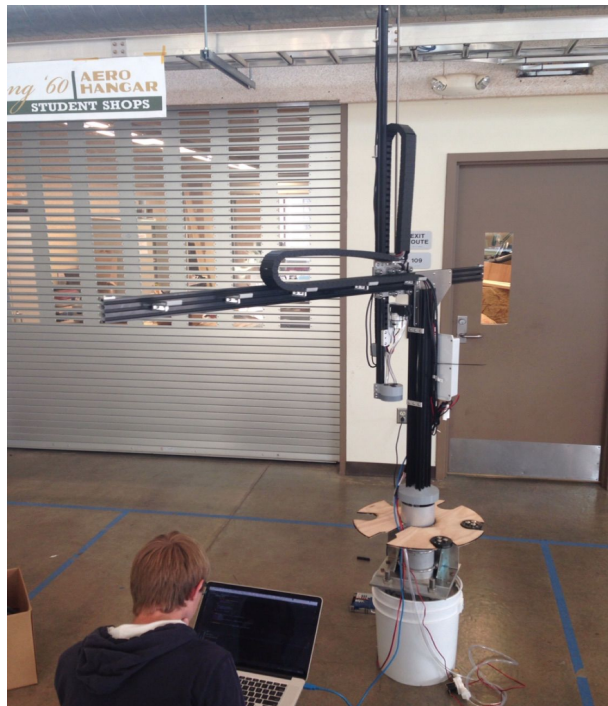


Figure 23: Testing Functionality Of Final Prototype

6.3.c Detailed Test Results

Only the more complicated tests will be discussed in more detail in this section.

Velocity Test: A video was used to determine the time taken for the farmbot tool to travel from one known location to another known location at 120° away. This test was done using a 99.05:1 reduction motor, and the rotation took 20 seconds to complete, meaning our rotational speed is 6° per second. When the arm is at 1.2m from the rotational axis, the tool speed is 251.2mm per second. This is roughly half of our spec for tool speed. We believe that using a 50.9:1 stepper motor, which was previously tested and has adequate torque, will roughly double the rotational speed of the FarmBot. This will increase the tool speed to approximately 500mm per second, which is right at our specification for the final design.

Accuracy Tests: The accuracy tests need to be explained because there are a few discrepancies that affected the test results that may not be obvious and misrepresent the actual accuracy and repeatability of the . The FarmBot passed the tool retrieval test with an ability to retrieve the tool 9/10 times, but mostly due in fact to the magnetic connectors that attach the tools to the tool holders. The magnets allowed for a misalignment between the tool holder and tool to be compensated for when magnetic force pushed the tool to the correct location in the tool bay directly under the tool holder. The tool return test was a failure at a success rate of only 5/10 times. The reason for such a bad tool return rate was because of both the backlash in the motors as well as high friction between the wood and plastic tools.

Seeding Test: The seeding tool was a definite failure mainly due to the fact that there was excessive vibration and clogging problems from a new prototype vacuum pump that the FarmBot research team has only recently started using. The vibration problem was due to the fact that the vacuum pump is mounted on the z axis extrusion as opposed to the vacuum pump being mounted at the base and wiring the hose through the cable carrier. This caused the whole z axis to vibrate during the seeding test, which made it difficult for the seed vacuum nozzle to hold the seeds. We discovered that this vacuum pump tends to intake dirt particles after the seed is pushed into the ground and the nozzle is exposed. The dirt particles travel up the vacuum and get caught in the one-way valve that controls the flow of air in the vacuum, and greatly reduces the suction of the pump. We found that this part of the pump must be cleaned about every 10 seeding operations.



Figure 24: Watering Attachment On The Tool Head

Chapter 7: Management Plan

7.1 Team Overview

- Main sponsor point of contact: Lucas Salem
- Commitment of at least 10 hours per student per week (including class time)
- Team member skillsets:
  - **Kasenia Colombo** - communication, project management, manufacturing, final report editing, accounting, organization.
  - **Lucas Salem** - organization, mechanical design, 2D/3D CAD, excel driven design calculations, irrigation design/ hydraulics, mechanics of materials/ stress calcs, urban farming/gardening
  - **Rory Stothers** - machining, mechanical design, design for manufacturing, rapid prototyping, sketching, interdisciplinary communication, brainstorming, 3D CAD
  - **Samuel Lees** - C programming, Java programming, CAD (SolidWorks), Raspberry Pi, Arduino, Scrum
  - **Ning Jeng** - project management, 2D/3D CAD mechanical design, CNC manufacturing/G-code, 3D printers, arduino programming, supply chain/vendor and factory management, agricultural systems
  - **Jack Brown** - project management, design for manufacturing and assembly, rapid prototyping, gardening, process improvement, CAD.

7.2 Gantt Chart:

Completed Gantt chart is shown in Appendix K, L, & M.

Chapter 8: Conclusions and Recommendations

Our prototype proved the viability of a polar coordinate FarmBot, and revealed the potential issues our sponsor may face in bringing this device to market. In comparison to the original cartesian FarmBot, our design has fewer parts, is potentially less costly and is portable (and therefore easier to install). However, as it is currently designed (and inherent to the polar form), it is less scalable and less accurate. With further iterations, these shortcomings could be mitigated and a commercially viable product could be produced. The following steps can be taken to further refine the design:

- Motor:
  - Use the 50.9:1 (as opposed to the currently-installed 100:1) geared reduction motor because it has enough torque to overcome the friction inside the base and will be fast enough to meet the 0.5m/s velocity specification.
- Encoders:
  - Implement the encoders that already exist on the Z- and R-axis motors to the Arduino to get feedback on what the actual position of the tool is.
  - Consider designing an auxiliary encoder that directly measures the rotational axis to account for the backlash in the rotational motor-to-base connection.
- Weatherproofing:
  - Test the sealant between the pipe shroud and the column to ensure adequate weatherproofing.
  - Add a filter to the vacuum hose that takes out dirt particles before reaching the vacuum pump.
- Manufacturability/production:
  - Use a standard size fastener for base connections to reduce the variety of parts required.
  - The 3/8" base plate could possibly be reduced to a 3/16" plate, try a 3/16" and inspect for deflection.
  - Do a comparison between drilling out turntable holes vs. bolt size reduction
- Parts to fine tune:
  - Shroud:
    - 3D print shroud without fillets at 8020 corners to see if it is easier to slide through the extrusions.
    - Adjust offset as necessary until shroud slides easily along the column. It can be sealed with silicone for weather after assembled.
- D-shape motor plate:
  - Test D-shape hole sizes so dremeling and filing won't be necessary.
  - Adjusting thickness and material as necessary to reduce on the D-slot taper when waterjet.
- Tool Bay:
  - Perform testing of tool retrieval/replacement with a different stiffer and flatter material than wood at proper thickness. (ie. metal, acrylic)
  - Try tapering the entry slots such that the tool is caught easily with a small offset.

- Base:
  - Reduce the size of base plate mounting hardware so that it matches the strength of the other hardware used throughout the base/column.

Acknowledgements

The Farmbot Revolution team would like to thank our sponsor, Rory Aronson, for creating this opportunity as well as our project advisor, Jim Widmann, for guiding us throughout the entire process.



From left: Kasenia, Rory, Sam, Ning, Lucas, and Jack

Top from left: Lucas, Jack, Jim, Rory (sponsor), Ning

Bottom from left: Kasenia and Rory



Appendices

Appendix A: Existing Cartesian Coordinate Requirements Table

Appendix B: QFD Table

Appendix C: Base Decision Matrix

Appendix D: Arm Attachments Decision Matrix

Appendix E: Base to Column Attachments Matrix

Appendix F: Custom Part Drawings

Appendix G: Bearing Mount Analysis

Appendix H: Bill of Materials

Appendix I: Hazard Identification Checklist

Appendix J: Design Verification Plan and Report

Appendix K: Fall Quarter Gantt Chart

Appendix L: Winter Quarter Gantt Chart

Appendix M: Spring Quarter Gantt Chart

Appendix N: Product Literature

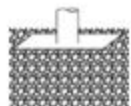
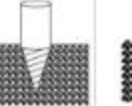
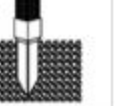
Appendix A. Existing Cartesian Coordinate Requirements Table

Cartesian Coordinate FarmBot		
Category	Parameter Description	Existing Spec
Geometry	Dimensions	3m x 1.5m
Kinematics	Farmable Area	4.5 m ²
	Cartesian Coordinates	Yes
	Velocity up to ___m/s	
Force	Torque rating from motor	4.4 kg.cm
Energy	Motor power draw	1.6 A
Materials	Aluminum	6063 T-5 extrusion
	3D Printed Plastics	ABS/PLA
Safety		
Production	3D printable	all plastic parts
Assembly	Assembly Time	15 hrs
	Number of Parts	799
Transportation	Shipping Weight	
	Shipping Size	
Operation	Motor Resolution	200 steps/rev
Maintenance	Language	Elixir
Costs	Cost to Manufacture	\$2,250
	Price to Customer	\$3,900
Software	Language	Elixir

Appendix B. QFD Table

Engineering Requirements (HOWs)															Benchmarks												
										Center		Overall															
Motors					Rotating Arm					Column	Materials	Attachments and Sensors	Safety														
Weighting (1 to 5)																											
Customer (Step #1) Requirements (Whats) 1. Final Customer/ Consumer					Ease of Initial Assembly					3						3	2	1	5								
					Large enough for sufficient crop output					2									5	2	3						
					Tail enough for variety of plants					3									3	5	5						
					Moves smoothly, without getting stuck					5	9	1	3							4	na	na					
					Will stop when this person/ object					3										1	na	na					
					Doesn't weed good plants/ waters bare soil					5										5	na	5					
					Software/Hardware integrates well					5										5	na	na					
					Can scale larger/ smaller					4				9	9					4	2	1					
					Can attach to ground, cement, stones, ceiling					5							9			3	5	5					
					Can add custom parts and code					2								1		9	3	4	3				
How Hackable It is					Easy to buy replacement parts					3							3	5	4								
					Easy to make replacement parts					3								4	2	3							
					Replacement Parts are Inexpensive					1						1			2	1	4						
How Much It Costs					Maintenance costs is low/ infrequent					2							3	1	1								
					Electricity usage is low					1									5	1	5						
					Shipping cost is low					2				1	9	9		3		3	1	na					
Misc					Overall system price is low					4				3	9			3	2	1							
					Accessibility of components					3										3	2	4					
					Ease of Maintenance					2											3	2	1				
Units					Kg, cm	#	Watts	m/s	in^3	grams	lbs	m	ft. lbs	m	y/n	ft. lbs	lbs	y/n	y/n	y/n	y/n						
● = 9																											
○ = 3																											
Δ = 1																											
Blank																											
Target					4	200	1.6	0.5	8	250	10	1.2	100	1	y	100	25	y	y	+5	6	6	6	y	y		
Benchmark #1 (Cartesian)					4	200	1.6	0.5	8	250	na	na	na	1	y	na	na	y	y	+5	4	2	6	y	n	y	
Weighted Value					45	12	14	15	9	2	27	93	72	33	9	80	36	60	72	81	90	51	66	3	33	27	24
Percent of Highest Value					48	13	15	16	10	2	29	100	77	35	10	86	39	65	77	87	97	55	71	3	35	29	26

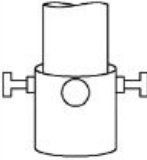
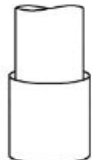
Appendix C. Base Decision Matrix

							
Jack Brown							
Decision Making Matrix: Base	Prototype	Concrete	Footed Plate	Ballast Bag	Soil Screw	Fence Post Spike	
Customer Requirement	Datum						
Ease of Initial Assembly			+	+	+	+	
Interference with Growing Space			+	S	+	+	
Can Scale Larger/Smaller			-	-	-	-	
Reliability			-	-	-	-	
Easy Maintenance			+	+	+	+	
Availability of parts			-	-	-	S	
Shipping			-	-	-	-	
Adjustability			+	-	S	S	
Price			-	-	-	+	
Soil Independence		S	S	-	-		
E'+				4	2	3	4
E'-				5	6	6	4
E(s)				1	2	1	2

Appendix D. Arm Attachments Decision Matrix

													
Decision Making Matrix: Base to Column Connection	Prototypes	Simple Radial Arm with metal support bracket	Radial arm with wheel	Radial arm with groove and track	Radial arm with wheel and flexible track	Radial arm with cable support	Cantilevered radial arm with counterweight	Radial scissor arm	Full arm with perimeter track	Full arm with perimeter wheels	Full arm with offset column	Full arm with moving counterweight	Radial Counterweight "Universal Mount"
Customer Requirements	Rory												
Ease of Initial Assembly	Datum	+	+	S	S	S	+	S	-	-		+	-
Moves smoothly, without getting stuck		S	-	+	+	S	S	S	+	-		S	S
Will stop when hits person/object		S	S	S	S	S	S	S	S	S		S	S
Can scale larger/ smaller		S	+	+	+	S	-	-	+	+		S	S
User can add custom parts and code		S	S	S	S	S	S	S	S	S		S	S
Easy to buy replacement parts		+	+	+	S	+	S	-	S	S		+	-
Easy to make replacement parts		+	+	+	S	+	+	-	S	S		S	-
Replacement Parts are Inexpensive		+	+	S	-	S	+	+	-	-		S	-
Maintenance cost is low/ infrequent		+	-	S	S	+	S	-	S	-		S	S
Shipping cost is low		+	+	-	+	+	+	S	S	S		S	+
Overall system price is low		+	+	+	S	+	+	+	S	S		S	S
Accessability of components		S	S	S	S	S	S	S	S	S		S	-
Ease of Maintenance (Bolt Access)		S	S	S	S	S	S	S	S	S		S	S
Ease of accessing locations in plot (rotation requirements)		-	-	-	-	-	-	-	-	-		-	S
Stability		S	+	+	+	S	S	-	+	+		S	+
Adaptability to environment		+	-	-	S	+	+	+	-	-		S	+
Holds up to weather		+	-	+	+	S	S	-	+	-		S	S
E'+		9	8	7	5	6	6	3	4	2		2	3
E'-		1	5	3	2	1	2	7	4	7		1	5
E(s)		7	4	7	10	10	9	7	9	8		14	9

Appendix E. Base to Column Attachments Decision Matrix

Decision Making Matrix: Base to Column Connection						
	<u>Prototypes</u>	Christmas Tree Style Base	Threaded Collar	Pressed Into Bearings/ Collar	Directly set in concrete/ soil	Bolted to Metal Bracket
<u>Customer Requirements</u>	Lucas Salem					
Ease of Connection to Base		+	+	-	-	Datum
Can scale larger/ smaller		S	S	S	-	
Can attach to ground, cement, stones, ceiling		-	S	-	-	
Easy to buy replacement parts		S	-	-	S	
Easy to make replacement parts		S	-	-	S	
Replacement Parts are Inexpensive		-	-	-	+	
Shipping cost is low		S	S	S	+	
Overall system price is low		S	S	S	+	
Ease of Maintenance/ Replacement		+	S	-	-	
Reliability (Quality over time)		S	S	S	S	
Precision Adjustment		+	S	S	S	
Adaptability to different bases		S	S	S	S	
	E(+)	3	1	0	3	
	E(-)	2	3	6	4	
	E(s)	7	8	6	5	

Appendix F. Custom Part Drawings

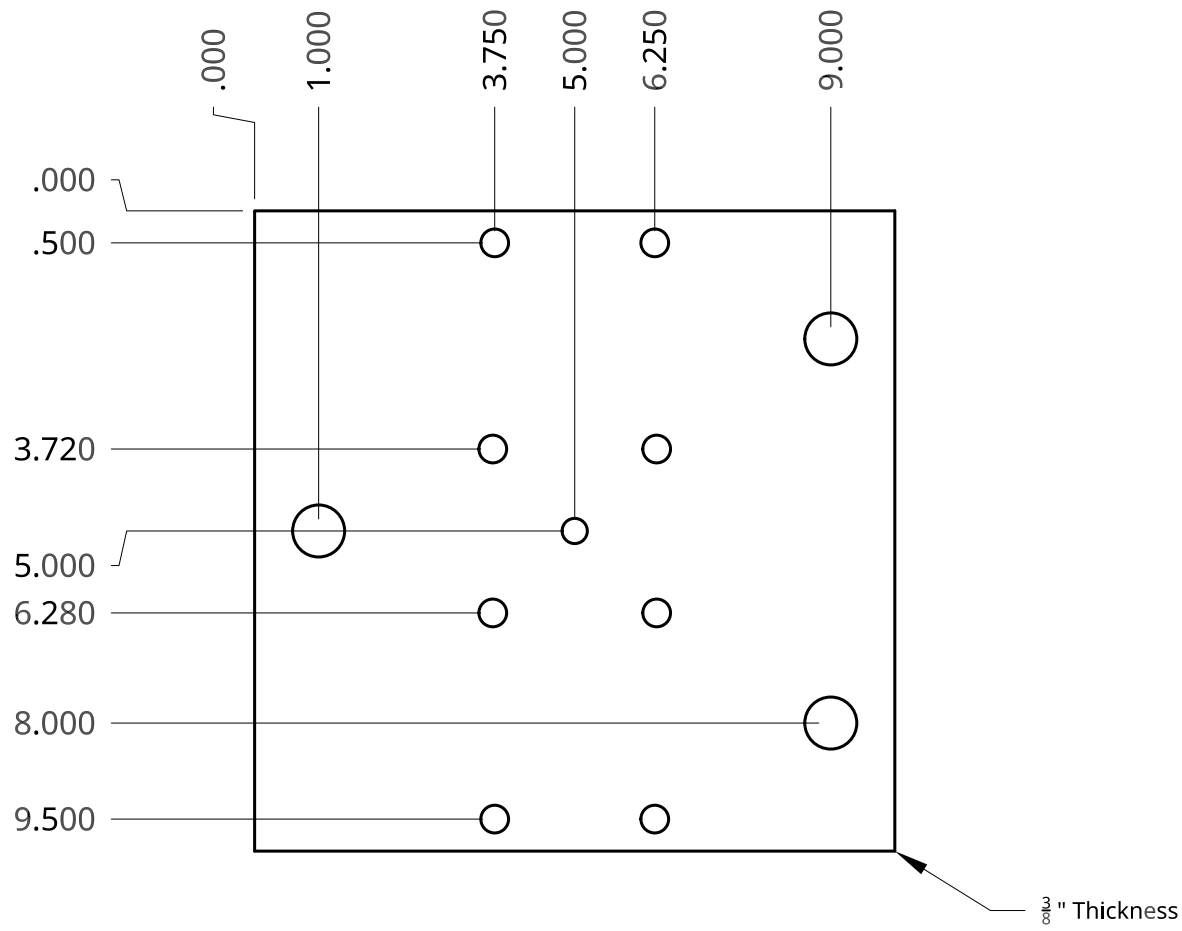
1. Adapter Plate
2. Bent U-Bolt Plate
3. Adjustable Bearing Bracket
4. Motor Housing
5. Drivetrain Motor Plate
6. Drivetrain Base Plate
7. T-Joining Plate
8. Tool Holder Plate
9. Pipe Clamp 1
10. Pipe Clamp 2
11. Column Shroud
12. Shoulder Plate

B

A

B

A



UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES .X = ±.1 .XX = ±.01 .XXX = ±.0031 ANGULAR ∠ = ±.1 ° FRACTIONAL = ±1/32	NAME		DATE		FARMBOT REVOLUTION					
	DRAWN BY:		Rory Sothers						02/14/2017	
	CHECKED BY:		Ning Jeng		02/14/2017		PART NAME ADAPTER PLATE			
	APPROVED BY:		Lucas Salem		02/14/2017					
	NOTES: xxx									
MATERIAL 6061		FINISH Factory		SUBASSEMBLY NAME Base				REV. 1		
				SCALE 1:3		SIZE A		SHEET 1 of 1		

2

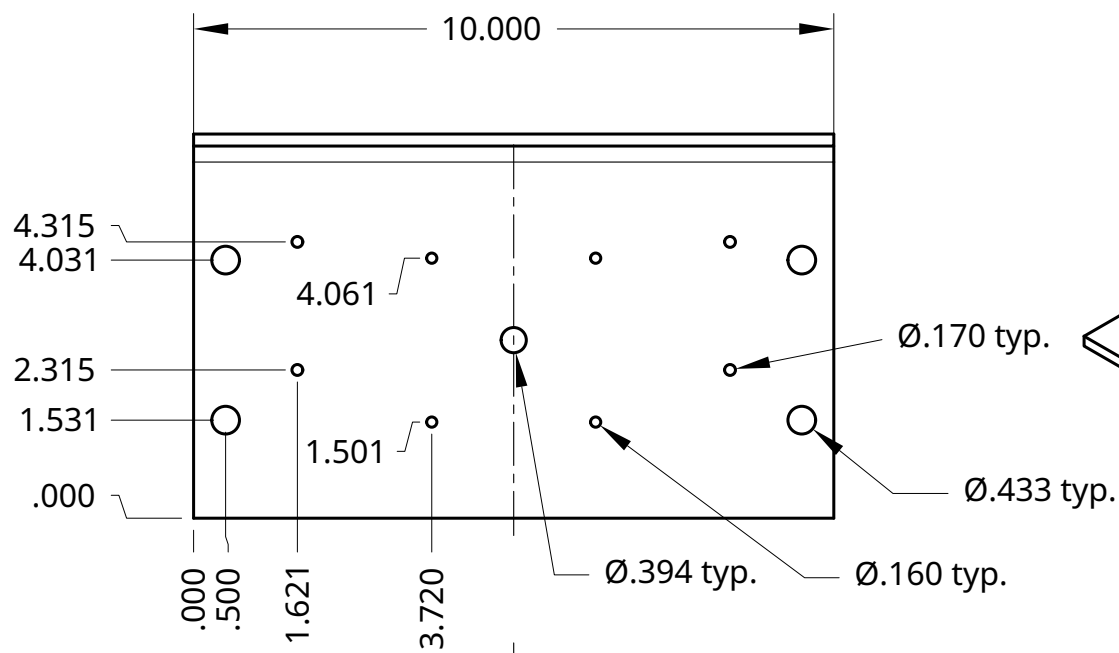
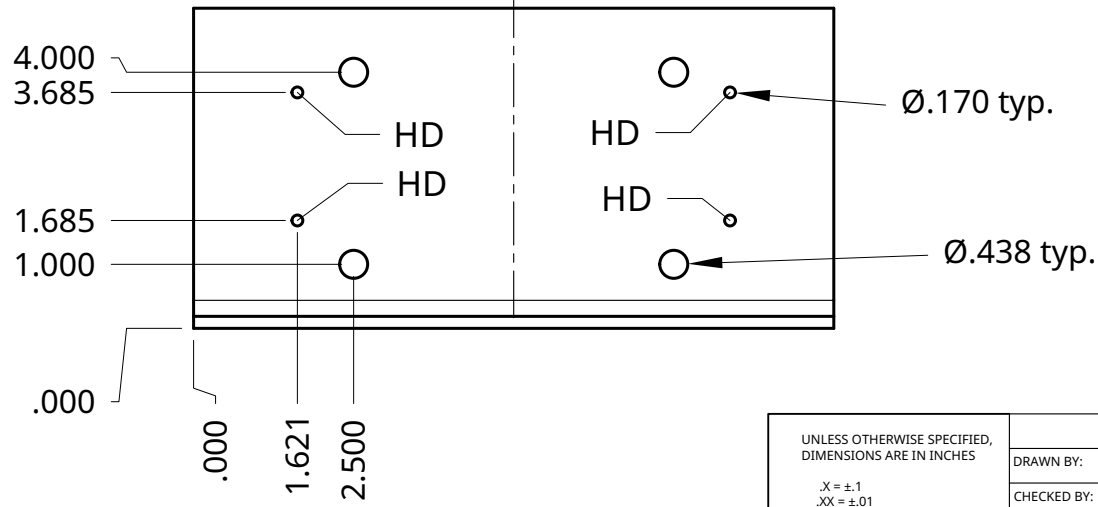
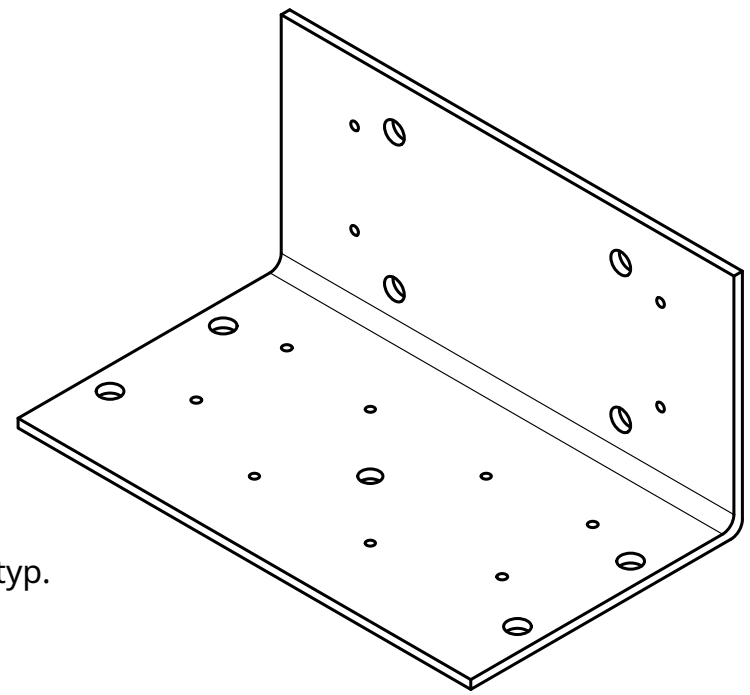
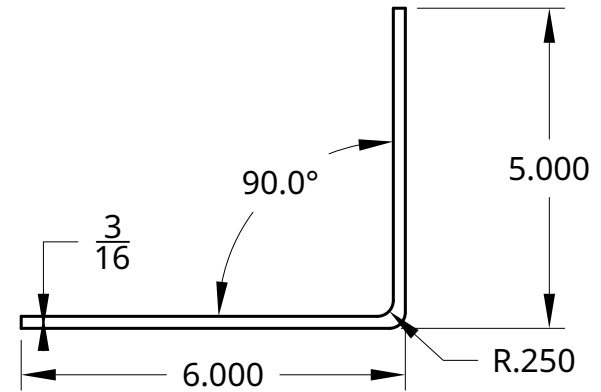
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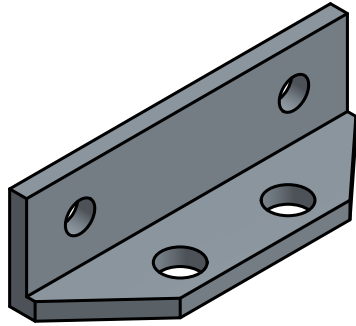
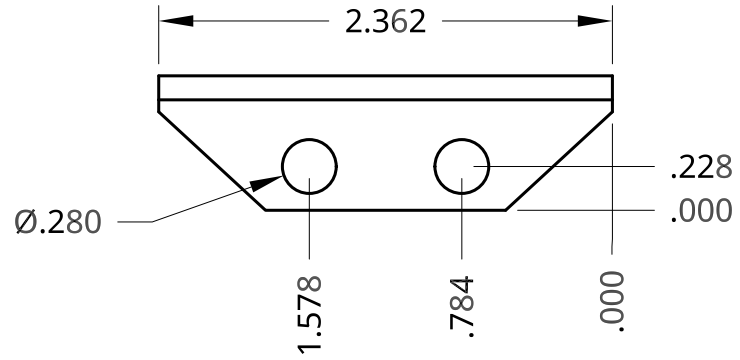
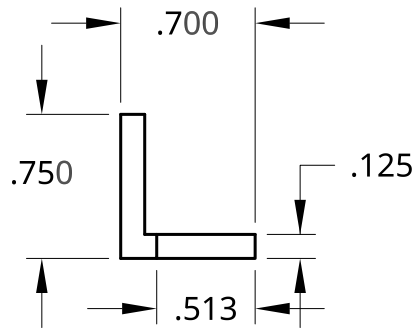
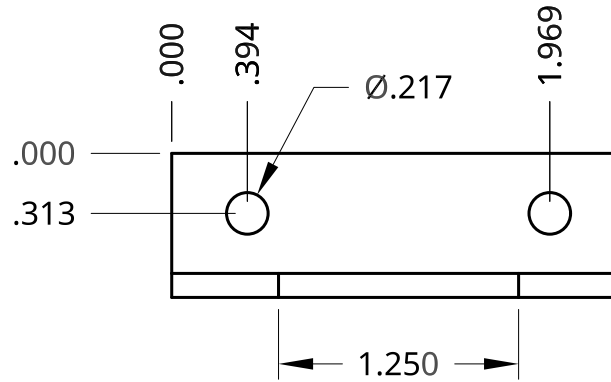
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B

