FarmBot

Final Design Report

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Farmbot

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Executive Summary

The following report is a description of the process we took in developing Farmbot over the course of 2014. When we joined our sponsor Rory Aronson to work on Farmbot in January, it was little more than just an idea in his head. He had roughed together a "Version 1.0" on a raised planter box in his backyard, which was mostly just a visual representation to show how the aluminum extrusions could fit and move around a garden plot. There were attached stepper motors to control the motion of the gantry, but they were not functional, and only manual movement was possible. Although Version 1.0 was not functional, it gave us a great starting point and allowed us to figure out the best way for our team to contribute to the development of Farmbot in the next stages toward eventually becoming a functional farming robot.

The end goal with Farmbot is to create a robot that will tend to a variety of plants in a garden, with minimal user interaction through a computer or mobile application. Each plant could be given specialized care according to their needs, and Farmbot could monitor the growth of each plant from seeding to harvesting time. Obviously this is a massive undertaking, so we honed the scope of our senior project down to take advantage of our expertise and to provide us with achievable goals.

We decided early on that it was best for our team to focus primarily on the task of designing the hardware for Farmbot to perform its primary functions, and to create a template for a system that would be adaptable for future users and developers. The scope of our project included creating a universal tool mount, a seeding system, and a watering and nutrient mixing system.

We went through an extensive brainstorming process for each part of our scope before beginning our design phase, where we were able to incorporate testing immediately due to easy access to rapid prototyping. This also allowed us to go through several reiterations of our designs over the course of the year, which eventually brought us to the creation of functional parts to implement onto Farmbot.

We each learned a lot through the long process of taking this project from start to finish, and will continue to use lessons we learned about time management, meeting deadlines, and the iterative design process throughout our lives, both within our careers and personal lives. We have to thank our Faculty Advisor Dr. Eileen Rossman, and our sponsor Rory Aronson for providing us with support and guidance every step along the way, as well as for the opportunity to work on this project.

1. Introduction

Most agricultural food production in the modern day is performed in large scale, monocrop farms on huge plots of land. While it has been streamlined to produce huge amounts of food at a relatively cheap price, monocrop farming puts a significant strain on the soil and the surrounding environment by using up specific nutrients for different crops, as well as using tremendous amounts of water. The idea with Farmbot is to shift dependence on large scale agriculture by giving people the ability to cultivate their own plants with little to no actual physical labor on their part. Farmbot would be able to remember the location of each plant, and provide specialized care to feed nutrients and water to each plant as needed based on an online database. This means that, with Farmbot, a person with little to no actual gardening experience could have the home-garden of their dreams with no more effort than a few taps on the screen of a tablet computer.

Rory Aronson, the mastermind behind Farmbot, has worked with us over the course of the past year to create several prototypes, each with increasing success. When we joined him in January, all he had was a non-working physical representation of his dream. Since then, we have transformed Farmbot into a functioning robot with the ability to move, use multiple tools, plant seeds, and feed plants necessary nutrients to thrive. We have also provided a template for future users to continue to develop new tools, which may include weed removal, plowing, or assorted types of data collection.

1.1. Design Requirements and Specifications

After discussing with our Project Sponsor, we narrowed down the scope of our project to the development of three main systems for Farmbot: (1) seed planting mechanism(s), (2) water and nutrient delivery system, and (3) universal tool mount system. While creating solutions for these main functions, we hoped to the cost of Farmbot. Our previous Customer Requirements and Engineering Specifications from the Project Proposal applied to the Farmbot machine as a whole. They have now been revised to focus on the three primary tasks determined by the scope of our project and are listed in Table 1 below:

Table 1: Revised List of Customer Requirements and Engineering Specifications.

Customer Requirements	Engineering Specifications
● Easy to install or pre-installed tool components ● Easy to operate and maintain ● Low cost ● Safe for people in the event of an accident ● Must not look ugly ● Minimum installation time ● Information, research, and development is open source ● Easy for customers to independently manufacture certain parts and tools	● Tool mount accommodates watering and seeding nozzles and universal tool holder ● Watering and seeding nozzles can be controlled to eject their contents when desired and how much ● Tools can be picked up and held securely by universal tool holder system ● Prototype accommodates at least one stock of one type of plant seed ● Tools readily attach to the universal tool holder ● Solenoid release actuator fully retracts pin out of tool ● Tool ejects from tool holder when actuated

Recalling that a Quality Function Deployment (QFD) chart was used to generate the list of customer requirements and engineering specifications presented above, we observed that many of the Customer Requirements have remained unchanged. However, because the scope of our project has now been limited to the watering, seeding, and a universal tool mount, several of the previous Engineering Specifications have been removed. New specifications have been added in their place to reflect the narrower scope of the project. Customer Requirements no longer have very much overlap with the Engineering Specifications. The original QFD chart is included in Appendix C.