A



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	CHECKED BY:		Ning Jeng		02/13/2017		PART NAME Bent U-Bolt Plate						
	APPROVED BY:		Rory Sothers		02/13/2017								
	NOTES: HD= Hand drill upon installation of corner bracket after sheet is bent				SUBASSEMBLY NAME Base				REV. 1				
MATERIAL		FINISH											
6061		Factory											
		SCALE		1:3		SIZE		A		SHEET		1 of 1	



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	CHECKED BY: Ning Jeng		02/13/2017	PART NAME Adjustable Bearing Bracket			
	APPROVED BY: John Brown		02/13/2017				
	NOTES:						
	MATERIAL		FINISH		SUBASSEMBLY NAME		REV.
	6061		Factory		Adjustable Bearing Mount		1
					SCALE 1:1	SIZE A	SHEET 1 of 1

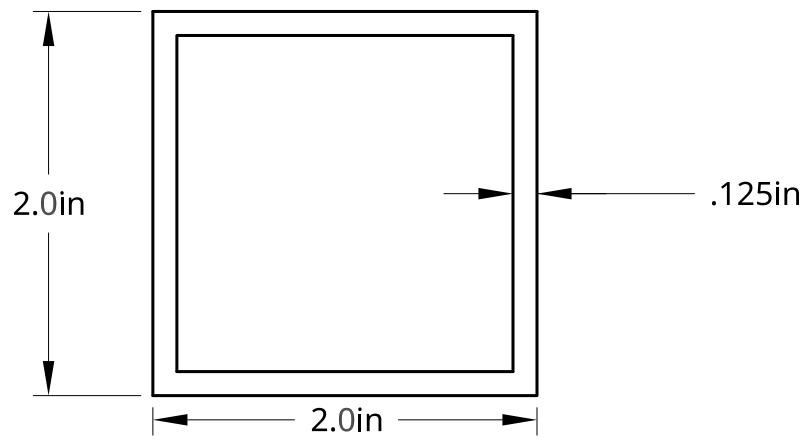
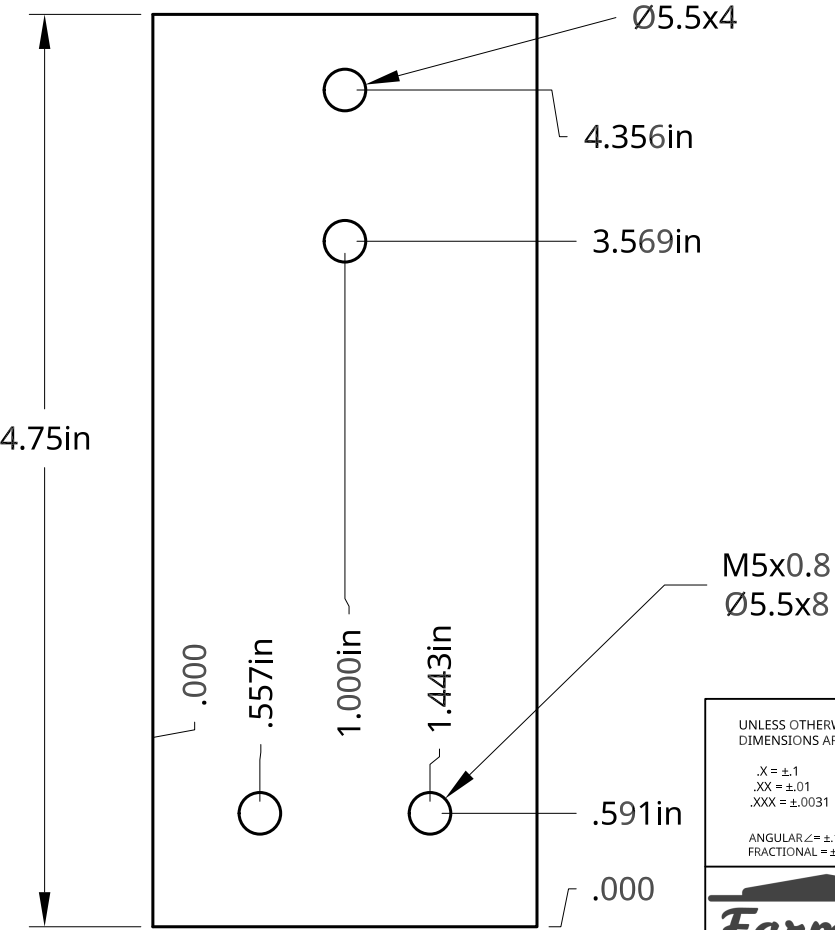
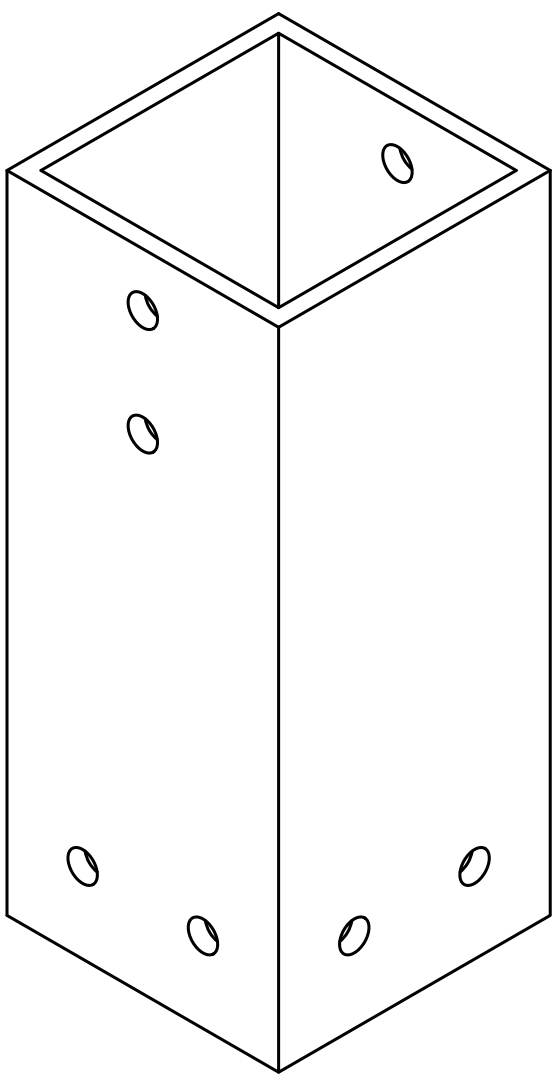
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A

4

B

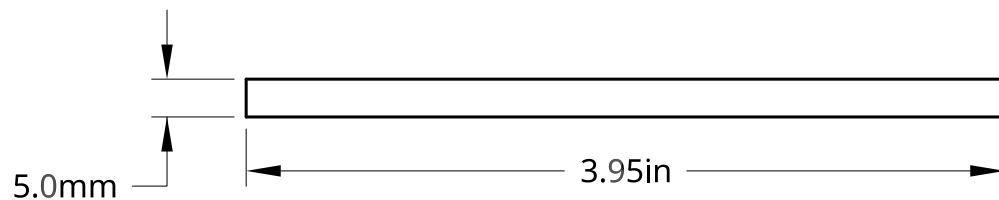
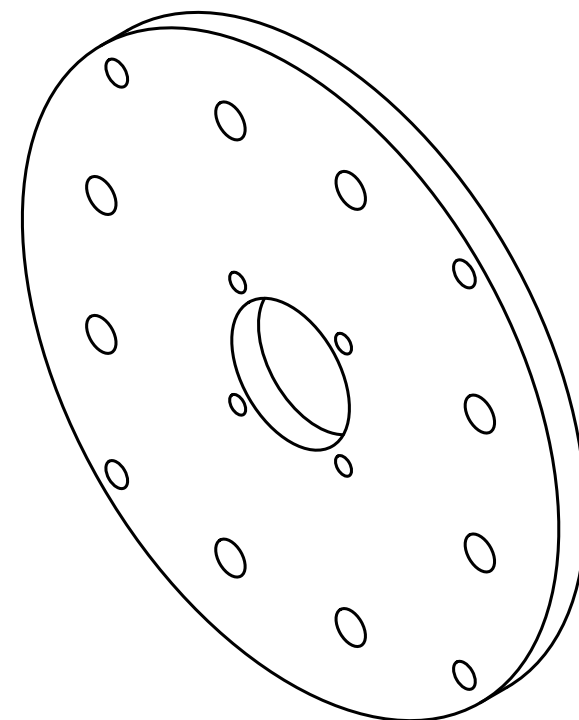
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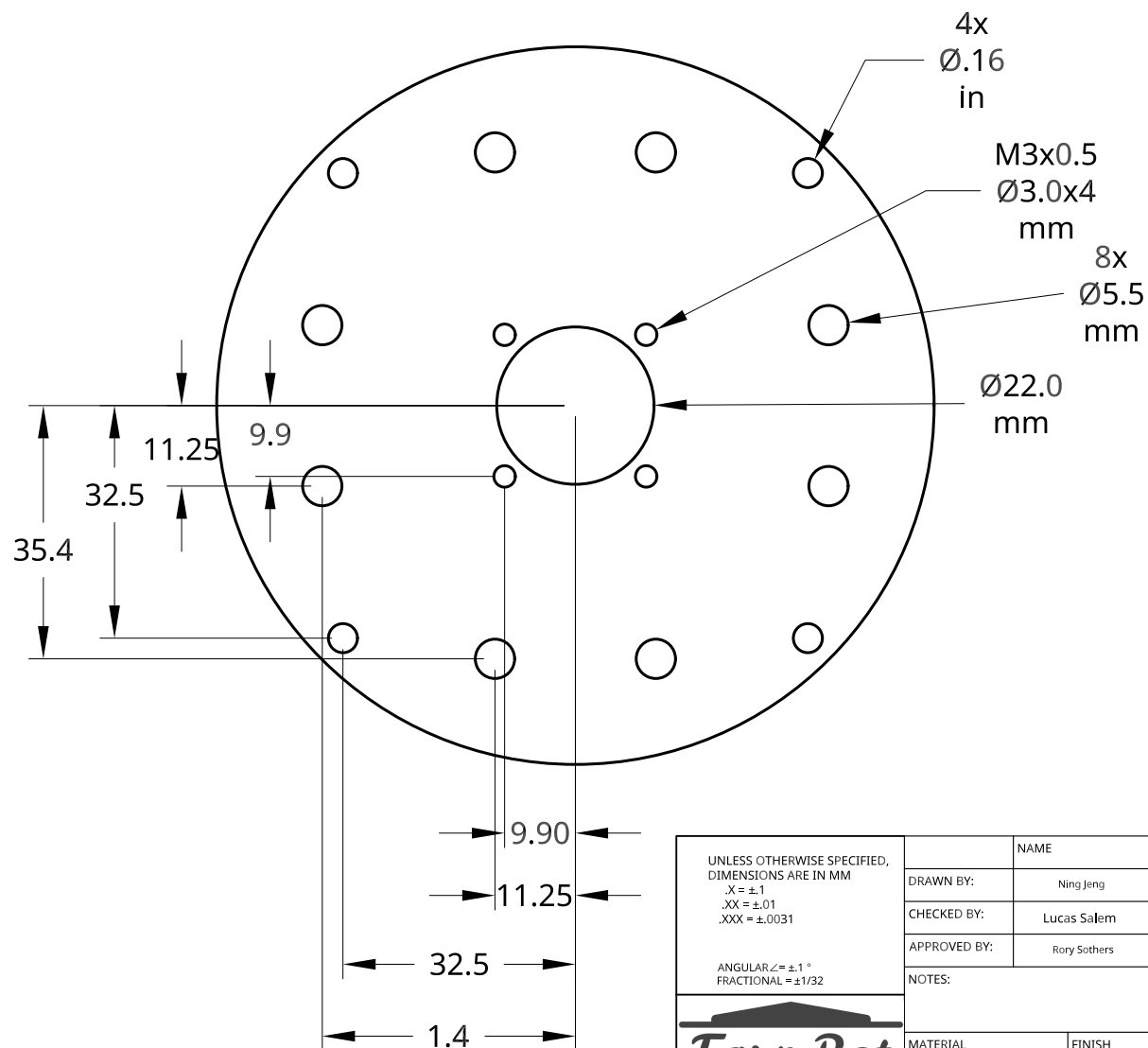
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	CHECKED BY:		Lucas Salem						02/13/2017		
	APPROVED BY:		Rory Sothers		02/13/2017		PART NAME Motor Housing				
	NOTES:										
	MATERIAL		FINISH		SUBASSEMBLY NAME				REV.		
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2

1



SCALE 1:1

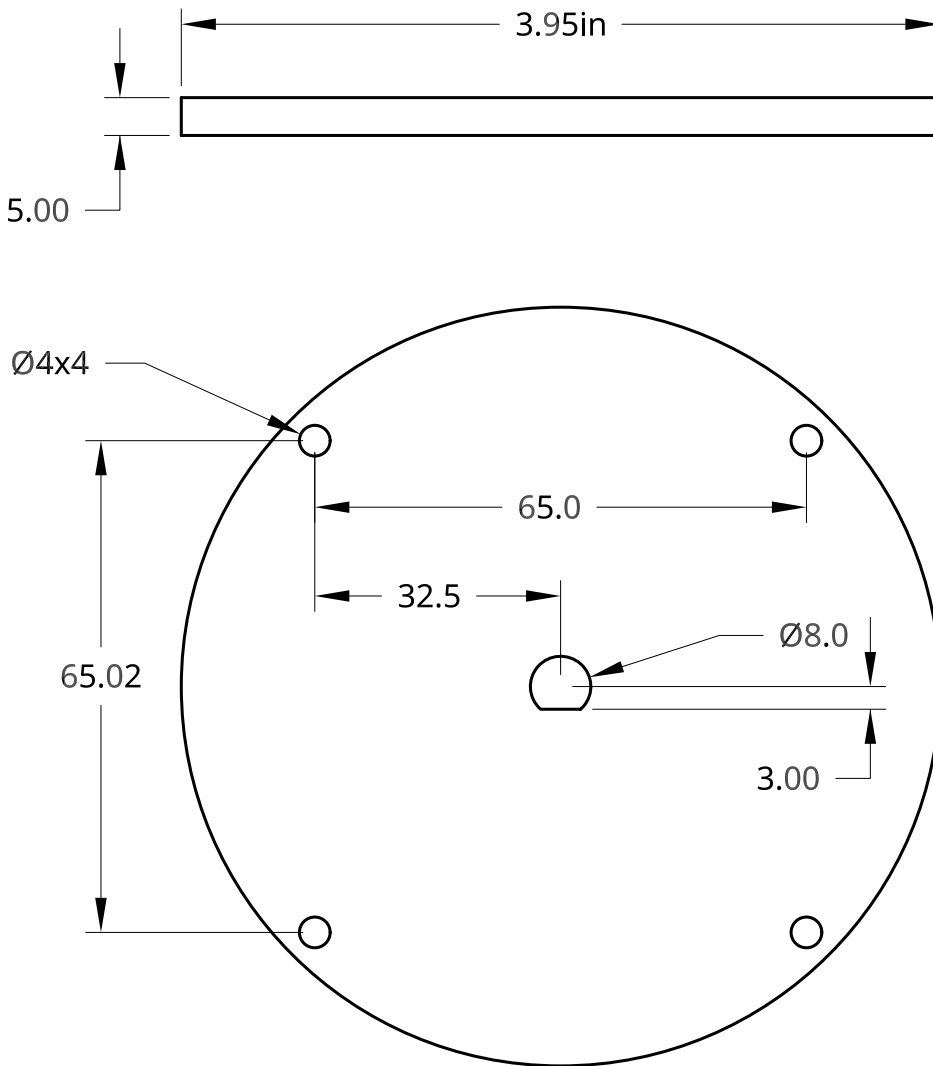
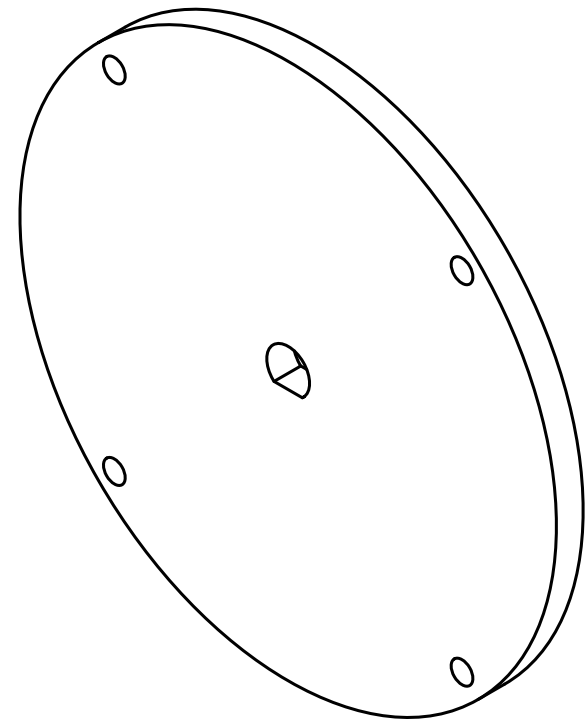


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FRACTIONAL = ±1/32



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CHECKED BY:	Lucas Salem	02/13/2017	PART NAME Drivetrain Motor Plate			
APPROVED BY:	Rory Sothers	02/14/2017				
NOTES:			SUBASSEMBLY NAME Drivetrain			
MATERIAL 6061 Aluminum		FINISH Tumble Finish		REV. 1		
		SCALE 1:1		SIZE A		
				SHEET 1 of 1		



SCALE 1:1

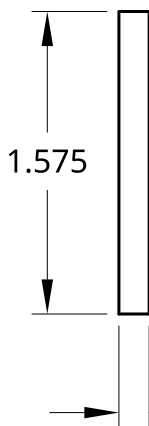
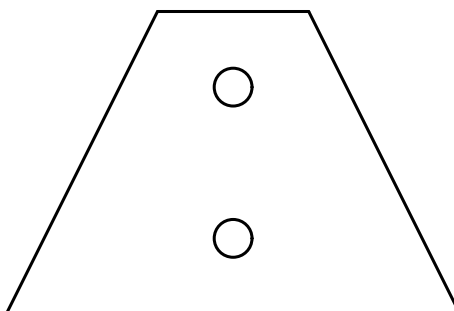
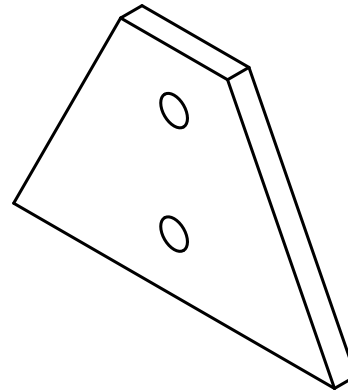
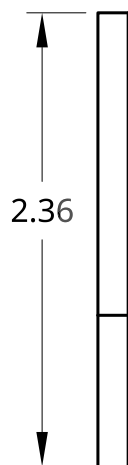
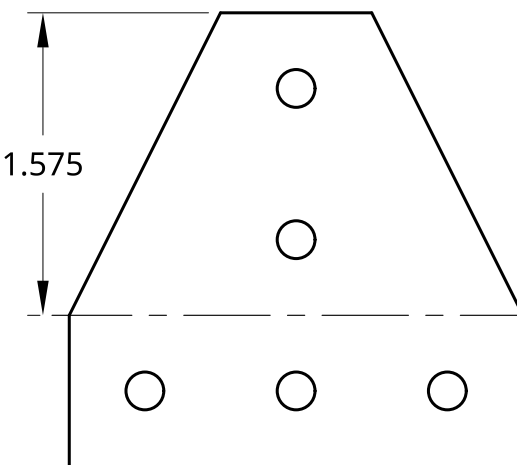
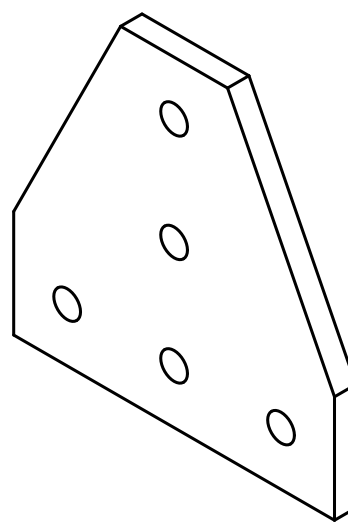
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	APPROVED BY:		John Brown	02/12/2017					
NOTES:									
	MATERIAL		FINISH		SUBASSEMBLY NAME			REV.	
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					SCALE	1:1	SIZE	A	SHEET

B

A

B

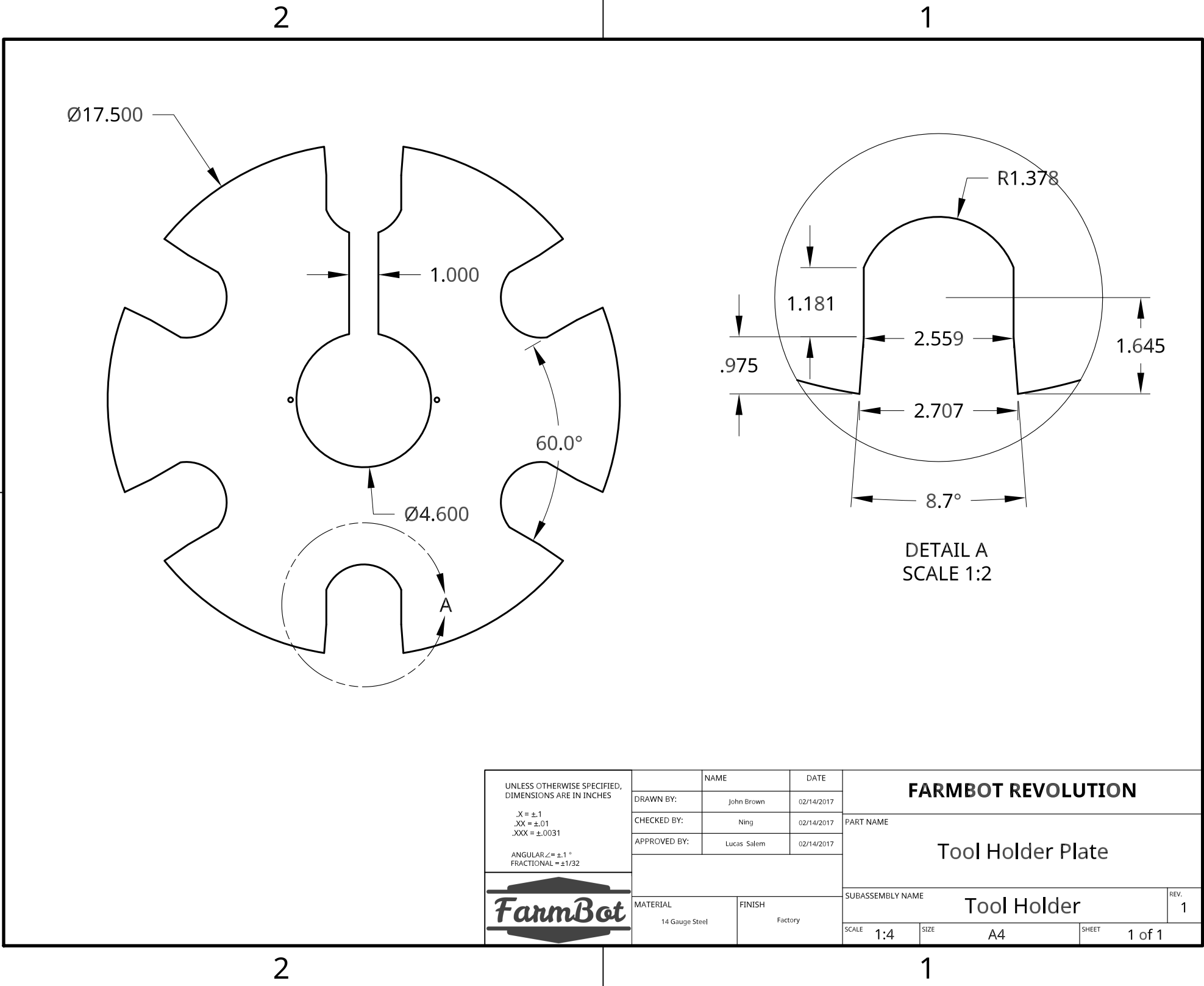
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	CHECKED BY: Lucas Salem		02/13/2017		PART NAME T - Joining Plate		
	APPROVED BY: Rory Sothers		02/13/2017				
	NOTES:						
MATERIAL 6105-T5 Aluminum		FINISH Clear Anodized		SUBASSEMBLY NAME Drivetrain			REV. 1
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2

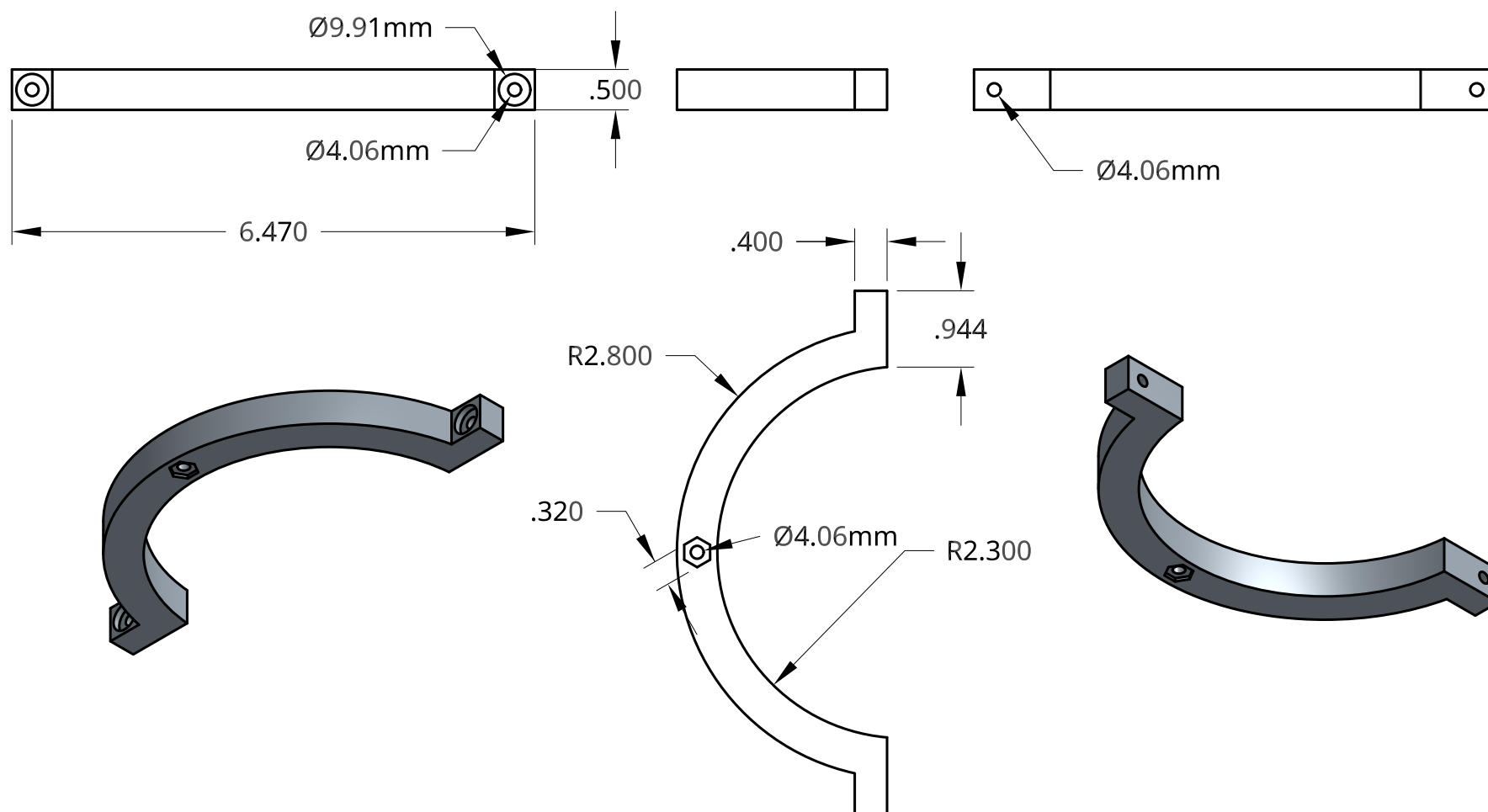
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	CHECKED BY:	Ning	02/14/2017			
	APPROVED BY:	Lucas Salem	02/14/2017	Tool Holder Plate		
	MATERIAL		FINISH	SUBASSEMBLY NAME		REV.
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	SCALE		1:4	SIZE	A4	SHEET 1 of 1

B

B



A

A

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	NOTES: xxx										
	MATERIAL		FINISH		SUBASSEMBLY NAME			REV.			
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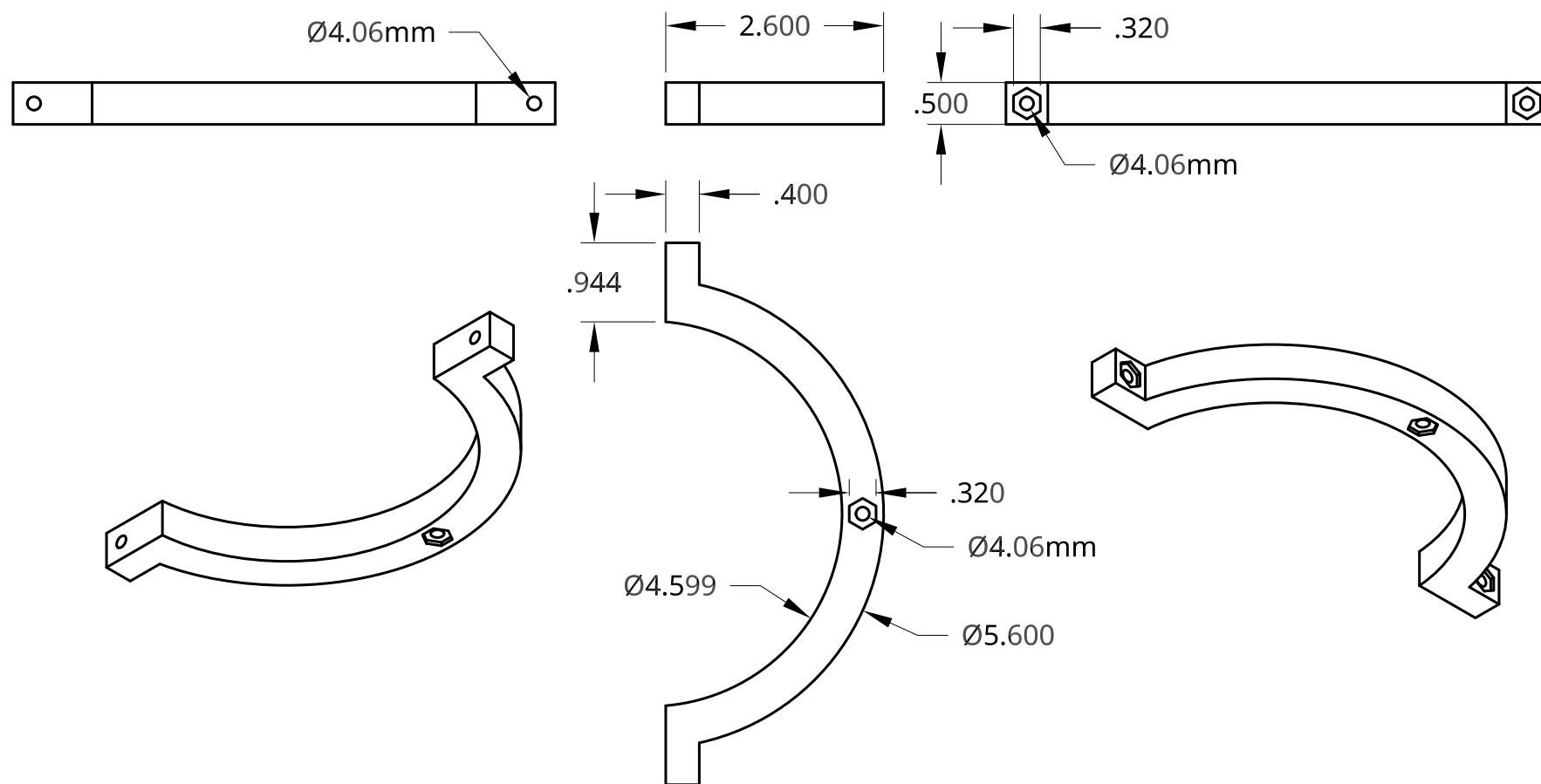
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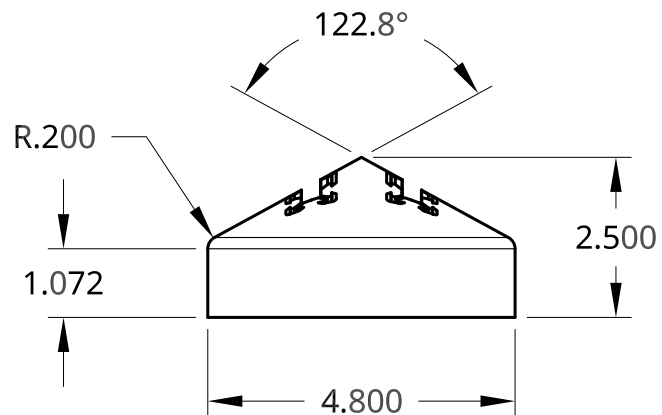
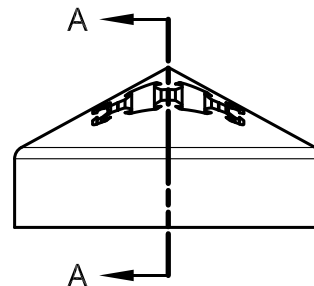
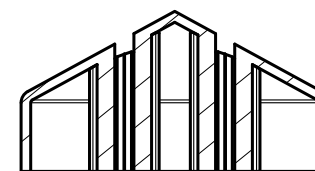
10



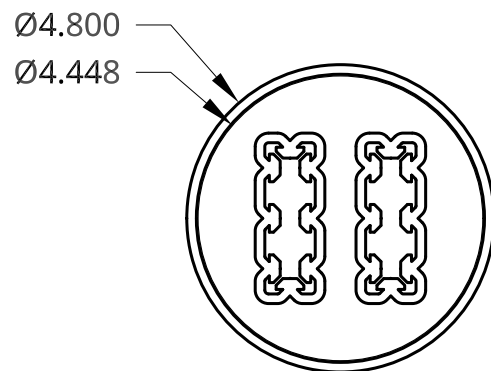
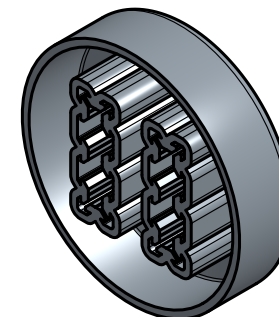
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES .X = ±.1 .XX = ±.01 .XXX = ±.0031 ANGULAR ∠ = ±.1 ° FRACTIONAL = ±1/32	NAME		DATE	FARMBOT REVOLUTION			
	DRAWN BY: John Brown		02/14/2017				
	CHECKED BY: Ning Jeng		02/14/2017	PART NAME PIPE CLAMP 2			
	APPROVED BY: Lucas Salem		02/14/2017				
	NOTES:						
	MATERIAL		FINISH		SUBASSEMBLY NAME		REV.
	3D Print - Photopolymer Resin		3d Print		Tool Holder		1
					SCALE 1:2	SIZE A	SHEET 1 of 1

2

1



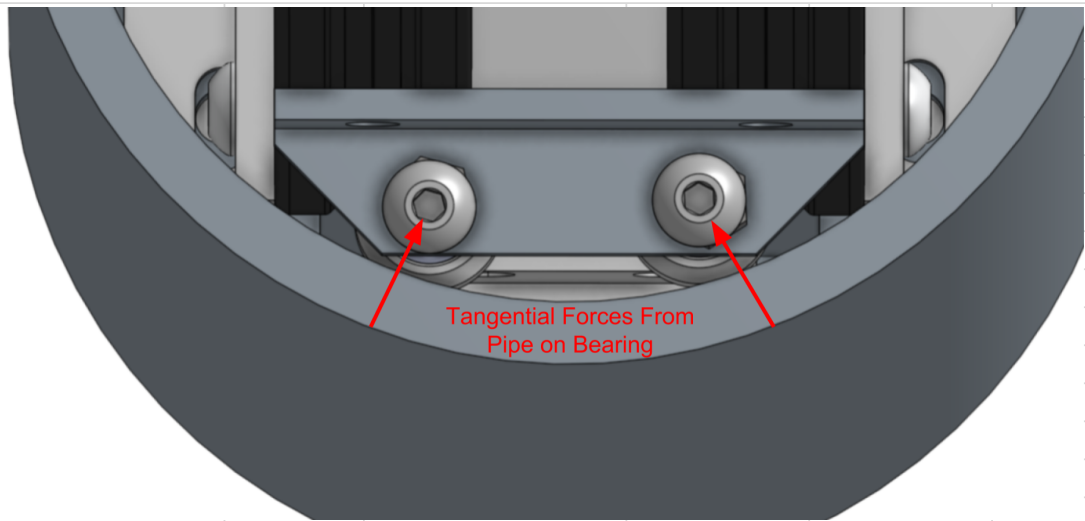
SECTION A - A



UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES .X = ±.1 .XX = ±.01 .XXX = ±.0031 ANGULAR ∠ = ±.1 ° FRACTIONAL = ±1/32	NAME		DATE	FARMBOT REVOLUTION			
	DRAWN BY:		Rory Sothers				02/14/2017
	CHECKED BY:		Lucas Salem	02/14/2017	PART NAME		
	APPROVED BY:		Ning Jeng	02/14/2017			
	NOTES:				Column Shroud		
Lucas Salem							
FarmBot	MATERIAL		FINISH		SUBASSEMBLY NAME		REV.
	Resin		3D Print		Column		1
	SCALE 1:3		SIZE A		SHEET 1 of 1		

Appendix G: Bearing Mount Analysis

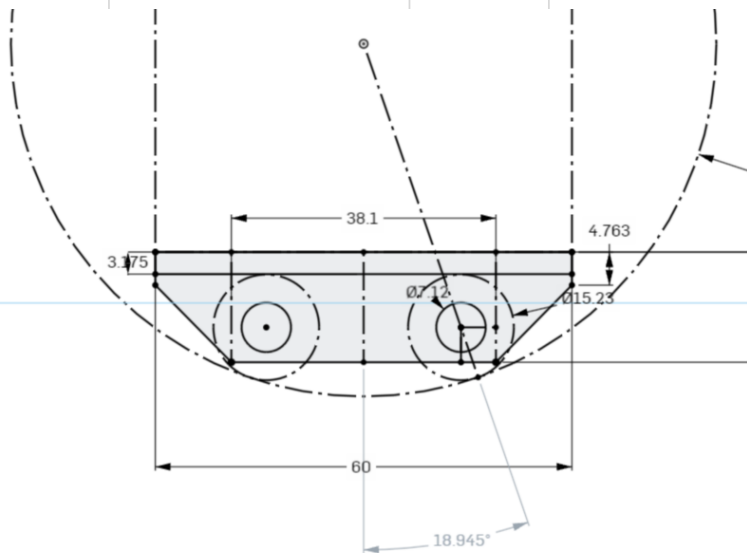
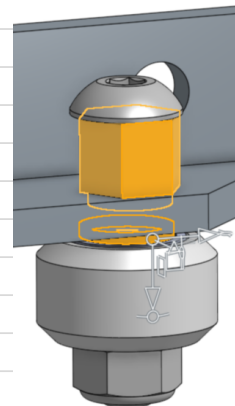
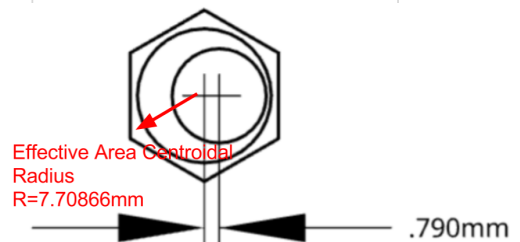
Scope: To determine the max force that can be applied at each wheel without the eccentric spacers rotating out of position.



Assumptions: The eccentric spacer will have to rotate in order for the bearing to become loose.

Calculations:

Eccentric Spacer					
Radius of Centroid Area	7.70866	mm	References		
Coefficient of Friction Stainless Steel on 6061	0.45	(dry and clean)	http://www.engineeringtoolbox.com/friction-coefficients-d_778.html		
Bolt Clamping Force	538	lbs	https://www.fastenal.com/content/feds/pdf/Torque-Tension%20Chart%20for%20Metric%20Fasteners.pdf		
Frictional Torque (Rotating)	$T = \mu RN$	1866.266586	mm-lbs		
Worst Case Scenario: When the eccentric spacer is aligned perpendicular to the tangential force from the pipe.					
Acting radius arm:	0.79	mm			
Allowable Tangential Force:	2362	lbs			
Allowable Force:	2352	lbs			



Appendix H: Bill of Materials

Subassembly	Components	Cost Per Unit	Quantity	Total Cost	Location
Column	Column Beams - 20mm X 60mm x 1500mm V-slot extrusion	25.30	2	\$50.60	http://openbuildspartstore.com/v-slot-linear-rail/
	Cut Column Spacers (20 x 20 x 250mm)	3.00	6	\$18.00	http://openbuildspartstore.com/v-slot-linear-rail/
	3 hole plate	2.05	6	\$12.30	http://openbuildspartstore.com/3-hole-joining-strip-plate/
	Weatherproof shroud	50.89	1	\$50.89	https://www.shapeways.com/
	Column endcaps	1.85	6	\$11.10	http://openbuildspartstore.com/end-cap/
	2.8 oz. Silicone Sealant	5.50	1	\$5.50	http://www.homedepot.com/p/GE-2-8-oz-Silicone-Sealant-GE-57/202038072
Gantry Arm	Gantry Main Beam - 20mm x 60mm x 1500mm V-slot extrusion	25.30	1	\$25.30	http://openbuildspartstore.com/v-slot-linear-rail/
	Cable Carrier Supports	12.43	6	\$74.58	https://www.shapeways.com/
	M5 x 10mm Screws	0.12	42	\$5.04	https://www.mcmaster.com/#92095a208/=1633yc9
	M5 tee nuts	0.28	12	\$3.36	http://www.peakstight.com/
Cross Slide	Arm to Column bracket	15	2	\$30.00	House built
	Cross-Slide Plate	0.00	1	\$0.00	https://www.bigbluesaw.com/
	M3 x 5mm Setscrews	0.25	2	\$0.50	https://www.mcmaster.com/
	M5 x 16mm Screws	0.17	4	\$0.68	https://www.mcmaster.com/
	M5 x 30mm Screws	0.17	12	\$2.04	https://www.mcmaster.com/
	M5 x 6mm Spacers	0.20	6	\$1.20	http://openbuildspartstore.com/
	M5 x 6mm Eccentric Spacers	2.00	6	\$12.00	http://openbuildspartstore.com/eccentric-spacer/
	M5 Washers	0.03	14	\$0.42	https://www.mcmaster.com/
	M5 Locknuts	0.08	16	\$1.28	https://www.mcmaster.com/
	Horizontal Motor Housing	32.50	1	\$32.50	https://farmbot-genesis.readme.io/docs/3d-prints#section-horizontal-motor-cover
	Long Cable Carrier Mount	13.84	1	\$13.84	https://farmbot-genesis.readme.io/docs/3d-prints#section-long-cable-carrier-mount
	Polycarbonate V-Wheel	3.95	12	\$47.40	http://openbuildspartstore.com/xtreme-solid-v-wheel/
	SS-625-2RS Bearings	0.30	24	\$7.20	http://zotyindustrial.com/index.php/product/index/id/34.html
	M5 Shim	0.25	12	\$3.00	http://openbuildspartstore.com/precision-shim-10x5x1mm/
	Leadscrew Block	6.95	1	\$6.95	http://openbuildspartstore.com/nut-block-for-8mm-metric-acme-lead-screw/
	20 tooth GT2 Pulley	5.50	1	\$5.50	http://openbuildspartstore.com/gt2-2mm-timing-pulley-20-tooth/
	Belt Clip Plates	3.00	2	\$6.00	https://www.bigbluesaw.com/
	M5 x 10mm Screws	0.12	2	\$0.24	https://www.mcmaster.com/
	M5 tee nuts	0.28	2	\$0.56	http://www.peakstight.com/
	GT2 Timing Belt	8.20	12	\$98.40	http://openbuildspartstore.com/
Z Axis	M3 x 10mm Screws	0.08	2	\$0.16	https://www.mcmaster.com/
	Z - Axis Beam - 20mm x 20mm x 1000mm V-slot extrusion	11.00	1	\$11.00	http://openbuildspartstore.com/v-slot-linear-rail/
	M3 x 10mm Screws	0.08	4	\$0.32	https://www.mcmaster.com/
	M5 x 10mm Screws	0.12	10	\$1.20	https://www.mcmaster.com/
	M5 x 16mm Screws	0.17	2	\$0.34	https://www.mcmaster.com/
	M5 x 25mm Screws	0.17	2	\$0.34	https://www.mcmaster.com/
	M5 x 20mm Spacers	0.2	2	\$0.40	https://www.mcmaster.com/
	M5 Washers	0.03	2	\$0.06	https://www.mcmaster.com/
	M5 Locknuts	0.06	2	\$0.12	http://www.mcmaster.com/#93625A200
	M5 Tee Nuts	0.28	12	\$3.36	http://www.peakstight.com/
	Z-Axis Motor Mount	40.99	1	\$40.99	https://farmbot-genesis.readme.io/docs/3d-prints#section-z-axis-motor-mount

	Vertical Motor Housing	48.41	1	\$48.41	https://farmbot-genesis.readme.io/docs/3d-prints#section-vertical-motor-cover
	Z-Axis Cable Carrier Guides	8.51	4	\$34.04	https://www.shapeways.com/
	5mm to 8mm Flex Coupling	4.95	1	\$4.95	https://www.adafruit.com/products/1176
	15mm 40mm x 1000mm Cable Carrier	25.45	2	\$50.90	https://www.inventables.com/technologies/drag-chain
	8 x 1000mm Leadscrew	31.5	1	\$31.50	http://openbuildspartstore.com/8mm-metric-acme-lead-screw/
Cables and Tubing	Liquid/Gas Tubes	0.79	9	\$7.11	https://www.mcmaster.com/#5233k56
	Barbs	5.60	3	\$16.80	https://www.mcmaster.com/#4406t14/=14ab6e0
	Barbed adapter	1.62	1	\$1.62	https://www.mcmaster.com/#5372k221/=14z0mfg
	Garden hose adapter	4.81	1	\$4.81	https://www.mcmaster.com/#70815t44/=14jz0ff
	O-rings	0.27	3	\$0.81	https://www.mcmaster.com/#1171n145/=14abs96
	Grommets	0.07	4	\$0.28	https://www.mcmaster.com/#9600k33/=14ac8cm
	Pressure Regulator	5.27	1	\$5.27	Home depot
	Solenoid valve	7.95	1	\$7.95	https://www.sparkfun.com/products/10456
Universal Tool Mount	M3 x 30mm Screws	0.17	12	\$2.04	http://www.mcmaster.com/#92855A335
	M3 x 10mm compressions springs	1.73	12	\$20.76	https://www.amazon.com/gp/product/B005S4HP6K?redirect=true&pldnSite=1
	M3 Locknuts	0.05	12	\$0.60	https://www.mcmaster.com/#93625a100/=1622y8k
	M5 x 12mm screws	0.15	2	\$0.30	https://www.mcmaster.com/#92095a210/=1622vcr
	M5 x 30mm screws	0.27	3	\$0.81	https://www.mcmaster.com/#92095a218/=1622xok
	M5 washers	0.03	3	\$0.09	https://www.mcmaster.com/#93475A240
	M5 tee nuts	0.28	2	\$0.56	http://www.peaksight.com/
	M5 locknuts	0.06	3	\$0.18	http://www.mcmaster.com/#93625A200
	Universal tool mount base	56.15	1	\$56.15	https://www.shapeways.com/
	Zipties	0.05	12	\$0.60	Home depot
	20 gauge, 12 wire cable, 3m length	19.20	1	\$19.20	https://www.mcmaster.com/#8082K14
	barb for 1/4" tube ID	5.60	3	\$16.80	https://www.mcmaster.com/#4406T14
	1.5mm wide, 9mm ID square-profile O-rings	0.27	3	\$0.81	https://www.mcmaster.com/#1171N145
	15 x 5 x 5mm ring magnets	1.69	3	\$5.07	https://www.apexmagnets.com/15-x-5-x-5mm-rings
Electronics Box	M2.5 x 4mm Screws	0.32	16	\$5.12	https://www.mcmaster.com/#92095a456/=1622ozu
	M2.5 x 6mm Standoffs	2.79	8	\$22.32	https://www.mcmaster.com/#93655a092/=1622qcp
	M3 x 4mm Screws	0.04	4	\$0.17	https://www.mcmaster.com/#92095a471/=1622toy
	M4 x 20mm Screws	0.13	6	\$0.78	https://www.mcmaster.com/#92095a196/=1622tcd
	M5 x 12mm Screws	0.15	2	\$0.30	https://www.mcmaster.com/#92095a210/=1622vcr
	M5 Tee Nuts	0.28	2	\$0.56	http://www.peaksight.com/
	Electronics Housing (with mounting plate)	32.34	1	\$32.34	https://www.mcmaster.com/#catalog/123/905/=1633w3m
	Raspberry Pi 3 Model B	39.95	1	\$39.95	https://www.adafruit.com/products/3055
	MicroSD card	12.89	1	\$12.89	https://www.amazon.com/SanDisk-Extreme-Adapter-SDSDQXN-016G-G46A-Version/dp/B00M55BX3G
	Arduino Mega 2560	11.83	1	\$11.83	http://www.sainsmart.com/arduino/control-boards/sainsmart-mega2560-r3-development-board-compatible-with-arduino-mega2560-r3.html
	RAMPS shield	12.82	1	\$12.82	http://www.sainsmart.com/sainsmart-3d-printer-control-board-ramps-1-4-for-arduino-reprap-mendel-prusa.html
	DRV8825 Stepper Drivers	5.95	4	\$23.80	https://www.pololu.com/product/1182
	Stepper Driver Heatsinks	1.50	1	\$1.50	https://ultimachine.com/products/heat-sink-6-3mm-x-4-8mm

	USB cable (Type A male to Type B male)	4.99	1	\$4.99	https://smile.amazon.com/Belkin-Components-Device-Daisy-Chain/dp/B000067RMY/ref=pd_sim_sbs_147_2?ie=UTF8&dpID=31G1ISlmR0L&dpSrc=sims&preST=_AC_UL320_SR320%2C320_&refRID=7P8Q2GQ8SQ8N2NM6EEH9
	5V power adapter (UBEC DC/DC Step-Down (Buck) Converter - 5V @ 3A output)	9.95	1	\$9.95	https://www.adafruit.com/products/1385
	Power jumper wire	0.31	2	\$0.62	https://www.mcmaster.com/#969712/
	3 connector lever nuts	0.30	2	\$0.60	https://www.amazon.com/Wago-222-413-LEVER-NUTS-Conductor-Connectors/dp/B01M12CRDH
	Vacumn Pump	25.99	1	\$25.99	https://smile.amazon.com/gp/product/B004GN3A2M/ref=oh_aui_search_detailpage?ie=UTF8&psc=1
Tool Bay	Power Supply	50.00	1	\$50.00	http://openbuildspartstore.com/12v-29a-power-supply/
	Sheet Metal Cutout	10.00	1	\$10.00	Home made
	Pipe Collar	41.30	1	\$41.30	https://www.shapeways.com/
	M5 x 40mm bolt	0.40	2	\$0.80	https://www.mcmaster.com/#standard-rounded-head-screws/=16339v/
	M5 Locknut	0.06	4	\$0.24	http://www.mcmaster.com/#93625A200
	M5 x 25mm bolt	0.25	2	\$0.50	https://www.mcmaster.com/#standard-rounded-head-screws/=1633b6r/
	Seeder Head	18.00	1	\$18.00	https://www.shapeways.com/
	Watering Nozzle	18.00	1	\$18.00	https://www.shapeways.com/
	Soil moisture sensor	4.95	1	\$4.95	sparkfun.com
	Weeding Head	18.00	1	\$18.00	https://www.shapeways.com/
	Seed Bin	22.00	2	\$44.00	https://www.shapeways.com/
Rotational Drivetrain	Nema 17 stepper motor + Planetary Hub				http://omc-stepperonline.kancart.com/item_detail/43-Gear-Ratio-27-1-Planetary-Gearbox-High-Torque-Nema-17-Stepper-17HS19-1684S-PG27
	Turntable	30.00	1	\$30.00	https://www.mcmaster.com/#6031k41/=15bw2kp
	Motor Housing Tube ((1/2ft) Multipurpose 6061 Aluminum Rectangular Tube 1/8" Wall Thickness, 2" x 2")	7.49	1	\$7.49	https://www.mcmaster.com/#6546k23/=1612i0s
	Double L - Brackets	1.25	4	\$5.00	http://openbuildspartstore.com/l-bracket/
	T - Joining Plate	4.65	4	\$18.60	http://openbuildspartstore.com/t-joining-plate/
	M5 x 6mm Screw Low Profile	0.11	8	\$0.90	http://openbuildspartstore.com/low-profile-screws-m5/
	5mm Tee Nuts	0.75	10	\$7.50	http://openbuildspartstore.com/drop-in-tee-nuts/
	Motor Plate	0.00	1	\$0.00	Machined
	Bottom Plate (motor shaft connection)	0.00	1	\$0.00	Machined
	M3 x 12mm Button Head Screw	0.08	4	\$0.32	http://openbuildspartstore.com/button-head-screws-m3-25-pack/
	M5 x 8mm Screw Low Profile	0.12	8	\$0.96	http://openbuildspartstore.com/low-profile-screws-m5/
	M5 x 10mm Button Head Screw	0.13	10	\$1.28	http://openbuildspartstore.com/low-profile-screws-m5/
	8-32 Thread Size, 5/8" Long 18-8 Stainless Steel Hex Head Screws	0.15	8	\$1.21	https://www.mcmaster.com/#92314a196/=166odhl
	18-8 Stainless Steel Narrow Hex Nut, 8-32 Thread Size, 1/4" Wide	0.04	8	\$0.30	https://www.mcmaster.com/#90730a009/=166oedz
	Rotary Encoder	34.49	1	\$34.49	http://www.usdigital.com/products/encoders/incremental/rotary/kit/E4T-200-197-D-H-M-B
Linear Drivetrain	NEMA 17 Stepper Motor, encoder and cables	70.00	2	\$140.00	https://www.alibaba.com/
Base/Base Connection	3/4"-10 Thread, 7-1/2" Long, Fully Threaded ASTM A193 Grade B7 Steel Threaded Stud	3.14	3	\$9.42	https://www.mcmaster.com/#98750a320/=166pxft
	Grade 5, 3/4"-10 Thread Size Medium-Strength Steel Hex Nut	0.44	6	\$2.64	https://www.mcmaster.com/#95505a608/=166pv8n
	50 lb bag of quickrete	4.00	1	\$4.00	Home Depot

	5 gallon bucket	2.97	1	\$2.97	http://www.homedepot.com/p/The-Home-Depot-5-gal-Homer-Bucket-05GLHD2/100087613
	304 Stainless Steel U-Bolt with Round Bracket 3/8"-16 Thread Size, 4-5/8" ID	14.71	2	\$29.42	https://www.mcmaster.com/#3042t64/=169970b
	4.5 OD Aluminum Pipe	52.28	1	\$52.28	https://www.mcmaster.com/#9056k32/=1669qtx
	Adapter Base Plate	40.61	1	\$40.61	house built
	Ubolt L plate	0.00	1	\$0.00	house built
	Corner Bracket	3.80	2	\$7.60	https://www.mcmaster.com/#1088a33/=1686kr9
	Size 8 x 7/8" bolts	0.07	8	\$0.59	https://www.mcmaster.com/#92210a198/=1687ibz
	size 8 nuts	0.03	8	\$0.25	https://www.mcmaster.com/#91841a009/=1686haz
	waterjet parts from BBS	120.00	1	\$120.00	
Adjustable bearing mounts	Xtra Wide- M5 x 6mm Eccentric Spacers *10mm socket size*				https://www.amazon.com/Eccentric-Spacer-Full-Size-Wheels/dp/B01D2FAV3K/ref=sr_1_fkmr0_1?s=industrial&ie=UTF8&qid=1485997601&sr=1-1-fkmr0&keywords=m5%2Beccentric%2Bspacers&th=1
		1.50	10	\$15.00	
	M5 x 25mm Flat Socket Screws	0.17	8	\$1.36	https://www.mcmaster.com/#91292a129/=161jdo9
	Xtreme Mini V Wheel Kit	5.95	8	\$47.60	http://openbuildspartstore.com/xtreme-mini-v-wheel-kit/
	Spring Loaded T-nut	1.20	8	\$9.60	http://openbuildspartstore.com/spring-loaded-tee-nuts/
	M5 x 12mm Screws	0.15	8	\$1.20	https://www.mcmaster.com/#92095a210/=1622vcr
	6061 Aluminum, 90 Degree Angle, 1/8" Thick, 3/4" x 3/4" Legs (1ft)	2.66	1	\$2.66	https://www.mcmaster.com/#8982k28/=1637ny9
Totals			565	\$1,940.66	

Appendix I. Hazard Identification Checklist

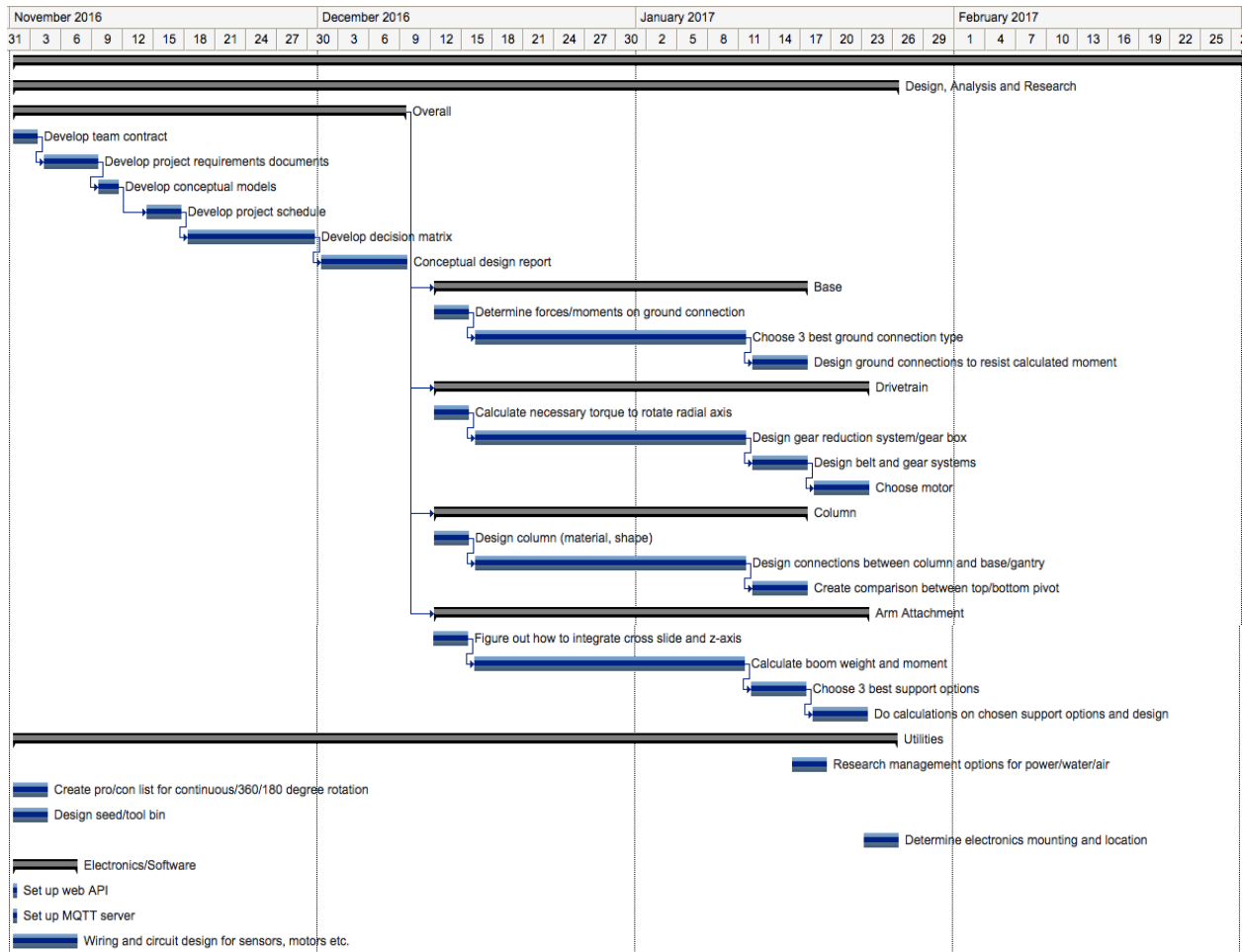
SENIOR PROJECT CONCEPTUAL DESIGN REVIEW HAZARD IDENTIFICATION CHECKLIST

Y	N	
☒	☐	Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☐	☒	Can any part of the design undergo high accelerations/decelerations?
☒	☐	Will the system have any large moving masses or large forces?
☐	☒	Will the system produce a projectile?
☒	☐	Would it be possible for the system to fall under gravity creating injury?
☒	☐	Will a user be exposed to overhanging weights as part of the design?
☐	☒	Will the system have any sharp edges?
☒	☐	Will all the electrical systems be properly grounded?
☒	☐	Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?
☐	☒	Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☒	Will there be any explosive or flammable liquids, gases, dust fuel part of the system?
☒	☐	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☒	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☒	Can the system generate high levels of noise?
☒	☐	Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc...?
☒	☐	Will the system be easier to use safely than unsafely?
☐	☒	Will there be any other potential hazards not listed above? If yes, please explain below?

DVP&R														
Report Date: 2/14/17			Sponsor: Rory Aronson									REPORTING ENGINEER: Lucas Salem		
TEST PLAN										TEST REPORT				
Item No	Specification or Clause Reference	Requirement	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
		Quantity					Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail		
1	Minimum Radius	1.2m	Measure radius	Radius > 1.2m	Jack	Complete	1	Measurement	4/18/2017	4/18/2017	Pass	1	0	Measured from center of R-axis to center of tool
2	Minimum Height Clearance Above Soil	1m	Measure height clearance	Height above ground > 1m	Jack	Complete	1	Measurement	4/18/2017	4/18/2017	Fail	0	1	Lead Screw not long enough
3	Farmable Area	4.5m^2	Run device to max and minimum positions. Use these measurements to calculate farmable area	Area of plot > 4.5 m^2	Jack	Complete	1	Measurement	4/18/2017	4/18/2017	Pass	1	0	Calculated from radius measurements
5	Velocity	0.5 m/s	Calculate velocity at outermost position on the radial arm, and x and z axes by measuring time to move over a set path	Tool holder achieves .5 m/s +/- .2 m/s	Lucas	Complete	2	Measurement / Calculation	6/6/2017	6/6/2017	Pass	2	0	Based off of video from tests
7	Rotational Range	360 degrees	Complete one full rotation of device, 180 clockwise and 180 counterclockwise	Achieves 360 degrees total	Lucas	Complete	40	Quantity	5/16/2017	5/16/2017	Pass	29	11	Some sticky spots after running it through many cycles at the exposition
8	Torque Rating from motor	3 N.m	Analyze torque output from the motor to the column based on motor curve and moment of inertia	Achieves 3 N.m +/- 1 N.m	Ning	Complete	1	Calculation	2/15/2017	2/15/2017	Pass	1	0	Calculated from motor data, friction was estimated and S. F. of 2.5 was used
15	Number of Pinch Points	<10	Analyze number of pinch points	Number of pinch points <10	Ning	Complete	1	Quantity	6/1/2017	6/1/2017	Pass	1	0	There are 4 main points, rollers on z and x axes, and bearings on inside lip of pipe
18	Assembly Time	15 hrs	Measure time for ourselves to assemble, in addition to one other individual unfamiliar with the system	Measured time is 15 hrs +/- 5 hours	Sam	Incomplete	0	Timing	4/6/2017	6/2/2017	n/a	n/a	n/a	Our time is ambiguous because we did not tear down and rebuild fully, but believed to be possible in under 15 hours
19	Number of Parts	799	Analyze BOM	Number of parts is < 799	Sam	Complete	1	Quantity	6/1/2017	6/1/2017	Pass	1	0	Total Part Count was 654
20	Shipping Weight	150 lbs (UPS requirement)	Weigh all parts to be shipped	Weight of parts <150 lbs	Sam	Complete	1	Measurement	6/1/2017	6/1/2017	Pass	1	0	Concrete sold seperatley
21	Shipping Size (L + Girth) Girth=2x(H+W)	165 in (UPS requirement)	Pack all parts to be shipped	Shipping size <165 in	Kassie	Incomplete	0	Measurement	n/a	n/a	n/a	n/a	n/a	We have not packaged all the parts, there box size is unknown
	Overall resolution	2.5 mm +/- 2.5 mm	Send tool head to pre-determined position and measure actual vs. measured position	Difference between measured and actual is less than 2.5mm +/- 2.5mm	Kassie	Incomplete	0	Measurement /Quantity	n/a	n/a	n/a	n/a	n/a	Our demonstration for the senior exposition had error coded into the script such that it was repeatable, but we did not calculate a raw point to point resoution.
23	Overall resolution: bearings in pipe	<.3mm	FEA Analysis of bearing bracket	Deflection < 2.5mm	Rory	Complete	1	Calculation	2/15/2017	3/1/2017	Pass	1	0	Calculated using expected max loading
24	Overall resolution: arm/bracket deflection	<1mm	FEA Analysis of Arm/bracket	Deflection < 2.5mm	Rory	Complete	1	Calculation	3/2/2017	3/16/2017	Pass	1	0	Calculated using expected max loading
25	Maintanance Frequency	once a month	Continually run the device on an accelerated schedule that simulates a months worth of usage (50 hours). After test period check against maintenance instructions	Device runs continuously for one month without any necessary maintenance	Rory	Incomplete	0	Inspection	5/23/2017	6/2/2017	n/a	n/a	n/a	Run for 4 hours straight during the senior exposition and testing up to that point.
26	Cost to Prototype	\$2,250	BOM analysis	Cost < \$2,250	Rory	Complete	1	Quantity	4/6/2017	6/2/2017	Pass	1	0	Total part cost is \$1875.05

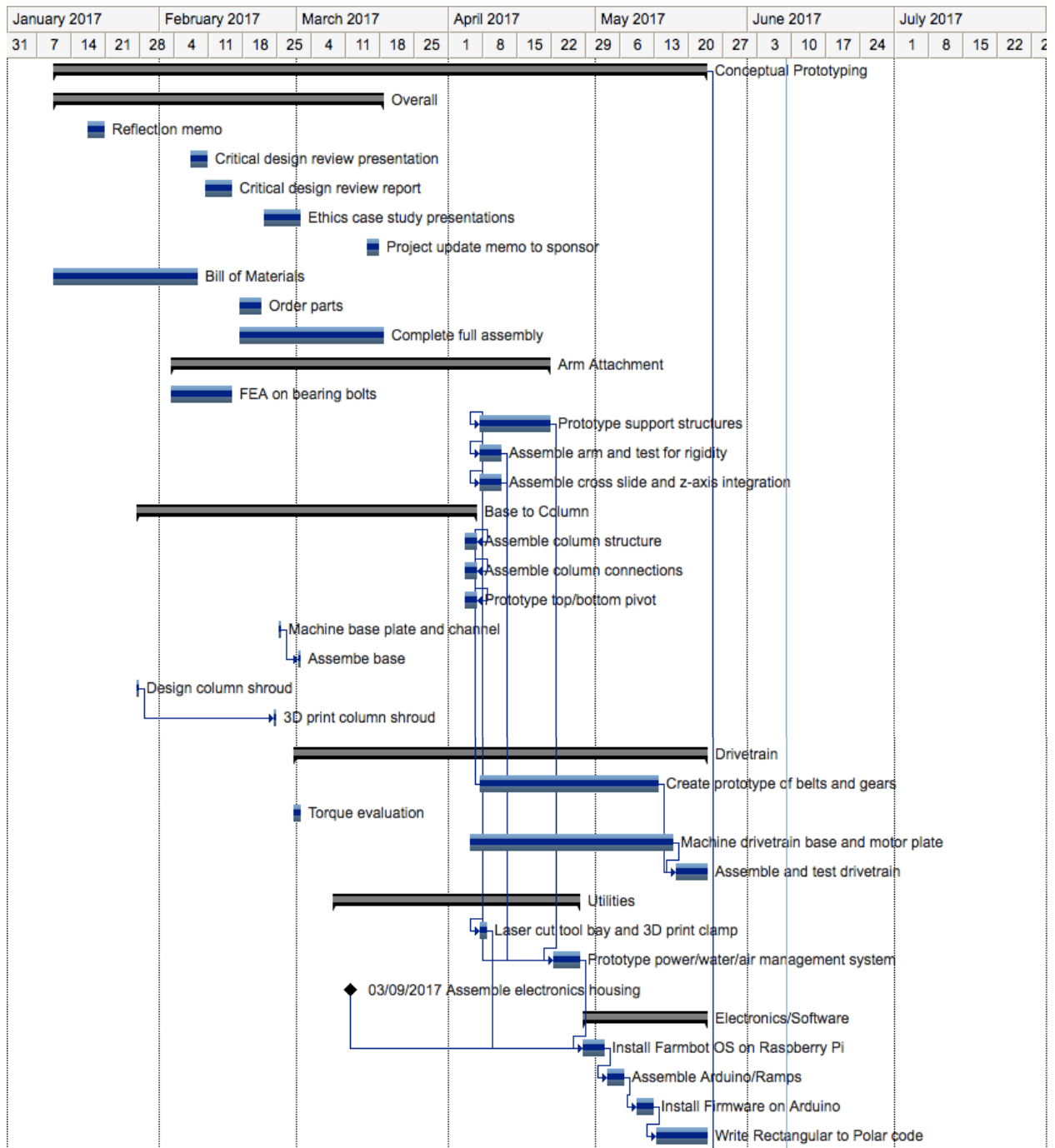
Appendix K: Fall Quarter Gantt Chart

		Name	Duration	Start	Finish	Predecessors
1	✓	☐ Polar FarmBot	140.5d?	11/01/2016	06/09/2017	
2	✓	☐ Design, Analysis and Research	44.5d?	11/01/2016	01/26/2017	
3	✓	☐ Overall	25.5d?	11/01/2016	12/09/2016	
4	✓	Develop team contract	3d?	11/01/2016	11/03/2016	
5	✓	Develop project requirements documents	4d?	11/04/2016	11/09/2016	4
6	✓	Develop conceptual models	3d?	11/09/2016	11/11/2016	5
7	✓	Develop project schedule	4d?	11/14/2016	11/17/2016	6
8	✓	Develop decision matrix	4d?	11/18/2016	11/30/2016	7
9	✓	Conceptual design report	7d?	12/01/2016	12/09/2016	8
10	✓	☐ Base	12d?	12/12/2016	01/17/2017	3
11	✓	Determine forces/moments on ground connection	4d?	12/12/2016	12/15/2016	
12	✓	Choose 3 best ground connection type	4d?	12/16/2016	01/11/2017	11
13	✓	Design ground connections to resist calculated moment	4d?	01/12/2017	01/17/2017	12
14	✓	☐ Drivetrain	16d?	12/12/2016	01/23/2017	3
15	✓	Calculate necessary torque to rotate radial axis	4d?	12/12/2016	12/15/2016	
16	✓	Design gear reduction system/gear box	4d?	12/16/2016	01/11/2017	15
17	✓	Design belt and gear systems	4d?	01/12/2017	01/17/2017	16
18	✓	Choose motor	4d?	01/18/2017	01/23/2017	17
19	✓	☐ Column	12d?	12/12/2016	01/17/2017	3
20	✓	Design column (material, shape)	4d?	12/12/2016	12/15/2016	
21	✓	Design connections between column and base/gantry	4d?	12/16/2016	01/11/2017	20
22	✓	Create comparison between top/bottom pivot	4d?	01/12/2017	01/17/2017	21
23	✓	☐ Arm Attachment	16d?	12/12/2016	01/23/2017	3
24	✓	Figure out how to integrate cross slide and z-axis	4d?	12/12/2016	12/15/2016	
25	✓	Calculate boom weight and moment	4d?	12/16/2016	01/11/2017	24
26	✓	Choose 3 best support options	4d?	01/12/2017	01/17/2017	25
27	✓	Do calculations on chosen support options and design	4d?	01/18/2017	01/23/2017	26
28	✓	☐ Utilities	44.5d?	11/01/2016	01/26/2017	
29	 ✓	Research management options for power/water/air	4d?	01/16/2017	01/19/2017	
30	✓	Create pro/con list for continuous/360/180 degree rotation	4d?	11/01/2016	11/04/2016	
31	✓	Design seed/tool bin	4d?	11/01/2016	11/04/2016	
32	 ✓	Determine electronics mounting and location	4d?	01/23/2017	01/26/2017	
33	✓	☐ Electronics/Software	5d?	11/01/2016	11/07/2016	
34	✓	Set up web API	1d?	11/01/2016	11/01/2016	
35	✓	Set up MQTT server	1d?	11/01/2016	11/01/2016	
36	✓	Wiring and circuit design for sensors, motors etc.	5d?	11/01/2016	11/07/2016	



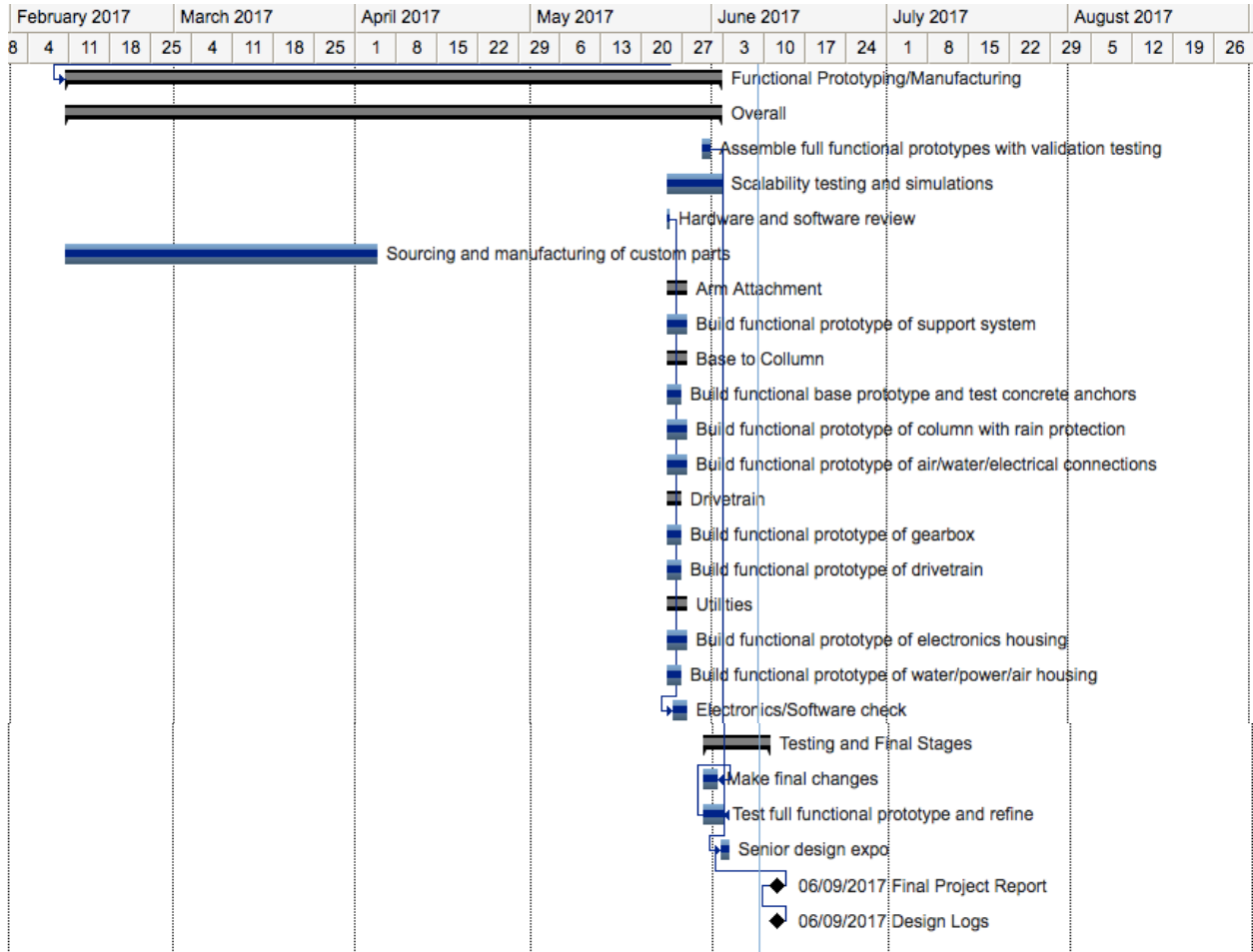
Appendix L: Winter Quarter Gantt Chart

		Name	Duration	Start	Finish	Predecessors
38		☐ Overall	50d?	01/09/2017	03/17/2017	
39		Reflection memo	4d?	01/16/2017	01/19/2017	
40		Critical design review presentation	4d?	02/06/2017	02/09/2017	
41		Critical design review report	4d?	02/09/2017	02/14/2017	
42		Ethics case study presentations	6d?	02/21/2017	02/28/2017	
43		Project update memo to sponsor	3d?	03/14/2017	03/16/2017	
44		Bill of Materials	22d?	01/09/2017	02/07/2017	
45		Order parts	3d?	02/16/2017	02/20/2017	
46		Complete full assembly	22d?	02/16/2017	03/17/2017	
47		☐ Arm Attachment	56d?	02/02/2017	04/20/2017	
48		FEA on bearing bolts	9d?	02/02/2017	02/14/2017	
49		Prototype support structures	11d?	04/06/2017	04/20/2017	53,54,55
50		Assemble arm and test for rigidity	3d?	04/06/2017	04/10/2017	53,54,55
51		Assemble cross slide and z-axis integration	3d?	04/06/2017	04/10/2017	53,54,55
52		☐ Base to Column	50d?	01/26/2017	04/05/2017	
53		Assemble column structure	3d?	04/03/2017	04/05/2017	61SF
54		Assemble column connections	3d?	04/03/2017	04/05/2017	61SF
55		Prototype top/bottom pivot	3d?	04/03/2017	04/05/2017	61SF
56		Machine base plate and channel	1d?	02/24/2017	02/24/2017	
57		Assemble base	1d?	02/28/2017	02/28/2017	56
58		Design column shroud	1d?	01/26/2017	01/26/2017	
59		3D print column shroud	1d?	02/23/2017	02/23/2017	58
60		☐ Drivetrain	61d?	02/27/2017	05/22/2017	
61		Create prototype of belts and gears	27d?	04/06/2017	05/12/2017	
62		Torque evaluation	2d?	02/27/2017	02/28/2017	
63		Machine drivetrain base and motor plate	30d?	04/04/2017	05/15/2017	
64		Assemble and test drivetrain	5d?	05/16/2017	05/22/2017	61,63
65		☐ Utilities	37d?	03/07/2017	04/26/2017	
66		Laser cut tool bay and 3D print clamp	2d?	04/06/2017	04/07/2017	53,54,55
67		Prototype power/water/air management system	4d?	04/21/2017	04/26/2017	49,50,51,53,54,55
68		Assemble electronics housing	3d?	03/07/2017	03/09/2017	
69		☐ Electronics/Software	18d?	04/27/2017	05/22/2017	
70		Install Farmbot OS on Raspberry Pi	24h?	04/27/2017	05/01/2017	66,67,68
71		Assemble Arduino/Ramps	32h?	05/02/2017	05/05/2017	70
72		Install Firmware on Arduino	32h?	05/08/2017	05/11/2017	71
73		Write Rectangular to Polar code	7d?	05/12/2017	05/22/2017	72



Appendix M: Spring Quarter Gantt Chart

		Name	Duration	Start	Finish	Predecessors
74		 Functional Prototyping/Manufacturing	81d?	02/09/2017	06/01/2017	37
75		 Overall	81d?	02/09/2017	06/01/2017	
76	 	Assemble full functional prototypes with validation testing	2d?	05/29/2017	05/30/2017	
77	 	Scalability testing and simulations	8d?	05/23/2017	06/01/2017	
78	 	Hardware and software review	1d?	05/23/2017	05/23/2017	69SF
79	 	Sourcing and manufacturing of custom parts	38d?	02/09/2017	04/03/2017	
80		 Arm Attachment	4d?	05/23/2017	05/26/2017	
81	 	Build functional prototype of support system	4d?	05/23/2017	05/26/2017	49,50,51
82		 Base to Column	4d?	05/23/2017	05/26/2017	
83	 	Build functional base prototype and test concrete anchors	3d?	05/23/2017	05/25/2017	
84		Build functional prototype of column with rain protection	4d?	05/23/2017	05/26/2017	53,54,55
85	 	Build functional prototype of air/water/electrical connections	4d?	05/23/2017	05/26/2017	53,54,55
86		 Drivetrain	3d?	05/23/2017	05/25/2017	
87	 	Build functional prototype of gearbox	3d?	05/23/2017	05/25/2017	61
88	 	Build functional prototype of drivetrain	3d?	05/23/2017	05/25/2017	61
89		 Utilities	4d?	05/23/2017	05/26/2017	
90	 	Build functional prototype of electronics housing	4d?	05/23/2017	05/26/2017	68
91	 	Build functional prototype of water/power/air housing	3d?	05/23/2017	05/25/2017	67
92	 	Electronics/Software check	3d?	05/24/2017	05/26/2017	73,78
93		 Testing and Final Stages	10d?	05/29/2017	06/09/2017	
94	 	Make final changes	3d?	05/29/2017	05/31/2017	95SF
95	 	Test full functional prototype and refine	4d?	05/29/2017	06/01/2017	76FF
96	 	Senior design expo	2d?	06/01/2017	06/02/2017	94
97	 	Final Project Report	1d?	06/09/2017	06/09/2017	96SF
98	 	Design Logs	1d?	06/09/2017	06/09/2017	97SF



Appendix N. Product Literature

Quick Reference

NEMA size 17 1.8°
2-phase stepper motor



IMS
INTELLIGENT MOTION
SYSTEMS, INC.



Notes and Warnings

- Installation, configuration and maintenance must be carried out by qualified technicians only. You must have detailed information to be able to carry out this work.
- Unexpected dangers may be encountered when working with this product!
  - Incorrect use may destroy this product and connected components!
- For more information, go to www.imshome.com

Specifications

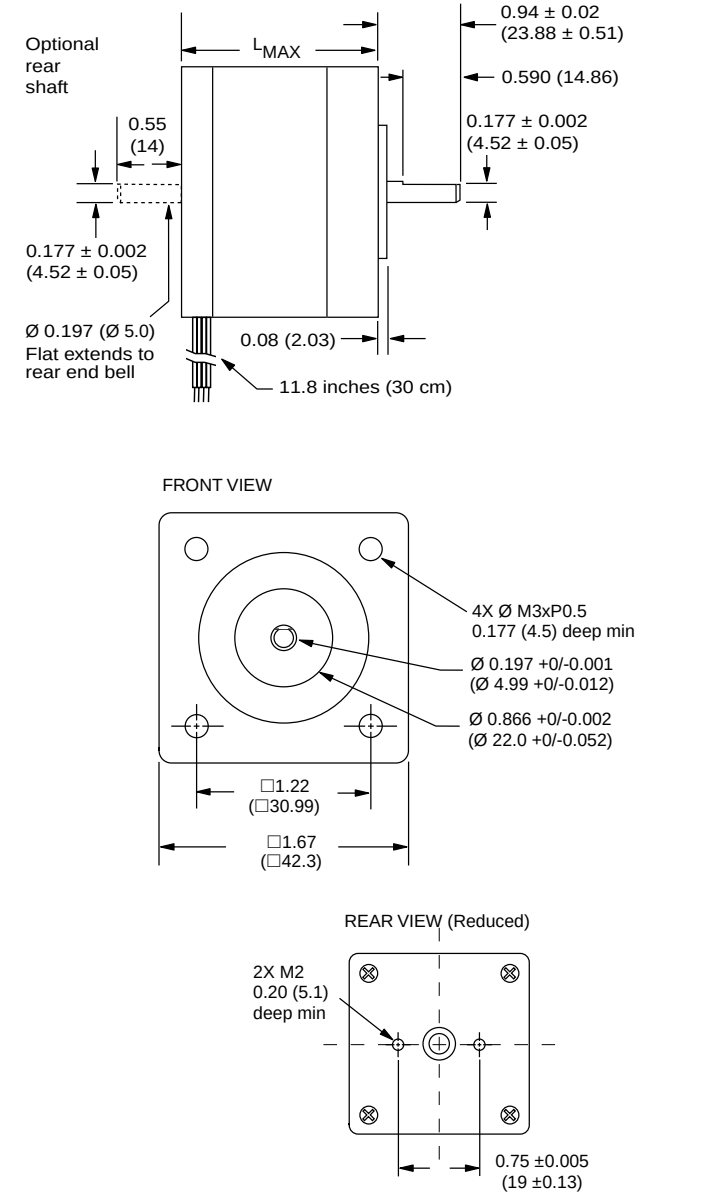
1.5 Amp motors		Single length	Double length	Triple length
Part number		M-1713-1.5 • (1)	M-1715-1.5 • (1)	M-1719-1.5 • (1)
Holding torque	oz-in	32	60	75
	N-cm	23	42	53
Detent torque	oz-in	1.7	2.1	3.5
	N-cm	1.2	1.5	2.5
Rotor inertia	oz-in-sec ²	0.000538	0.0008037	0.0011562
	kg-cm ²	0.038	0.057	0.082
Weight	oz	7.4	8.1	12.7
	grams	210	230	360
Phase current	amps	1.5	1.5	1.5
Phase resistance	ohms	1.3	2.1	2.0
Phase inductance	mH	2.1	5.0	3.85

(1) Indicate S for single-shaft or D for double-shaft. Example M-1713-1.5S

Wiring and Connections

Signals and wire colors	
Phase A	Red
Phase /A	Blue
Phase B	Green
Phase /B	Black

Mechanical Specifications
Dimensions in inches (mm)



Motor stack length inches (mm)	Single	Double	Triple
L _{MAX}	1.34 (34.0)	1.57 (40)	1.89 (48)

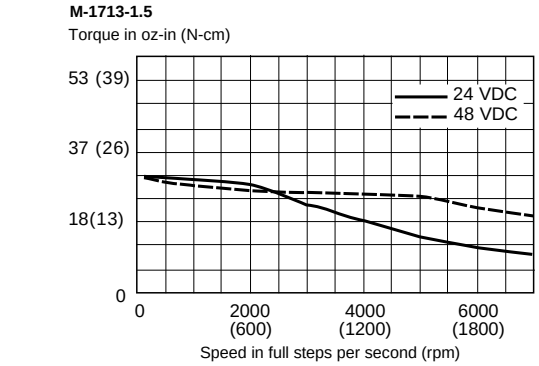
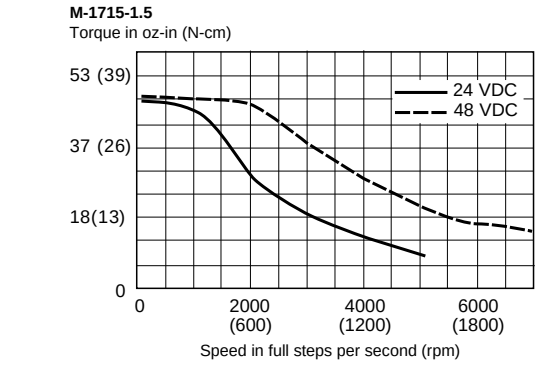
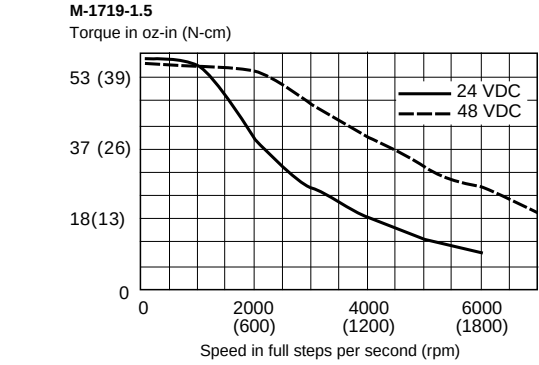
Part Numbers

Example:	M - 1 7 1 3 - 1.5 S
Stepper motor frame size	M - 1 7 1 3 - 1.5 S
M-17 = NEMA 17 (1.7"/42 mm)	
Motor length	M - 1 7 1 3 - 1.5 S
13- = single stack	
15- = double stack	
19- = triple stack	
Phase current	M - 1 7 1 3 - 1.5 S
1.5 = 1.5 Amps	
Shaft	M - 1 7 1 3 - 1.5 S
S = single, front shaft only	
D = double, front and rear shafts	
Optional optical encoder (1)	M - 1 7 1 3 - 1.5 E S 1 0 0
ES = Single-end	
ED = Differential	
Line count	
100, 200, 250, 400, 500 or 1000 (2)	

(1) An encoder replaces the shaft designator in the part number.
(2) All encoders have an index mark, except the 1000 line count version.

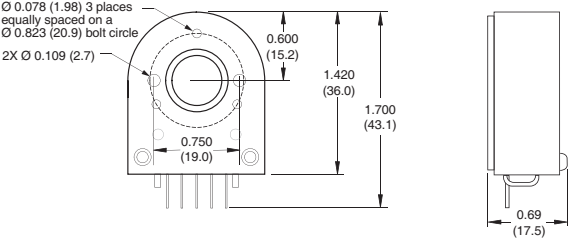
Torque-speed performance

Measured at 1.5 Amps RMS



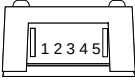
Optical Encoder Option

Dimensions in inches (mm)



Connectivity

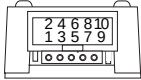
single-end encoder



wire	function
1 Brown	Ground
2 Violet	Index
3 Blue	Channel A
4 Orange	+5 VDC input
5 Yellow	Channel B

optional interface cable
available: ES-CABLE-2

differential encoder

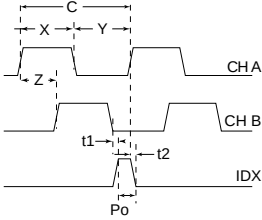


pin	function	pin	function
1	no connect	6	Channel A+
2	+5 VDC input	7	Channel B -
3	Ground	8	Channel B+
4	no connect	9	Index -
5	Channel A -	10	Index +

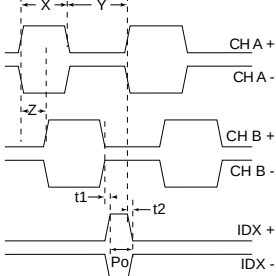
interface cable included

Timing

single-end encoder

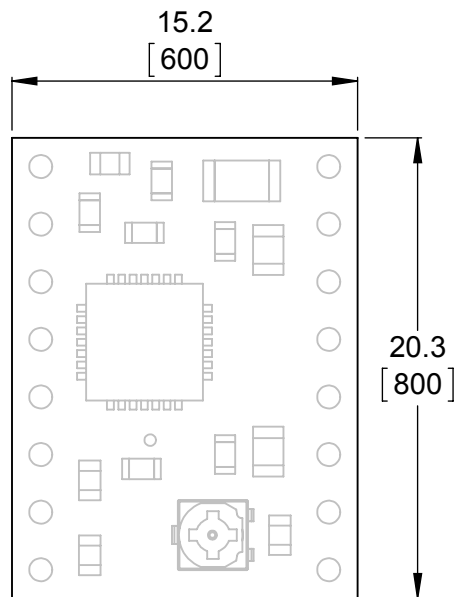


differential encoder

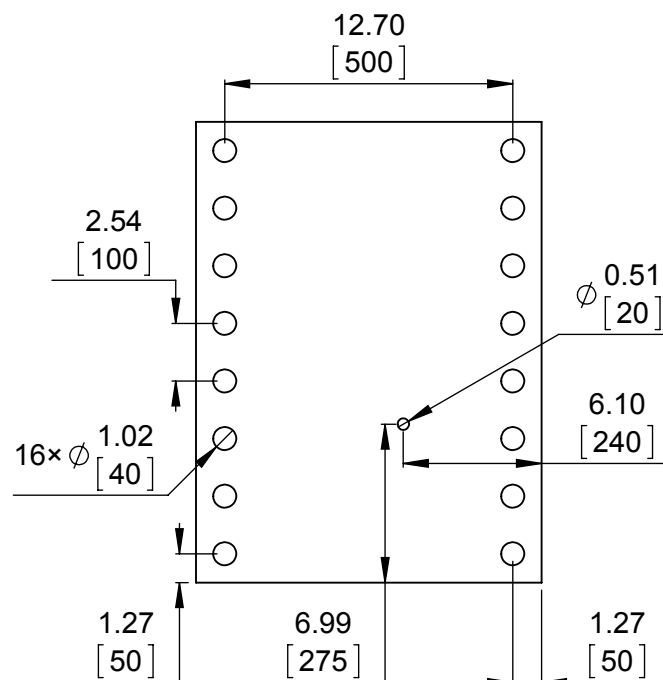


Parameter	Symbol	Min	Typ	Max	Units
Cycle error			3	5.5	°e
Symmetry		130	180	230	°e
Quadrature		40	90	140	°e
Index pulse width	Po	60	90	120	°e
Index rise (after Ch A or B rise)	t1	-300	100	250	ns
Index fall (after Ch A or B fall)	t2	70	150	1000	ns

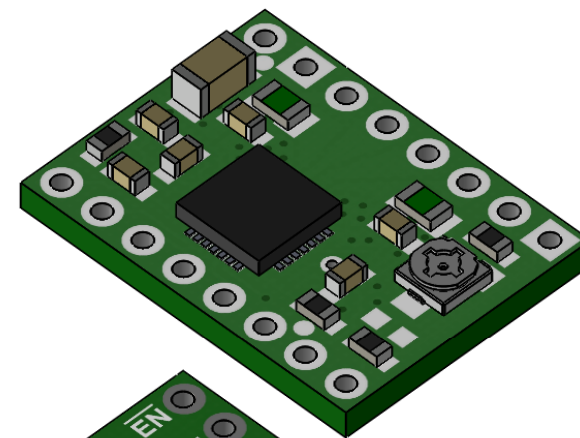
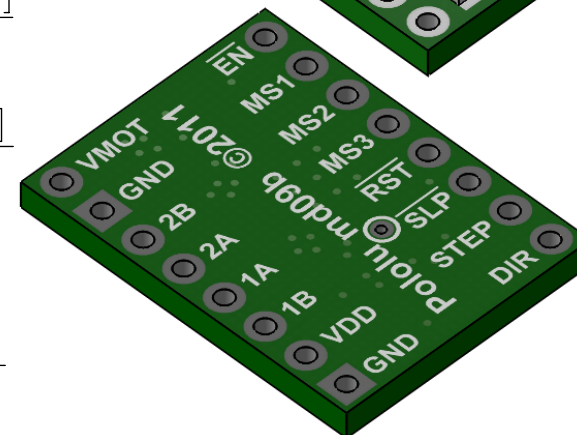
C One cycle: 360 electrical degrees (°e).
X/Y Symmetry: the measure of the relationship between X and Y, nominally 180°e.
Z Quadrature: the phase lead or lag between channels A and B, nominally 90°e.
Po Index pulse width, nominally 90 °e.
NOTE: Rotation is as viewed from the cover side of the encoder.



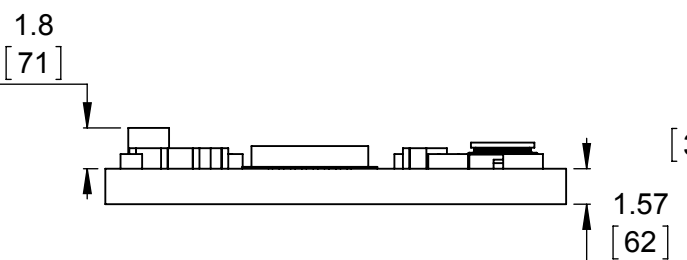
① Board dimensions (top view)
Scale 3:1



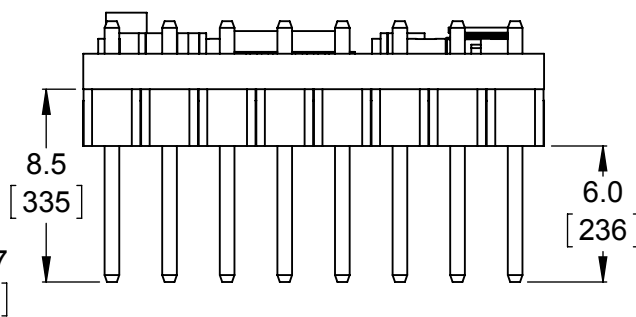
② Connector callouts (bottom view)
Scale 3:1



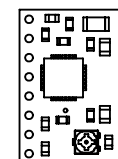
③ Isometric view
Scale 3:1



④ Profile
Scale 3:1



⑤ Profile with headers
Scale 3:1



⑥ Actual size
Scale 1:1

1. To get the specified scale, select 100% in print settings.
2. Drill location tolerance: ± 0.1 [± 5].
3. Board edge tolerance: ± 0.3 [± 10].

<https://www.pololu.com/category/156>

Name: A4988 Stepper Motor
Driver Carrier

Item numbers:
1182, 2975, 2980, 2985

Drawing date:
15 December 2015

Units: mm
[mil]

PCB dev code:
md09b

Pololu
Robotics & Electronics
© 2015 Pololu Corporation

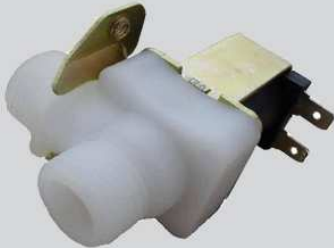
Aqua Tech Trading Corp. Ltd, located in Chongqing, China, which is focused on developing, manufacturing and distributing water valves and associated water used equipments.

We are a rapidly expanding company perceived as a growing force in the area of fluid control, we attribute our success to extensive product knowledge, our understanding of and responsiveness to market requirements and the value we place on excellent customer service.

Aqua Valves have been widely used in agriculture, water supply, water control and water purification industries.

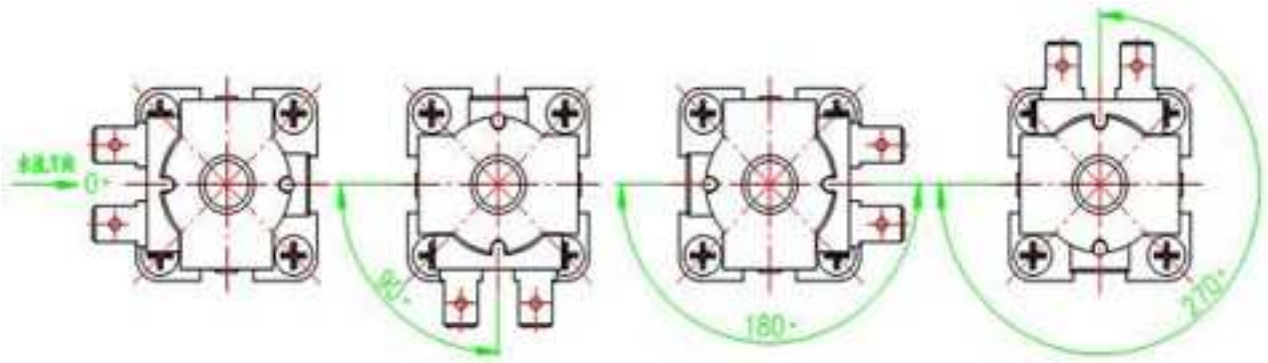
The following products are our solenoid valves.

			
Model No.	AQT15S	Model No.	AQT15SC
Thread Size	1/2" BSP inlet and outlet	Thread Size	1/2" BSP inlet and outlet
Material	PET	Material	PET
Working Temp	0-40℃	Working Temp	0-40℃
Working Pressure	0.02~0.8MPa	Working Pressure	0.02~0.8MPa
Voltage	DC12V,DC24V,AC220V	Voltage	AC/DC 6/9/12/24/36110/220V
Voltage Range	15%	Voltage Range	15%
Style	Closed Valve	Style	Closed Valve
Working Environment	Water, Gas and Oil	Working Environment	Water, Gas and Oil
Lifespan	More than 200,000 times	Lifespan	More than 200,000 times
Certification	CQC/CE	Certification	CQC/CE
Usage: Suit for many kinds of washing machine, drinking water machine, sanitary equipment, water heater, etc. Our products have passed CQC and CE. And it meets the requirement of WEEE and ROHS.			

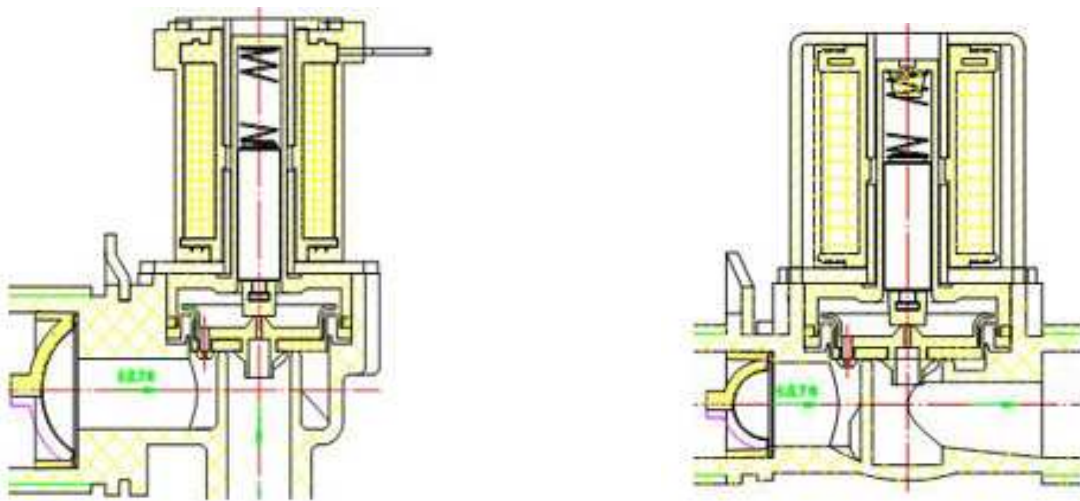
			
Model No.	AQT10S	Model No.	AQT15SL
Thread Size	1/2"10mm BSP inlet and outlet	Thread Size	1/2" BSP inlet and outlet
Material	Plastic and Brass	Material	Plastic and Brass
Working Temp	0~60/100℃	Working Temp	0~100℃
Working Pressure	0.02~0.8MPa, static pressure ≥ 2.0MPa	Working Pressure	400 millimeter water column
Voltage	DC12V,DC24V,AC220V	Voltage	AC/DC 6/9/12/24/36110/220V
Voltage Range	15%	Voltage Range	15%
Style	Closed Valve	Style	Opened Valve
Working Environment	Water, Gas and Oil	Working Environment	Water, Gas and Oil
Lifespan	More than 200,000 times	Lifespan	More than 200,000 times
Certification	CQC/CE	Certification	CQC/CE
Usage: washing machine used solenoid valve		Usage: Specially working in low pressure environment	

			
Model No.	AQT12SL	Model No.	AQT12SLT
Thread Size	1/2"BSP inlet and 12mm outlet	Thread Size	1/2"BSP inlet and 12mm outlet
Material	Plastic and Brass	Material	Plastic and Brass
Working Temp	0~100℃	Working Temp	0~100℃
Working Pressure	400 millimeter water column	Working Pressure	400 millimeter water column
Voltage	DC12V,DC24V,AC220V	Voltage	AC/DC 6/9/12/24/36110/220V
Voltage Range	15%	Voltage Range	15%
Style	Opened Valve	Style	Opened Valve
Working Environment	Water, Gas and Oil	Working Environment	Water, Gas and Oil
Lifespan	More than 200,000 times	Lifespan	More than 200,000 times
Certification	CQC/CE	Certification	CQC/CE

Usage: Specially working in low pressure environment		Usage: Specially working in low pressure environment	
			
Model No.	AQT15SCB	Model No.	AQT15SP
Thread Size	1/2"BSP inlet and let	Thread Size	1/2"BSP inlet and 12mm outlet
Material	Brass	Material	Plastic
Working Temp	0~100℃	Working Temp	1℃-75℃
Working Pressure	0.02~0.8MPa	Flow rate	0.02Mpa≥3 L/min, 0.1Mpa≥12 L/min, 0.8Mpa≥35 L/min
Voltage	DC12V,DC24V,AC220V	Voltage	AC220V
Voltage Range	15%	Voltage Range	15%
Style	Closed Valve	Resistance Coil	4.75K Ω ±0.25K Ω (20℃)
Working Environment	Water, Gas and Oil	Working Environment	Water
Lifespan	More than 200,000 times	Lifespan	More than 1,000,000times
Certification	CQC/CE	Certification	0
Usage: Specially working in low pressure environment		Usage: Water used solenoid valve	



And the diagram picture of these valves as follows:



Nylon Cable Drag Chain

Specifications:

Material: Nylon PA66

Inside Measurement: 15 * 30mm

Outside Measurement: 20 * 38.2mm

Bending Radius: 28mm

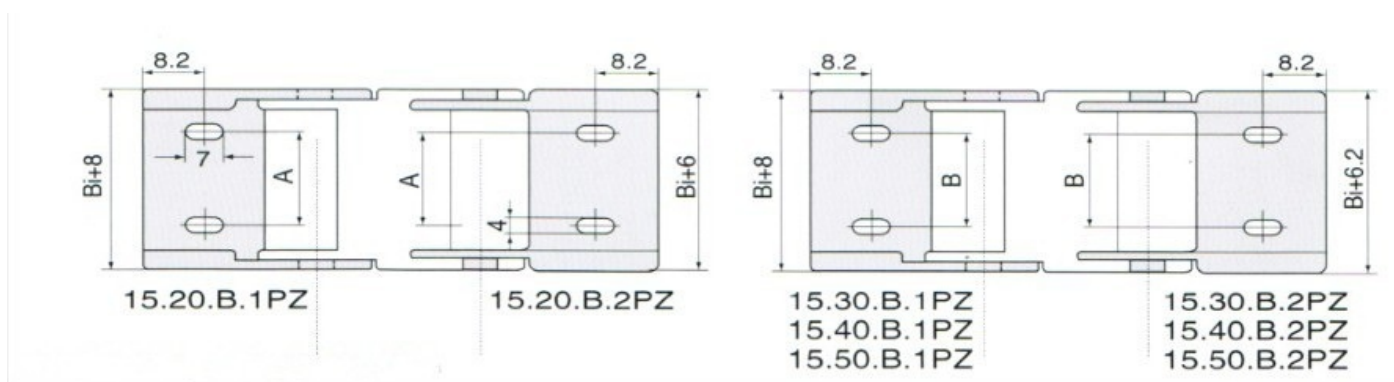
Pitch: 20mm

Number of Chain: 50

Length: 1000mm(40")



Mounting Drawing for Bridge Style 15mm Series



Mounting Chart for Bridge Style 15mm Series

IH	IW	OH	OW	Bending Radius	Style	Connecting Pitch
15	20	20	28.2	18 28 38		A=11
15	30	30	38.2			A=14
15	40	20	48.2			B=20
15	50	20	58.2			B=20

IH= Inner Height IW= Inner Width OH=Outer Height OW= Outer Width

Unit= mm

INVENTABLES®

Description

The E4T miniature transmissive optical encoder is designed to provide digital quadrature encoder feedback for high volume, limited space applications. The E4T is designed to be a drop in replacement for the E4P that offers higher maximum speed and increased output drive. The E4T utilizes an innovative, push-on encoder disk which accepts shaft diameters of 2.0mm to .250".

The E4T miniature encoder base provides mounting holes for two #3-48, length 3/16" or two M2.5, length 4mm screws on a .586" bolt circle. The encoder cover is easily snapped onto the base and is marked with the connector pin-out.

The E4T series encoder is connected using a 4-conductor, high retention, polarized, 1.25mm pitch connector. Mating cables and connectors (see the Cables / Connectors web page) are not included, and are available separately.

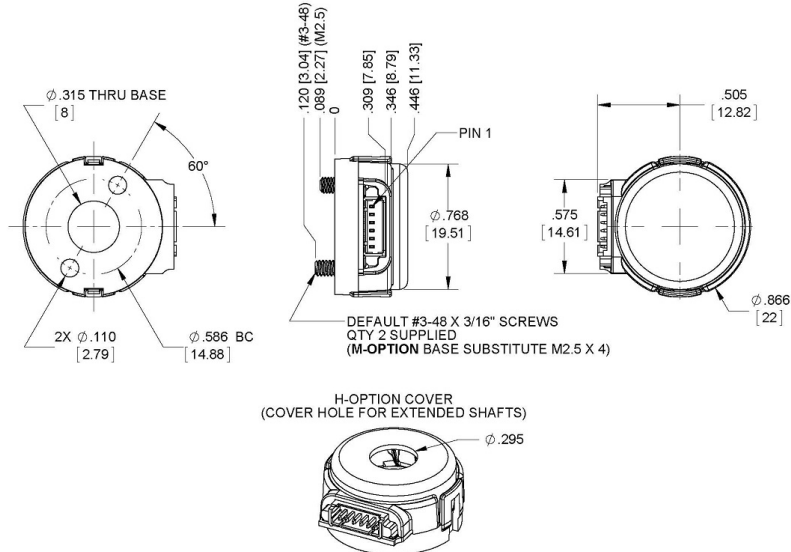


Features

- E4T Optical Kit Encoder
- Push-on hub - spring loaded collet design
- Minimum shaft length of .275"
- Fits shaft diameters of .079" to .250"
- 100 to 500 cycles per revolution (CPR)
- 400 to 2,000 pulses per revolution (PPR)
- Single +5V supply

E4T Differential

E4T Differential OEM Miniature Optical Kit Encoder



RELEASE DATE: 02/17/2014



1400 NE 136th Avenue
Vancouver, Washington 98684, USA

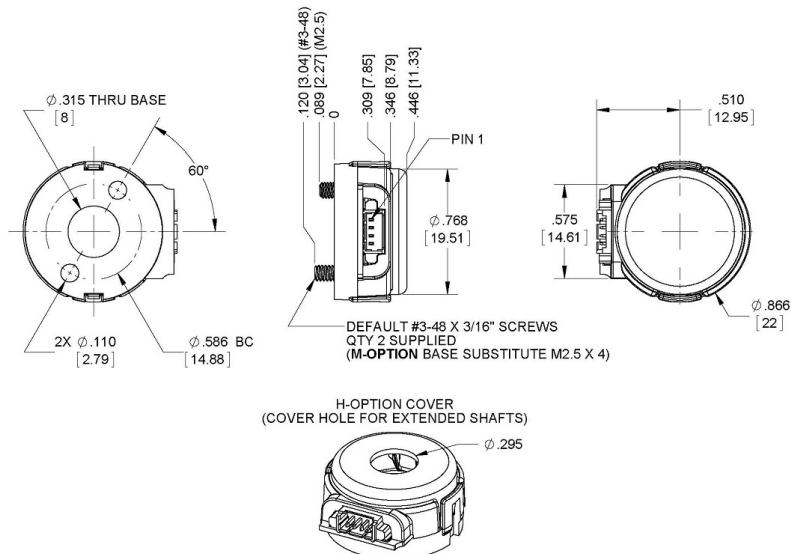
info@usdigital.com
www.usdigital.com

Local: 360.260.2468
Toll-free: 800.736.0194

UNITS: INCHES (MM)
METRIC SHOWN FOR REFERENCE ONLY

E4T Single Ended

E4T Single-Ended OEM Miniature Optical Kit Encoder



RELEASE DATE: 02/17/2014



1400 NE 136th Avenue
Vancouver, Washington 98684, USA

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www.usdigital.com

Local: 360.260.2468
Toll-free: 800.736.0194

UNITS: INCHES (MM)
METRIC SHOWN FOR REFERENCE ONLY

Environmental

Parameter	Value	Units
Operating Temperature	-20 to 100	C
Electrostatic Discharge, IEC 61000-4-2		
Single-ended (-S version)	± 12	kV
Differential (-D version)	± 7	
Shock, 6 millisecond, half-sine	75	G
Vibration (20Hz to 2kHz, sinusoidal)	20	G

Mechanical

Parameter	Value	Units
Max. Shaft Axial Play	± .010	in.
Max. Shaft Runout (TIR)	.002	in.
Max. Acceleration	250,000	rad/sec ²
Maximum RPM (1) e.x. CPR = 300, max. rpm = 20,000 e.x. CPR = 200, max. rpm = 30,000	minimum value of (6,000,000/CPR) and (60,000)	rpm
Max. Codewheel Moment of Inertia	5.1 x 10 ⁻⁷	oz-in-s ²
Mounting Screw Size Default (D-option base) Metric (M-option base)	#3-48 x 3/16" M2.5, length 4mm	
Screw Bolt Circle Diameter	.586 ±.005	in.
Minimum Shaft Length (2)	.275	in.
Maximum Shaft Length (2)	.395 (D option) / no limit (H option)	in.
Mounting Screw Torque	2-3	in-lbs

Technical Bulletin TB1001 - Shaft and Bore Tolerances

[Download](#)

(1) 60,000 rpm is the maximum rpm due to mechanical considerations. The maximum rpm due to the module's 100kHz maximum output frequency is (6,000,000/CPR).

(2) Including axial play.

Single-ended Electrical

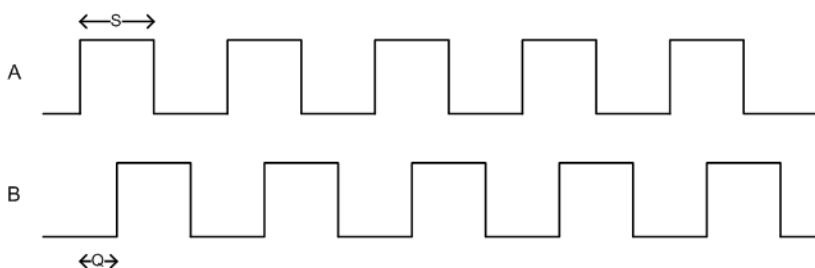
Specifications	Min.	Typ.	Max.	Units	Notes

Supply Voltage	4.5	5.0	5.5	V	
Supply Current		25	30	mA	no load
Low-level Output			0.4	V	IOL = 8 mA
		0.035		V	no load
High-level Output	2.4			V	IOH = -8 mA
		4.0		V	no load
Output Rise Time		100		ns	no load
Output Fall Time		50		ns	no load

Differential Electrical

Specifications	Min.	Typ.	Max.	Units	Notes
Supply Voltage	4.5	5.0	5.5	V	
Supply Current		27	32	mA	no load
Single-Ended Output Voltage High	4.75	5.0		V	Min. @ 25mA load, Typ. @ no load
Single-Ended Output Voltage Low		0.25	0.60	V	Typ. @ no load, Max. @ 4.5mA load
Differential Output Voltage	3.0	3.8		V	RL = 100 ohm
Differential Output Rise/Fall Time			20	ns	

Phase Relationship



Parameter	Min.	Typ.	Max.	Units
Symmetry, S	105	180	255	electrical degrees
Quadrature Delay, Q	30	90	150	electrical degrees

- (1) A leads B for clockwise shaft rotation, B leads A for counter clockwise shaft rotation viewed from the cover side of the encoder.
- (2) Typical values represent the encoder performance at typical mounting alignment, whereas the maximum values represent the encoder performance across the range of recommended mounting tolerance.

Pin-out

4-pin Single-ended

Pin	Description	Pin	Description
1	+5VDC power	1	Ground
2	A channel	2	A channel
3	Ground	3	A- channel
4	B channel	4	+5VDC power
		5	B channel
		6	B- channel

(1) 4-pin single-ended mating connector is CON-MIC4

(2) 6-pin differential mating connector is CON-MIC6

 Options

H-option (Hole In Cover)

The **H**-option adds a 0.295" diameter hole in the cover for the shaft to pass through.

M-option (Metric Mounting Screws)

Provides alternate metric M2.5, length 4mm screws. When **M**-option is NOT specified the default is #3-48 x 3/16" screws.

 Accessories

1. Centering Tool*

Part #: MCTOOL - (Shaft Diameter)

Description: This reusable tool is used to accurately center the **E4T** base on the shaft.

2. Spacer Tool*

Part #: SPACER-E4T

Description: This reusable tool is used to properly space the codewheel from the encoder.

*Both the MCTOOL and SPACER-E4T tools are included with all packaging options.

 Assembly Instructions

E4T Assembly Instructions - <http://usdigital.com/assets/assembly/E4T%20Assembly%20Instructions.pdf>

 Ordering Information

E4T - - - - - -

CPR	Bore	Output	Cover	Base	Packaging
100	079 =2mm	S =Single	D =Default	D =Default	B =Encoder components packaged in bulk.
108	098 =	Ended	H =Hole in	M =Alternate metric	One spacer and one centering tool per 100 encoders.
120 =	2.5mm	D =Differential	Cover	M2.5, length 4mm	
125 =	118 =3mm			screws	1 =Each encoder packaged individually.
128 =	125 =1/8"				One spacer tool and one centering tool per 100 encoders.
200 =	157 =4mm				
250 =	188 =3/16"				2 =Each encoder packaged individually.
256 =	197 =5mm				One spacer and one centering tool per encoder.
300 =	236 =6mm				
360 =	250 =1/4"				
400 =					
500 =					

Notes

- Cables and connectors are not included and must be ordered separately.
- US Digital® warrants its products against defects in materials and workmanship for two years. See complete warranty for details.

DESCRIPTION

The MP2307 is a monolithic synchronous buck regulator. The device integrates 100mΩ MOSFETs that provide 3A of continuous load current over a wide operating input voltage of 4.75V to 23V. Current mode control provides fast transient response and cycle-by-cycle current limit.

An adjustable soft-start prevents inrush current at turn-on and in shutdown mode, the supply current drops below 1μA.

This device, available in an 8-pin SOIC package, provides a very compact system solution with minimal reliance on external components.

EVALUATION BOARD REFERENCE

Board Number	Dimensions
EV2307DN-00A	2.0"X x 1.5"Y x 0.5"Z

FEATURES

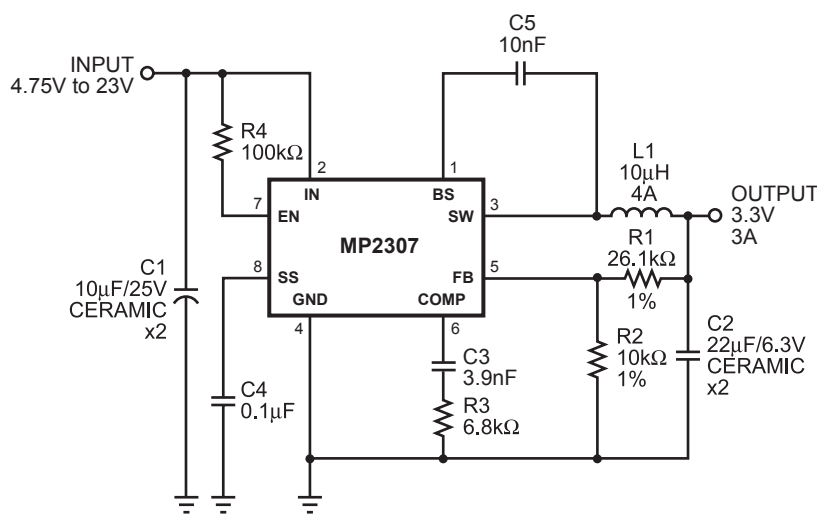
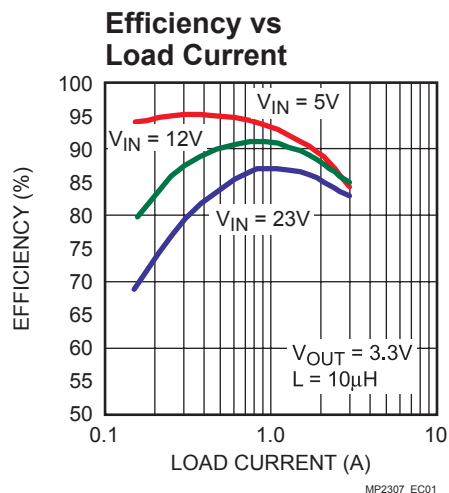
- 3A Continuous Output Current
4A Peak Output Current
- Wide 4.75V to 23V Operating Input Range
- Integrated 100mΩ Power MOSFET Switches
- Output Adjustable from 0.925V to 20V
- Up to 95% Efficiency
- Programmable Soft-Start
- Stable with Low ESR Ceramic Output Capacitors
- Fixed 340KHz Frequency
- Cycle-by-Cycle Over Current Protection
- Input Under Voltage Lockout
- Thermally Enhanced 8-Pin SOIC Package

APPLICATIONS

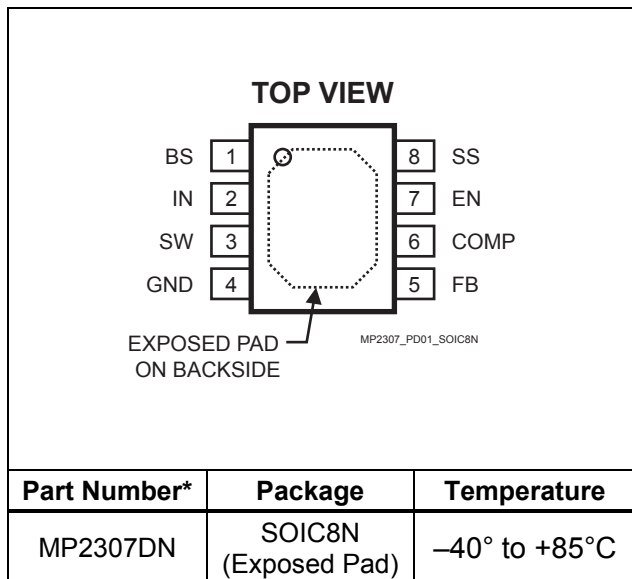
- Distributed Power Systems
- Networking Systems
- FPGA, DSP, ASIC Power Supplies
- Green Electronics/Appliances
- Notebook Computers

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TYPICAL APPLICATION



PACKAGE REFERENCE



* For Tape & Reel, add suffix -Z (eg. MP2307DN-Z)
For Lead Free, add suffix -LF (eg. MP2307DN-LF-Z)

ABSOLUTE MAXIMUM RATINGS ⁽¹⁾

Supply Voltage V_{IN} ..... -0.3V to +26V
Switch Voltage V_{SW} ..... -1V to $V_{IN} + 0.3V$
Boost Voltage V_{BS} ..... $V_{SW} - 0.3V$ to $V_{SW} + 6V$
All Other Pins..... -0.3V to +6V
Junction Temperature..... 150°C
Lead Temperature ..... 260°C
Storage Temperature ..... -65°C to +150°C

Recommended Operating Conditions ⁽²⁾

Input Voltage V_{IN} ..... 4.75V to 23V
Output Voltage V_{OUT} ..... 0.925V to 20V
Ambient Operating Temp ..... -40°C to +85°C

Thermal Resistance ⁽³⁾ θ_{JA} θ_{JC}
SOIC8N ..... 50 ..... 10... °C/W

Maximum Power Dissipation Operating ($T_A = 25^\circ\text{C}$)

SOIC8N ⁽⁴⁾, P_{OUT} 2W

Notes:

- 1) Exceeding these ratings may damage the device.
- 2) The device is not guaranteed to function outside of its operating conditions.
- 3) Measured on approximately 1" square of 1 oz copper.
- 4) Derating 20mW/°C at $T_A > 25^\circ\text{C}$

ELECTRICAL CHARACTERISTICS

$V_{IN} = 12V$, $T_A = +25^\circ\text{C}$, unless otherwise noted.

Parameter	Symbol	Condition	Min	Typ	Max	Units
Shutdown Supply Current		$V_{EN} = 0V$		0.3	3.0	μA
Supply Current		$V_{EN} = 2.0V$, $V_{FB} = 1.0V$		1.3	1.5	mA
Feedback Voltage	V_{FB}	$4.75V \leq V_{IN} \leq 23V$	0.900	0.925	0.950	V
Feedback Overvoltage Threshold				1.1		V
Error Amplifier Voltage Gain ⁽⁵⁾	A_{EA}			400		V/V
Error Amplifier Transconductance	G_{EA}	$\Delta I_C = \pm 10\mu A$		820		$\mu A/V$
High-Side Switch On-Resistance ⁽⁵⁾	$R_{DS(ON)1}$			100		m Ω
Low-Side Switch On-Resistance ⁽⁵⁾	$R_{DS(ON)2}$			100		m Ω
High-Side Switch Leakage Current		$V_{EN} = 0V$, $V_{SW} = 0V$		0	10	μA
Upper Switch Current Limit		Minimum Duty Cycle	4.0	5.8		A
Lower Switch Current Limit		From Drain to Source		0.9		A
COMP to Current Sense Transconductance	G_{CS}			5.2		A/V
Oscillation Frequency	F_{osc1}		300	340	380	KHz
Short Circuit Oscillation Frequency	F_{osc2}	$V_{FB} = 0V$		110		KHz
Maximum Duty Cycle	D_{MAX}	$V_{FB} = 1.0V$		90		%
Minimum On Time ⁽⁵⁾	T_{ON}			220		ns
EN Shutdown Threshold Voltage		V_{EN} Rising	1.1	1.5	2.0	V
EN Shutdown Threshold Voltage Hysteresis				220		mV

ELECTRICAL CHARACTERISTICS *(continued)*

$V_{IN} = 12V$, $T_A = +25^{\circ}C$, unless otherwise noted.

Parameter	Symbol	Condition	Min	Typ	Max	Units
EN Lockout Threshold Voltage			2.2	2.5	2.7	V
EN Lockout Hysteresis				210		mV
Input Under Voltage Lockout Threshold		V_{IN} Rising	3.80	4.05	4.40	V
Input Under Voltage Lockout Threshold Hysteresis				210		mV
Soft-Start Current		$V_{SS} = 0V$		6		μA
Soft-Start Period		$C_{SS} = 0.1\mu F$		15		ms
Thermal Shutdown ⁽⁵⁾				160		$^{\circ}C$

Note:

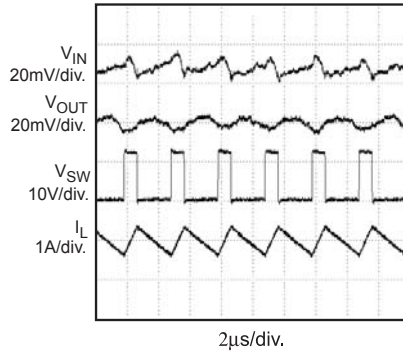
5) Guaranteed by design, not tested.

TYPICAL PERFORMANCE CHARACTERISTICS

C1 = 2 x 10 μ F, C2 = 2 x 22 μ F, L = 10 μ H, C_{SS} = 0.1 μ F, T_A = +25°C, unless otherwise noted.

Steady State Test Waveforms

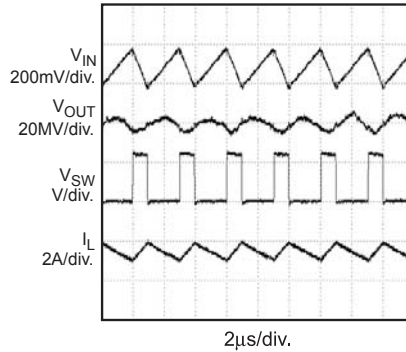
V_{IN} = 12V, V_{OUT} = 3.3V, I_{OUT} = 0A



MP2307-TPC01

Steady State Test Waveforms

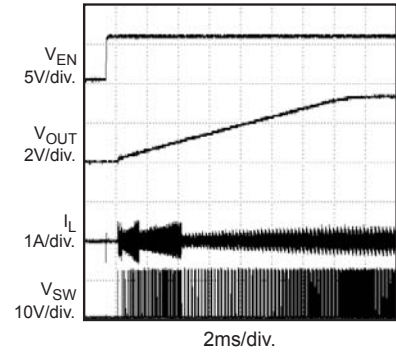
V_{IN} = 12V, V_{OUT} = 3.3V, I_{OUT} = 3A



MP2307-TPC02

Startup through Enable Waveforms

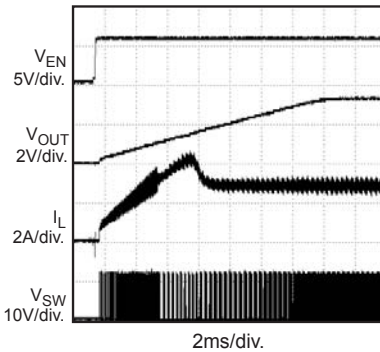
V_{IN} = 12V, V_{OUT} = 3.3V, No Load



MP2307-TPC03

Startup Through Enable Waveforms

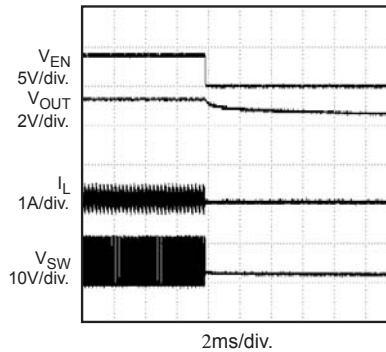
V_{IN} = 12V, V_{OUT} = 3.3V,
I_{OUT} = 3A (Resistance Load)



MP2307-TPC04

Shutdown Through Enable Waveforms

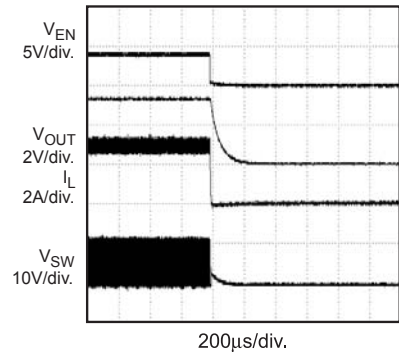
V_{IN} = 12V, V_{OUT} = 3.3V, No Load



MP2307-TPC05

Shutdown Through Enable Waveforms

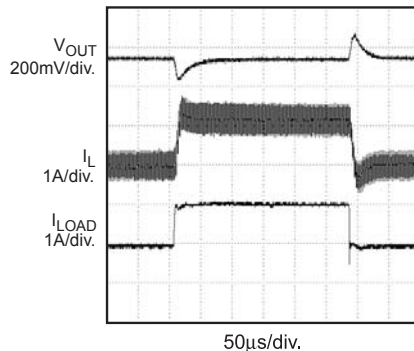
V_{IN} = 12V, V_{OUT} = 3.3V,
I_{OUT} = 3A (Resistance Load)



MP2307-TPC06

Load Transient Test Waveforms

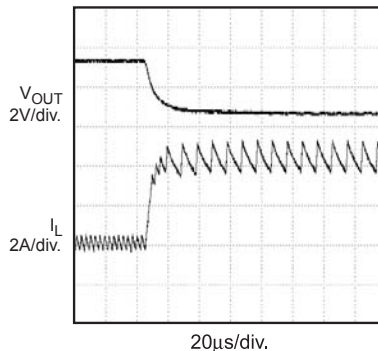
V_{IN} = 12V, V_{OUT} = 3.3V,
I_{OUT} = 1A to 2A step



MP2307-TPC07

Short Circuit Test Waveforms

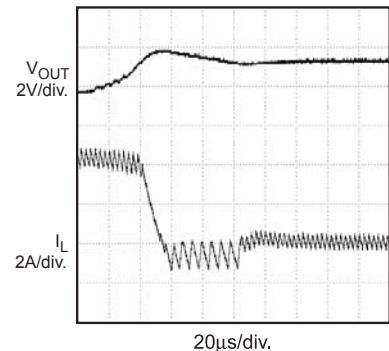
V_{IN} = 12V, V_{OUT} = 3.3V



MP2307-TPC08

Short Circuit Recovery Waveforms

V_{IN} = 12V, V_{OUT} = 3.3V



MP2307-TPC09

PIN FUNCTIONS

Pin #	Name	Description
1	BS	High-Side Gate Drive Boost Input. BS supplies the drive for the high-side N-Channel MOSFET switch. Connect a 0.01 μ F or greater capacitor from SW to BS to power the high side switch.
2	IN	Power Input. IN supplies the power to the IC, as well as the step-down converter switches. Drive IN with a 4.75V to 23V power source. Bypass IN to GND with a suitably large capacitor to eliminate noise on the input to the IC. See <i>Input Capacitor</i> .
3	SW	Power Switching Output. SW is the switching node that supplies power to the output. Connect the output LC filter from SW to the output load. Note that a capacitor is required from SW to BS to power the high-side switch.
4	GND	Ground (Connect the exposed pad to Pin 4).
5	FB	Feedback Input. FB senses the output voltage and regulates it. Drive FB with a resistive voltage divider connected to it from the output voltage. The feedback threshold is 0.925V. See <i>Setting the Output Voltage</i> .
6	COMP	Compensation Node. COMP is used to compensate the regulation control loop. Connect a series RC network from COMP to GND. In some cases, an additional capacitor from COMP to GND is required. See <i>Compensation Components</i> .
7	EN	Enable Input. EN is a digital input that turns the regulator on or off. Drive EN high to turn on the regulator; low to turn it off. Attach to IN with a 100k Ω pull up resistor for automatic startup.
8	SS	Soft-Start Control Input. SS controls the soft-start period. Connect a capacitor from SS to GND to set the soft-start period. A 0.1 μ F capacitor sets the soft-start period to 15ms. To disable the soft-start feature, leave SS unconnected.

OPERATION

FUNCTIONAL DESCRIPTION

The MP2307 regulates input voltages from 4.75V to 23V down to an output voltage as low as 0.925V, and supplies up to 3A of load current.

The MP2307 uses current-mode control to regulate the output voltage. The output voltage is measured at FB through a resistive voltage divider and amplified through the internal transconductance error amplifier. The voltage at the COMP pin is compared to the switch current (measured internally) to control the output voltage.

The converter uses internal N-Channel MOSFET switches to step-down the input voltage to the regulated output voltage. Since the high side MOSFET requires a gate voltage greater than the input voltage, a boost capacitor connected between SW and BS is needed to drive the high side gate. The boost capacitor is charged from the internal 5V rail when SW is low.

When the FB pin voltage exceeds 20% of the nominal regulation value of 0.925V, the over voltage comparator is tripped and the COMP pin and the SS pin are discharged to GND, forcing the high-side switch off.

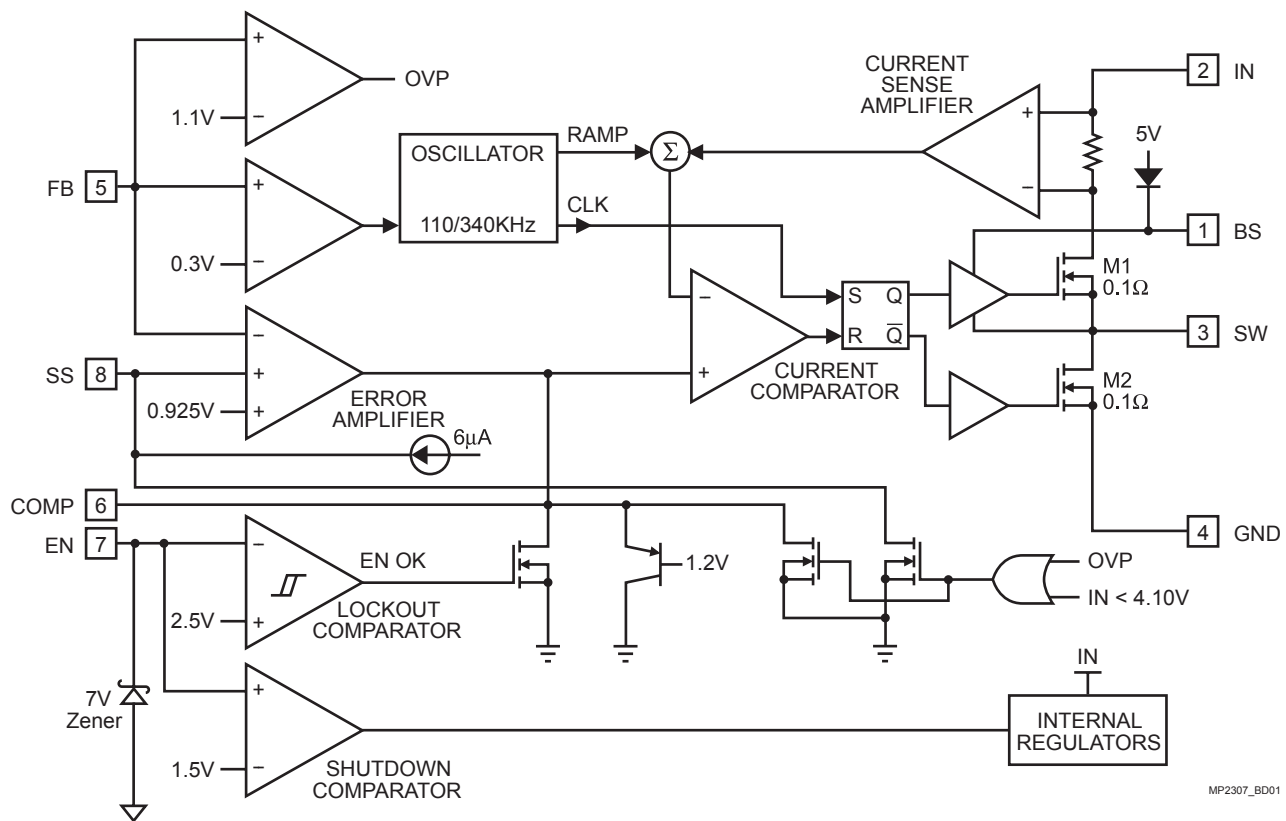


Figure 1—Functional Block Diagram

MP2307_BD01

APPLICATIONS INFORMATION

COMPONENT SELECTION

Setting the Output Voltage

The output voltage is set using a resistive voltage divider connected from the output voltage to FB. The voltage divider divides the output voltage down to the feedback voltage by the ratio:

$$V_{FB} = V_{OUT} \frac{R2}{R1 + R2}$$

Thus the output voltage is:

$$V_{OUT} = 0.925 \times \frac{R1 + R2}{R2}$$

R2 can be as high as 100kΩ, but a typical value is 10kΩ. Using the typical value for R2, R1 is determined by:

$$R1 = 10.81 \times (V_{OUT} - 0.925) \text{ (k}\Omega\text{)}$$

For example, for a 3.3V output voltage, R2 is 10kΩ, and R1 is 26.1kΩ. Table 1 lists recommended resistance values of R1 and R2 for standard output voltages.

Table 1—Recommended Resistance Values

VOUT	R1	R2
1.8V	9.53kΩ	10kΩ
2.5V	16.9kΩ	10kΩ
3.3V	26.1kΩ	10kΩ
5V	44.2kΩ	10kΩ
12V	121kΩ	10kΩ

Inductor

The inductor is required to supply constant current to the load while being driven by the switched input voltage. A larger value inductor will result in less ripple current that will in turn result in lower output ripple voltage. However, the larger value inductor will have a larger physical size, higher series resistance, and/or lower saturation current. A good rule for determining inductance is to allow the peak-to-peak ripple current to be approximately 30% of the maximum switch current limit. Also, make sure that the peak inductor current is below the maximum switch current limit.

The inductance value can be calculated by:

$$L = \frac{V_{OUT}}{f_s \times \Delta I_L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right)$$

Where V_{OUT} is the output voltage, V_{IN} is the input voltage, f_s is the switching frequency, and ΔI_L is the peak-to-peak inductor ripple current.

Choose an inductor that will not saturate under the maximum inductor peak current, calculated by:

$$I_{LP} = I_{LOAD} + \frac{V_{OUT}}{2 \times f_s \times L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right)$$

Where I_{LOAD} is the load current.

The choice of which style inductor to use mainly depends on the price vs. size requirements and any EMI constraints.

Optional Schottky Diode

During the transition between the high-side switch and low-side switch, the body diode of the low-side power MOSFET conducts the inductor current. The forward voltage of this body diode is high. An optional Schottky diode may be paralleled between the SW pin and GND pin to improve overall efficiency. Table 2 lists example Schottky diodes and their Manufacturers.

Table 2—Diode Selection Guide

Part Number	Voltage/Current Rating	Vendor
B130	30V, 1A	Diodes, Inc.
SK13	30V, 1A	Diodes, Inc.
MBRS130	30V, 1A	International Rectifier

Input Capacitor

The input current to the step-down converter is discontinuous, therefore a capacitor is required to supply the AC current while maintaining the DC input voltage. Use low ESR capacitors for the best performance. Ceramic capacitors are preferred, but tantalum or low-ESR electrolytic capacitors will also suffice. Choose X5R or X7R dielectrics when using ceramic capacitors.

Since the input capacitor (C1) absorbs the input switching current, it requires an adequate ripple current rating. The RMS current in the input capacitor can be estimated by:

$$I_{C1} = I_{LOAD} \times \sqrt{\frac{V_{OUT}}{V_{IN}} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right)}$$

The worst-case condition occurs at $V_{IN} = 2V_{OUT}$, where $I_{C1} = I_{LOAD}/2$. For simplification, use an input capacitor with a RMS current rating greater than half of the maximum load current.

The input capacitor can be electrolytic, tantalum or ceramic. When using electrolytic or tantalum capacitors, a small, high quality ceramic capacitor, i.e. 0.1μF, should be placed as close to the IC as possible. When using ceramic capacitors, make sure that they have enough capacitance to provide sufficient charge to prevent excessive voltage ripple at input. The input voltage ripple for low ESR capacitors can be estimated by:

$$\Delta V_{IN} = \frac{I_{LOAD}}{C1 \times f_S} \times \frac{V_{OUT}}{V_{IN}} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right)$$

Where C1 is the input capacitance value.

Output Capacitor

The output capacitor (C2) is required to maintain the DC output voltage. Ceramic, tantalum, or low ESR electrolytic capacitors are recommended. Low ESR capacitors are preferred to keep the output voltage ripple low. The output voltage ripple can be estimated by:

$$\Delta V_{OUT} = \frac{V_{OUT}}{f_S \times L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \times \left(R_{ESR} + \frac{1}{8 \times f_S \times C2}\right)$$

Where C2 is the output capacitance value and R_{ESR} is the equivalent series resistance (ESR) value of the output capacitor.

When using ceramic capacitors, the impedance at the switching frequency is dominated by the capacitance which is the main cause for the output voltage ripple. For simplification, the output voltage ripple can be estimated by:

$$\Delta V_{OUT} = \frac{V_{OUT}}{8 \times f_S^2 \times L \times C2} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right)$$

When using tantalum or electrolytic capacitors, the ESR dominates the impedance at the switching frequency. For simplification, the output ripple can be approximated to:

$$\Delta V_{OUT} = \frac{V_{OUT}}{f_S \times L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \times R_{ESR}$$

The characteristics of the output capacitor also affect the stability of the regulation system. The MP2307 can be optimized for a wide range of capacitance and ESR values.

Compensation Components

MP2307 employs current mode control for easy compensation and fast transient response. The system stability and transient response are controlled through the COMP pin. COMP is the output of the internal transconductance error amplifier. A series capacitor-resistor combination sets a pole-zero combination to govern the characteristics of the control system.

The DC gain of the voltage feedback loop is given by:

$$A_{VDC} = R_{LOAD} \times G_{CS} \times A_{EA} \times \frac{V_{FB}}{V_{OUT}}$$

Where V_{FB} is the feedback voltage (0.925V), A_{VEA} is the error amplifier voltage gain, G_{CS} is the current sense transconductance and R_{LOAD} is the load resistor value.

The system has two poles of importance. One is due to the compensation capacitor (C3) and the output resistor of the error amplifier, and the other is due to the output capacitor and the load resistor. These poles are located at:

$$f_{P1} = \frac{G_{EA}}{2\pi \times C3 \times A_{VEA}}$$

$$f_{P2} = \frac{1}{2\pi \times C2 \times R_{LOAD}}$$

Where G_{EA} is the error amplifier transconductance.

The system has one zero of importance, due to the compensation capacitor (C3) and the compensation resistor (R3). This zero is located at:

$$f_{Z1} = \frac{1}{2\pi \times C3 \times R3}$$

The system may have another zero of importance, if the output capacitor has a large capacitance and/or a high ESR value. The zero, due to the ESR and capacitance of the output capacitor, is located at:

$$f_{ESR} = \frac{1}{2\pi \times C2 \times R_{ESR}}$$

In this case, a third pole set by the compensation capacitor (C6) and the compensation resistor (R3) is used to compensate the effect of the ESR zero on the loop gain. This pole is located at:

$$f_{P3} = \frac{1}{2\pi \times C6 \times R3}$$

The goal of compensation design is to shape the converter transfer function to get a desired loop gain. The system crossover frequency where the feedback loop has the unity gain is important. Lower crossover frequencies result in slower line and load transient responses, while higher crossover frequencies could cause system instability. A good standard is to set the crossover frequency below one-tenth of the switching frequency.

To optimize the compensation components, the following procedure can be used.

1. Choose the compensation resistor (R3) to set the desired crossover frequency.

Determine R3 by the following equation:

$$R3 = \frac{2\pi \times C2 \times f_C}{G_{EA} \times G_{CS}} \times \frac{V_{OUT}}{V_{FB}} < \frac{2\pi \times C2 \times 0.1 \times f_S}{G_{EA} \times G_{CS}} \times \frac{V_{OUT}}{V_{FB}}$$

Where f_C is the desired crossover frequency which is typically below one tenth of the switching frequency.

2. Choose the compensation capacitor (C3) to achieve the desired phase margin. For applications with typical inductor values, setting the compensation zero (f_{Z1}) below one-fourth of the crossover frequency provides sufficient phase margin.

Determine C3 by the following equation:

$$C3 > \frac{4}{2\pi \times R3 \times f_C}$$

Where R3 is the compensation resistor.

3. Determine if the second compensation capacitor (C6) is required. It is required if the ESR zero of the output capacitor is located at less than half of the switching frequency, or the following relationship is valid:

$$\frac{1}{2\pi \times C2 \times R_{ESR}} < \frac{f_S}{2}$$

If this is the case, then add the second compensation capacitor (C6) to set the pole f_{P3} at the location of the ESR zero. Determine C6 by the equation:

$$C6 = \frac{C2 \times R_{ESR}}{R3}$$

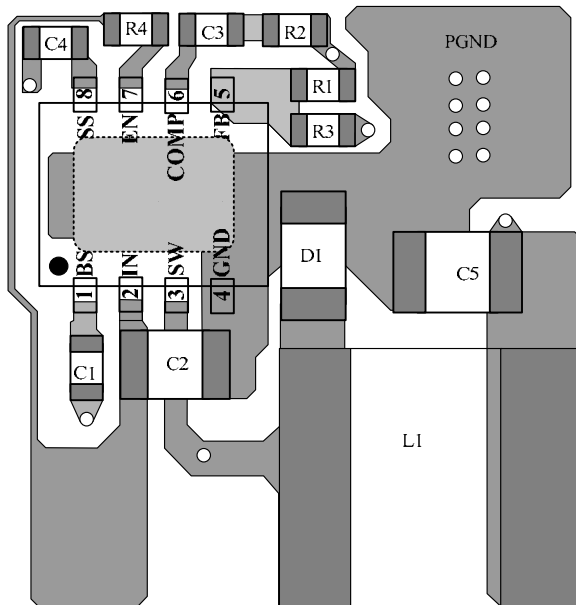
PCB Layout Guide

PCB layout is very important to achieve stable operation. It is highly recommended to duplicate EVB layout for optimum performance.

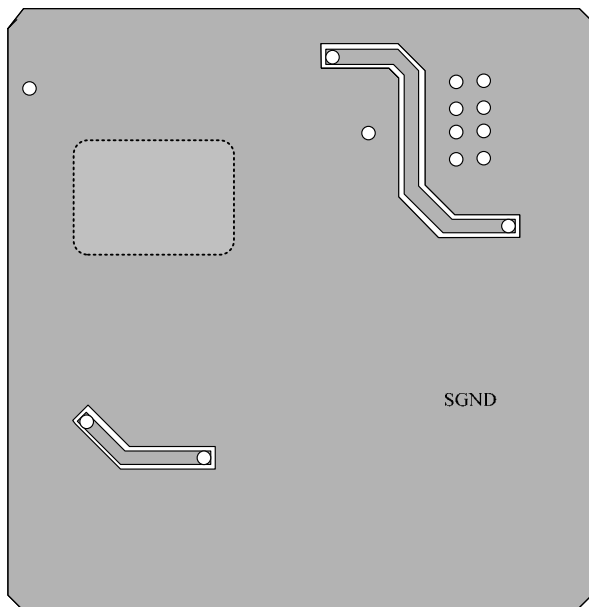
If change is necessary, please follow these guidelines and take Figure2 for reference.

- 1) Keep the path of switching current short and minimize the loop area formed by Input cap., high-side MOSFET and low-side MOSFET.
- 2) Bypass ceramic capacitors are suggested to be put close to the Vin Pin.
- 3) Ensure all feedback connections are short and direct. Place the feedback resistors and compensation components as close to the chip as possible.
- 4) R_{OUT} SW away from sensitive analog areas such as FB.

- 5) Connect IN, SW, and especially GND respectively to a large copper area to cool the chip to improve thermal performance and long-term reliability.



TOP Layer



Bottom Layer

Figure 2—PCB Layout (Double Layer)

External Bootstrap Diode

An external bootstrap diode may enhance the efficiency of the regulator, the applicable conditions of external BS diode are:

- V_{OUT} is 5V or 3.3V; and
- Duty cycle is high: $D = \frac{V_{OUT}}{V_{IN}} > 65\%$

In these cases, an external BS diode is recommended from the output of the voltage regulator to BS pin, as shown in Figure3

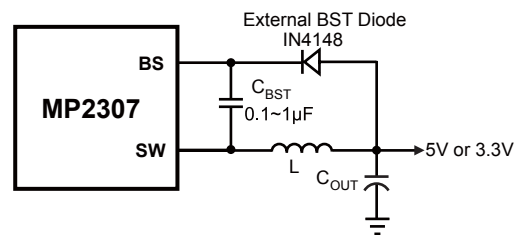


Figure 3—Add Optional External Bootstrap Diode to Enhance Efficiency

The recommended external BS diode is IN4148, and the BS cap is 0.1~1μF.

TYPICAL APPLICATION CIRCUIT

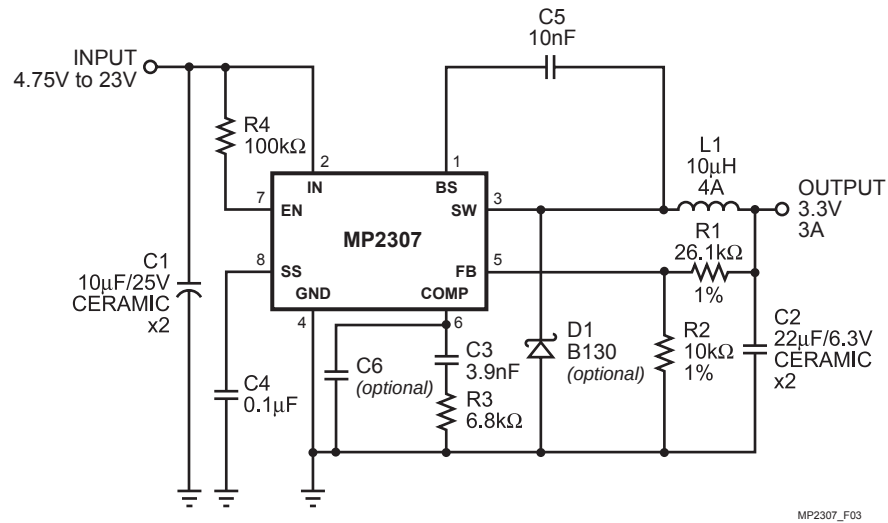
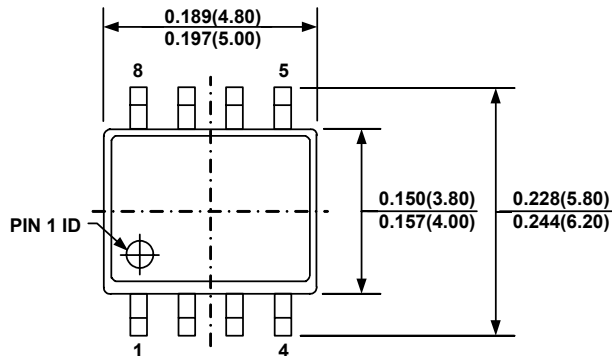


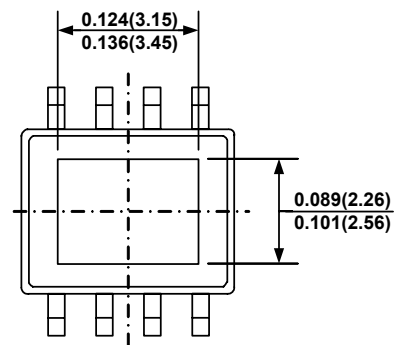
Figure 4—MP2307 with 3.3V Output, 22μF/6.3V Ceramic Output Capacitor

PACKAGE INFORMATION

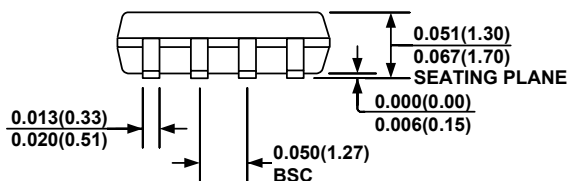
SOIC8N (EXPOSED PAD)



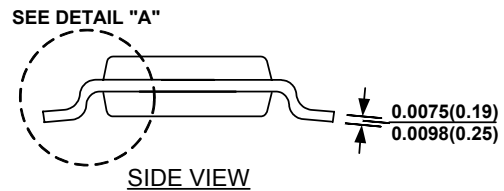
TOP VIEW



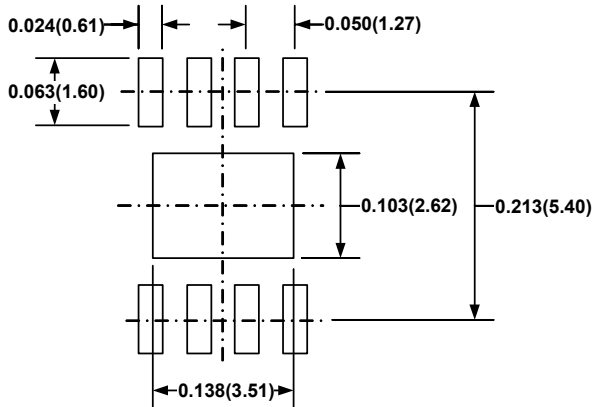
BOTTOM VIEW



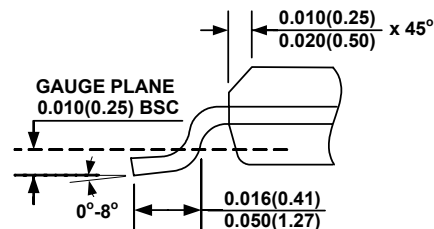
FRONT VIEW



SIDE VIEW



RECOMMENDED LAND PATTERN



DETAIL "A"

NOTE:

- 1) CONTROL DIMENSION IS IN INCHES. DIMENSION IN BRACKET IS IN MILLIMETERS.
- 2) PACKAGE LENGTH DOES NOT INCLUDE MOLD FLASH, PROTRUSIONS OR GATE BURRS.
- 3) PACKAGE WIDTH DOES NOT INCLUDE INTERLEAD FLASH OR PROTRUSIONS.
- 4) LEAD COPLANARITY (BOTTOM OF LEADS AFTER FORMING) SHALL BE 0.004" INCHES MAX.
- 5) DRAWING CONFORMS TO JEDEC MS-012, VARIATION BA.
- 6) DRAWING IS NOT TO SCALE.

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■ Features

- AC input range selectable by switch
- Withstand 300VAC surge input for 5 second
- Protections: Short circuit / Overload / Over voltage / Over temperature
- Forced air cooling by built-in DC fan
- Built-in cooling Fan ON-OFF control
- 1U low profile
- Withstand 5G vibration test
- LED indicator for power on
- No load power consumption<0.75W
- 100% full load burn-in test
- High operating temperature up to 70°C
- Operating altitude up to 5000 meters (Note.8)
- High efficiency, long life and high reliability
- 3 years warranty

■ Applications

- Industrial automation machinery
- Industrial control system
- Mechanical and electrical equipment
- Electronic instruments, equipments or apparatus

■ Description

LRS-350 series is a 350W single-output enclosed type power supply with 30mm of low profile design. Adopting the input of 115VAC or 230VAC (select by switch), the entire series provides an output voltage line of 3.3V, 4.2V, 5V, 12V, 15V, 24V, 36V and 48V.

In addition to the high efficiency up to 89%, with the built-in long life fan LRS-350 can work under -25~+70°C with full load. Delivering an extremely low no load power consumption (less than 0.75W), it allows the end system to easily meet the worldwide energy requirement. LRS-350 has the complete protection functions and 5G anti-vibration capability; it is complied with the international safety regulations such as UL60950-1. LRS-350 series serves as a high price-to-performance power supply solution for various industrial applications.

■ Model Encoding

LRS - 350 - 3.3

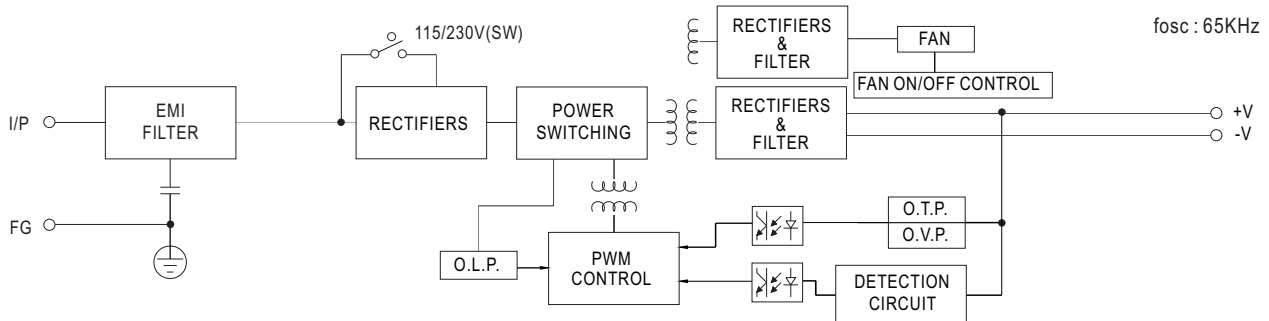
Output voltage
Output power
Series name



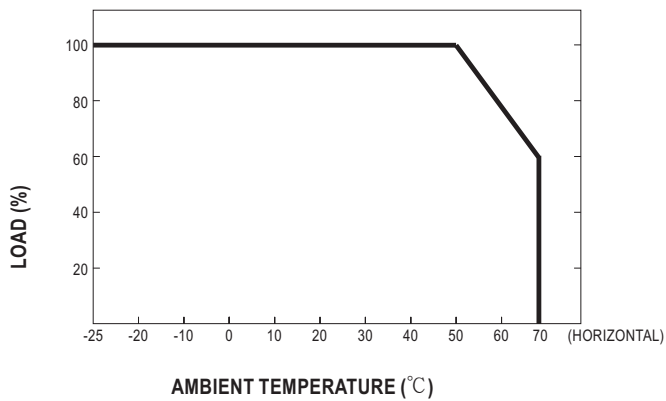
SPECIFICATION

MODEL		LRS-350-3.3	LRS-350-4.2	LRS-350-5	LRS-350-12	LRS-350-15	LRS-350-24	LRS-350-36	LRS-350-48
OUTPUT	DC VOLTAGE	3.3V	4.2V	5V	12V	15V	24V	36V	48V
	RATED CURRENT	60A	60A	60A	29A	23.2A	14.6A	9.7A	7.3A
	CURRENT RANGE	0 ~ 60A	0 ~ 60A	0 ~ 60A	0 ~ 29A	0 ~ 23.2A	0 ~ 14.6A	0 ~ 9.7A	0 ~ 7.3A
	RATED POWER	198W	252W	300W	348W	348W	350.4W	349.2W	350.4W
	RIPPLE & NOISE (max.) Note.2	150mVp-p	150mVp-p	150mVp-p	150mVp-p	150mVp-p	150mVp-p	200mVp-p	200mVp-p
	VOLTAGE ADJ. RANGE	2.97 ~ 3.6V	3.6 ~ 4.4V	4.5 ~ 5.5V	10.2 ~ 13.8V	13.5 ~ 18V	21.6 ~ 28.8V	32.4 ~ 39.6V	43.2 ~ 52.8V
	VOLTAGE TOLERANCE Note.3	±4.0%	±4.0%	±3.0%	±1.5%	±1.0%	±1.0%	±1.0%	±1.0%
	LINE REGULATION Note.4	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%
	LOAD REGULATION Note.5	±2.5%	±2.5%	±2.0%	±1.0%	±0.5%	±0.5%	±0.5%	±0.5%
	SETUP, RISE TIME	1300ms, 50ms/230VAC 1300ms,50ms/115VAC at full load							
HOLD UP TIME (Typ.)	16ms/230VAC 12ms/115VAC at full load								
INPUT	VOLTAGE RANGE	90 ~ 132VAC / 180 ~ 264VAC by switch 240 ~ 370VDC (switch on 230VAC)							
	FREQUENCY RANGE	47 ~ 63Hz							
	EFFICIENCY (Typ.)	79.5%	81.5%	83.5%	85%	86%	88%	88.5%	89%
	AC CURRENT (Typ.)	6.8A/115VAC 3.4A/230VAC							
	INRUSH CURRENT (Typ.)	60A/115VAC 60A/230VAC							
	LEAKAGE CURRENT	<2mA / 240VAC							
PROTECTION	OVER LOAD	110 ~ 140% rated output power Protection type : Hiccup mode, recovers automatically after fault condition is removed							
	OVER VOLTAGE	3.8 ~ 4.45V	4.6 ~ 5.4V	5.75 ~ 6.75V	13.8 ~ 16.2V	18 ~ 21V	28.8 ~ 33.6V	41.4 ~ 46.8V	55.2 ~ 64.8V
		Protection type : Hiccup mode, recovers automatically after fault condition is removed							
	OVER TEMPERATURE	Hiccup mode, recovers automatically after fault condition is removed							
FUNCTION	FAN ON/OFF CONTROL (Typ.)	RTH3≥50℃ FAN ON, ≤40℃ FAN OFF							
ENVIRONMENT	WORKING TEMP.	-25 ~ +70℃ (Refer to "Derating Curve")							
	WORKING HUMIDITY	20 ~ 90% RH non-condensing							
	STORAGE TEMP., HUMIDITY	-40 ~ +85℃, 10 ~ 95% RH							
	TEMP. COEFFICIENT	±0.03%/℃ (0 ~ 50℃)							
	VIBRATION	10 ~ 500Hz, 5G 10min./1cycle, 60min. each along X, Y, Z axes							
SAFETY	SAFETY STANDARDS	UL60950-1 approved							
	WITHSTAND VOLTAGE	I/P-O/P:3KVAC I/P-FG:2KVAC O/P-FG:0.5KVAC							
	ISOLATION RESISTANCE	I/P-O/P, I/P-FG, O/P-FG:100M Ohms/500VDC / 25℃ / 70% RH							
OTHERS	MTBF	327.9K hrs min. MIL-HDBK-217F (25℃)							
	DIMENSION	215*115*30mm (L*W*H)							
	PACKING	0.76Kg; 15pcs/12.4Kg/0.78CUFT							
NOTE	1. All parameters NOT specially mentioned are measured at 230VAC input, rated load and 25℃ of ambient temperature. 2. Ripple & noise are measured at 20MHz of bandwidth by using a 12" twisted pair-wire terminated with a 0.1uf & 47uf parallel capacitor. 3. Tolerance : includes set up tolerance, line regulation and load regulation. 4. Line regulation is measured from low line to high line at rated load. 5. Load regulation is measured from 0% to 100% rated load. 6. Length of set up time is measured at cold first start. Turning ON/OFF the power supply very quickly may lead to increase of the set up time. 7.The 150% peak load capability is built in for up to 1 second for 12~48V.LRS-350 will enter hiccup mode if the peak load is delivered for over 1 second and will recover once it resumes to the rated current level(115VAC/230VAC). 8. The ambient temperature derating of 5℃/1000m is needed for operating altitude greater than 2000m(6500ft).								

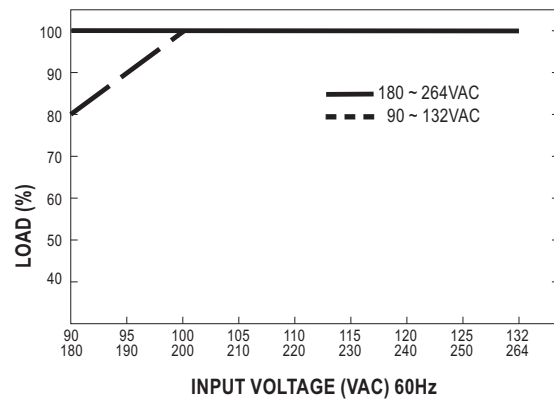
■ Block Diagram



■ Derating Curve



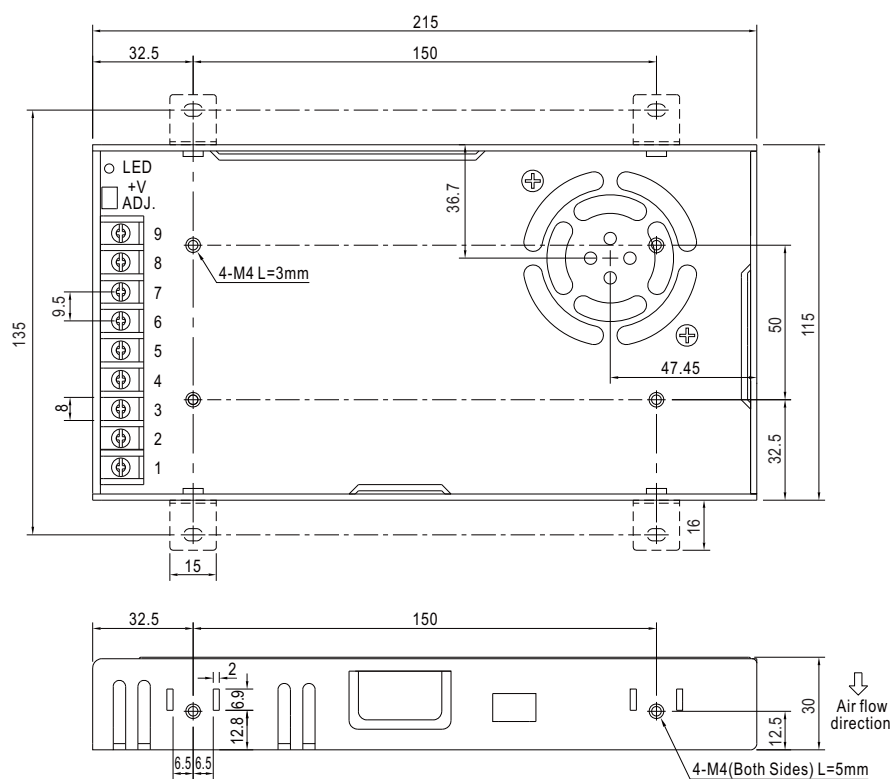
■ Static Characteristics



■ Mechanical Specification

Case No.207A

Unit:mm



Terminal Pin No. Assignment :

Pin No.	Assignment	Pin No.	Assignment
1	AC/L	4~6	DC OUTPUT -V
2	AC/N	7~9	DC OUTPUT +V
3	FG $\perp$		

■ Installation Manual

Please refer to : <http://www.meanwell.com/webnet/search/InstallationSearch.html>

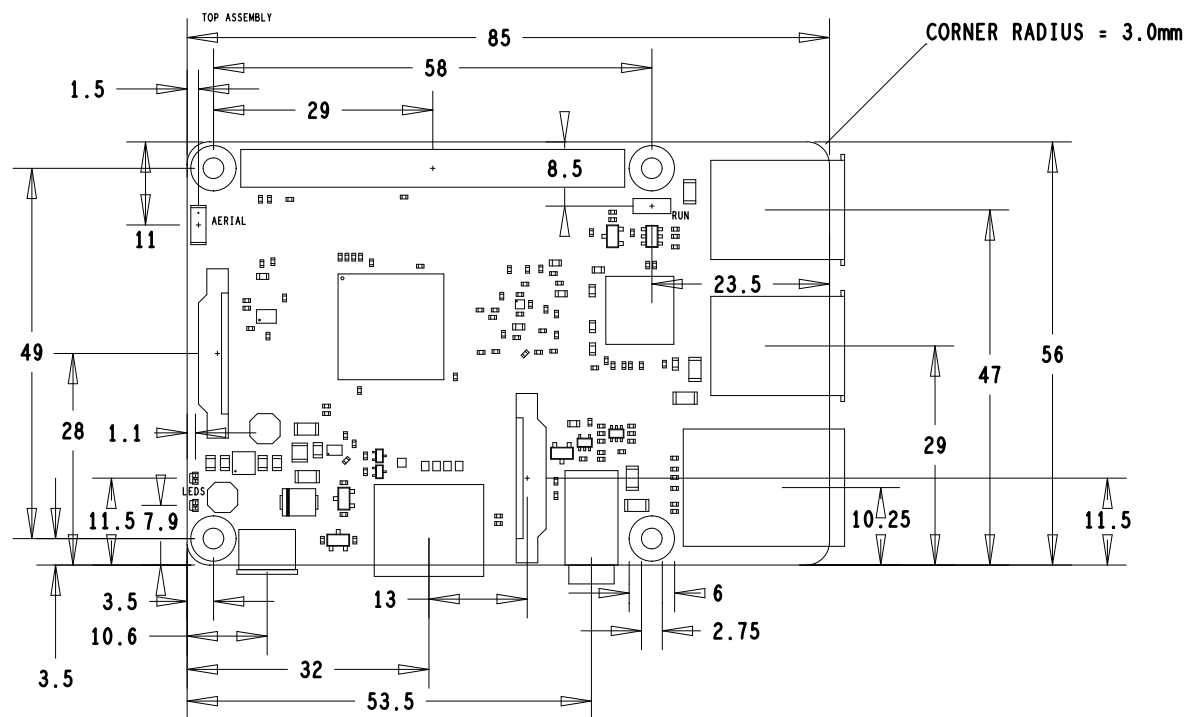
Mouser Electronics

Authorized Distributor

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[Mean Well:](#)

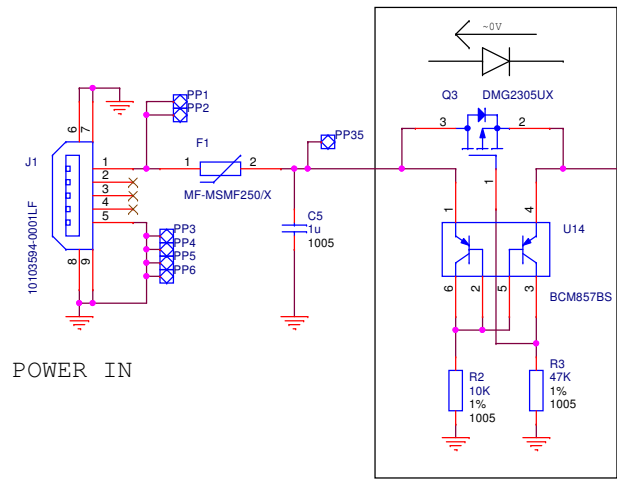
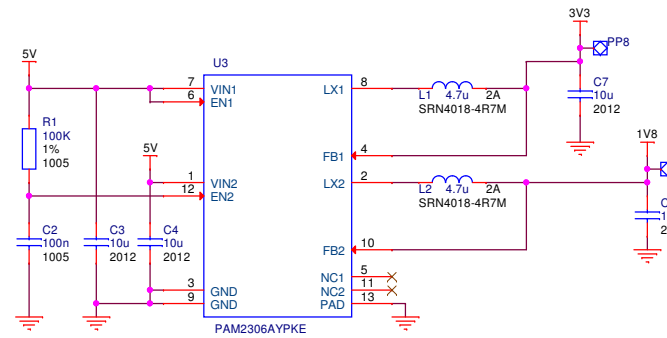
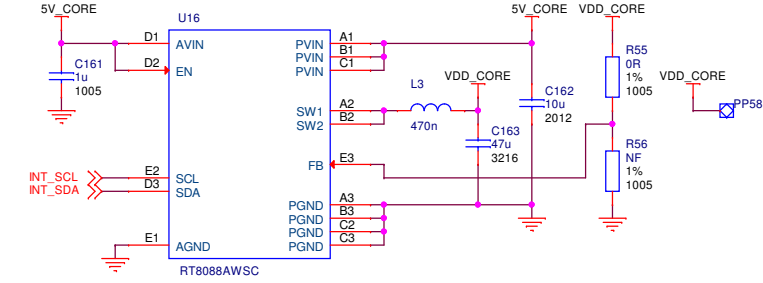
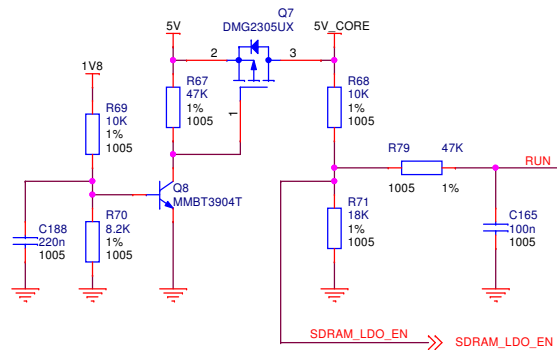
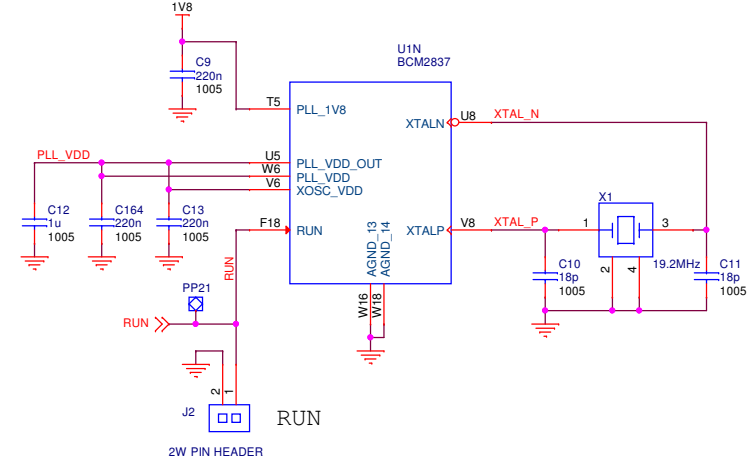
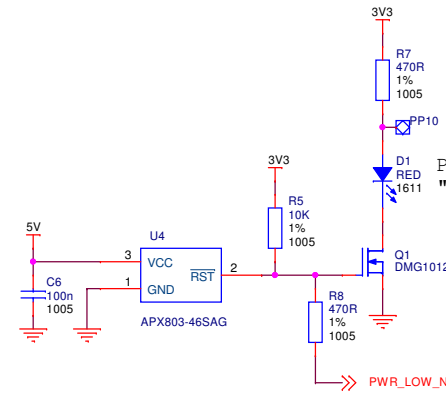
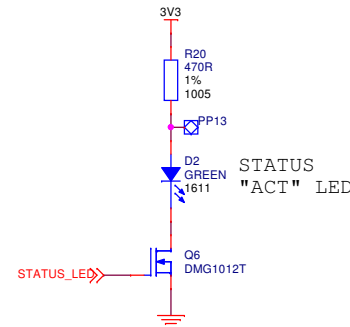
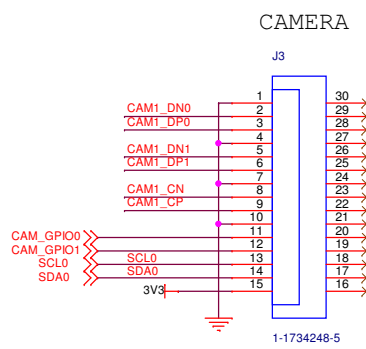
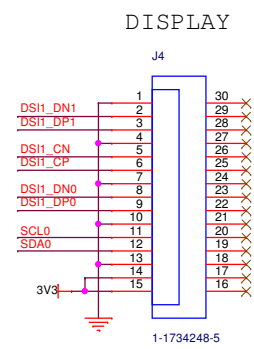
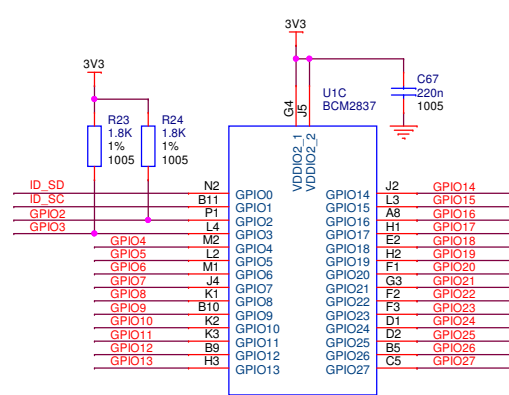
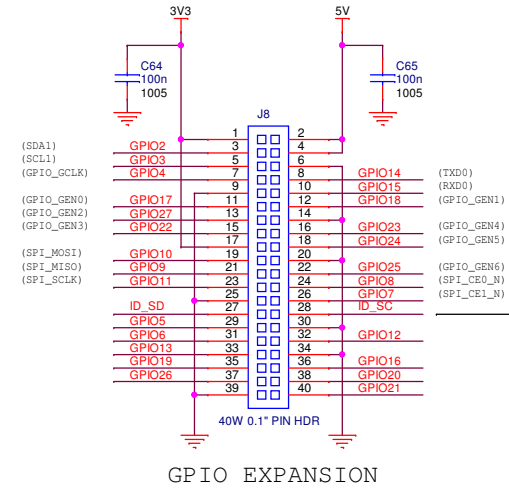
[LRS-350-12](#) [LRS-350-3.3](#) [LRS-350-4.2](#) [LRS-350-15](#) [LRS-350-48](#) [LRS-350-5](#) [LRS-350-36](#) [LRS-350-24](#)



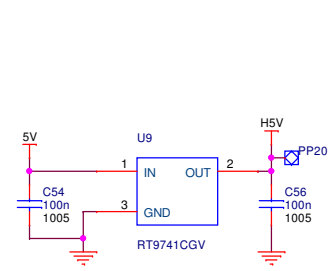
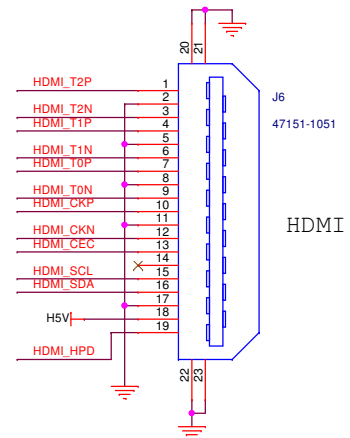
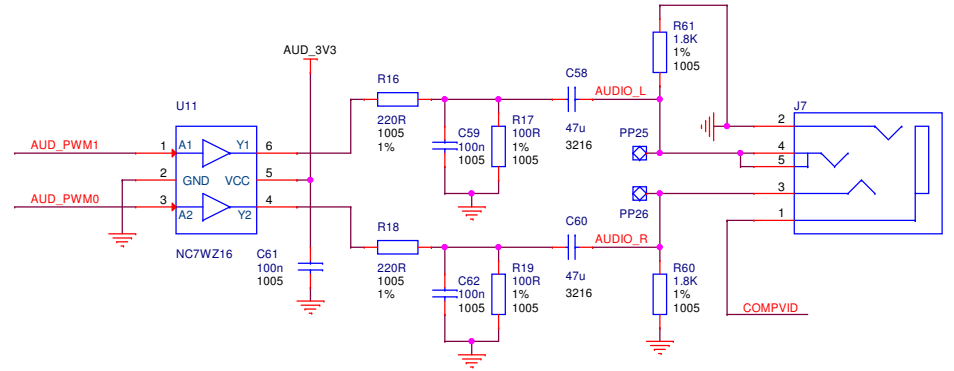
CORNER RADIUS = 3.0mm

4x M2.5 MOUNTING HOLES
DRILLED TO 2.75 +/- 0.05mm

 Raspberry Pi www.raspberrypi.org © Raspberry Pi 2015			
TITLE	RASPBERRY PI 3 MODEL B		
DATE	06/10/2015	REF	RPI-3B-V1_2
DRAWN	James Adams	APVD	James Adams

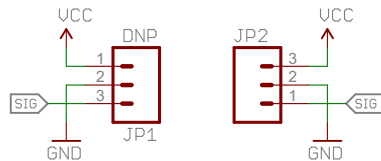


ID_SD and ID_SC PINS:
These pins are reserved for HAT ID EEPROM.
At boot time this I2C interface will be interrogated to look for an EEPROM that identifies the attached board and allows automatic setup of the GPIOs (and optionally, Linux drivers).
DO NOT USE these pins for anything other than attaching an I2C ID EEPROM. Leave unconnected if ID EEPROM not required.



Connectors:
JST Jumper 3 Wire Assembly - PRT-09915
Screw Terminals 3.5mm Pitch (3-Pin) - PRT-08235

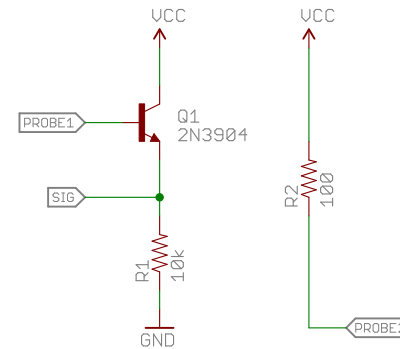
VCC = 3.3V-5V



DO NOT POWER CONSTANTLY

It is recommended that you use a digital GPIO pin on whichever microcontroller or IC you're using to control the sensor to power the sensor.

Probe Circuit



Test different values for R1 to get lower power consumption while still getting a good ADC reading.

Rod length and spacing were not the most significant variables.

In general you want the probes long enough to reach the moist soil and not so close together that they are likely to touch accidentally. Keeping them about an inch apart works great.

The big variable is the composition of the soil itself (especially salts), so ideally you would calibrate for each type of soil.

-Rob Faludi

Based off the Soil Moisture Circuit found at: <http://www.faludi.com/2006/11/02/moisture-sensor-circuit/>

PCB design inspired by the Soil Moisture Sensor from DFRobot
http://www.dfrobot.com/index.php?route=product/product&product_id=599



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Attribution Share-Alike 4.0 License
<https://creativecommons.org/licenses/by-sa/4.0/>

TITLE: SparkFun_Soil_Moisture_Sensor

Design by: Joel Bartlett

REV:
v10

Date: not saved!

Sheet: 1/1