A software development team is currently working on implementing a user interface for Farmbot. Since this is an open-source project, Farmbot is open to anyone willing to contribute their skills and expertise. Additionally, anyone is able to access the information necessary to build their own Farmbot via the project wiki online at wiki.farmbot.it/Welcome.

2. Project Background and Research

In order to develop a product that will be able to function well in an agricultural environment, we have to take into consideration the effects of soil and nutrients, plant seasons, and planting depths. For our scope, the information that will weigh into our design the most is planting depths and plant nutrients. Additionally, an overview of current available systems for each function and patents will be needed in order to avoid any patent infringements. Finally, we need to incorporate US Safety and Health Guidelines for machine guarding into our design.

According to the *Handbook of Plant Nutrition*, there are 17 essential plant nutrients: Carbon, Hydrogen, Oxygen, Nitrogen, Phosphorous, Potassium, Calcium, Magnesium, Sulfur, Iron, Manganese, Copper, Boron, Zinc, Molybdenum, Chlorine, and Nickel [2]. The first three are derived from the air and water, while the other 14 are from soil and nutrient solutions. Each different plant type grows best under different nutrient conditions. These nutrients are able to be combined into a liquid solution, for ease of transportation. Additionally, different plants need to be planted at different depths, different time of the season, and different spacing from each other. When creating our design, we took these into account.

Current available machines are very expensive and usually only perform one or two functions. For example, combined harvesters combine the different operations that go into harvesting grain. They only allow for a farmer to cut and separate out the edible portions of the grain. Additionally, these harvesters cost at a minimum of about $400,000 for the smallest John Deere model [4]. A search of current models for our type of farming machine shows that a current system does not exist. However, there are multiple patents and designs related to the functions in our design.

One aspect that had many options for design was the seeding function. Engineers from Cornell University developed a Universal Jamming Gripper that allows a mass of granular material encased in an elastic membrane to envelop a material [5]. This allows for the mechanism to grip and release a wide range of objects. However, we did find a very similar mechanism that uses all household materials on a Do-It-Yourself site [3]. This universal gripper uses a vacuum created by suction from a syringe in order to provide the sufficient pressure to be able to grip an object. An Arduino is used to control the stem of the syringe, which is easily adaptable into the open-source design of this project. Another device relating to seeding and planting is a mechanism called the Stand & Plant Seeder and Planter [9]. It is made primarily of PVC pipe, which means it is easily reconstructable. Additionally, the original inventors provide pre-built mechanisms for sale. This could be useful when considering seeding mechanisms, especially ones with easily accessible materials. Finally, we also found that a Precision English Seeder could be useful in coming up with the design of the seeding mechanism [7]. This design uses suction to pick up a seed, and then lets it go into the soil.

When investigating power and data transfer for the tools, we found two standards that could potentially work well: I2C bus and USB. Both are relatively common in industry. We found specification manuals for each protocol [11], [12].

For considerations of quick-connections for air, we looked at three methods. The first was the quick-release mechanism used on air compressor hoses [8]. The second was the simple mechanism used when inflating sports balls [10]. Each has it's benefits and downsides. For the compressor hoses, they are safe and reliable, yet require an actuator to release the mechanism. For the ball needle, they do not require much actuation, but air may leak. The third method, and the one we ended up implementing, was to use

the attraction of two magnets, with a rubber washer in between them to create a seal. This method was easy to implement, and proved to create sufficient seals for both liquid and air lines.

Regarding existing systems for rapid automated tool swapping systems, we discovered that CNC machines use a variety of such systems. One particular example we found was the Sherline Headstock Tool Changer System. However, this system is costly, and we would prefer a much less expensive solution. We also noted that the Sherline and other CNC tool changing systems do not seem to provide a means to transfer data or power to the tools.

Finally, certain safety standards exist for consumer machines. In our case, applicable standards include enclosure regulations. Standard 1928 from the Occupation Safety and Health Administration includes rules for agricultural machines [6]. We will need to include these standards if we want to be able to use this project as a consumer product.

3. Design Development

The design development for our project was an incredible learning experience. We spent multiple weeks in our first quarter exploring existing solutions and developing new concepts for the systems we wanted to develop for Farmbot. For each of these components, we generated concepts and followed a detailed selection process. We presented our best ideas to our sponsor, modified and improved them, and in some cases scrapped the primary idea when we found a better and more effective solution as a team.

Due to easy access to a 3D printer, we were able to produce and test each of our designs to quickly make modifications to improve each design. We repeated this process several times in order to find an optimal solution, until time constraints required us to stop iterating to focus on the final presentation.

Our sponsor Rory was deeply involved in this entire process. We held (nearly) weekly meetings to discuss our progress, re-design parts, add features, and discuss our future plans. We came to expect that our current designs weren't completely permanent, because we saw that our product development was a dynamic process, and there always seemed to be areas for improvement. Rory's constant input and contributions to the design process was great, and it made him more like a fourth member of our team rather than a "boss" that we periodically reported to with a myriad of ideas.

3.1. Universal Tool Mount System

Farmbot requires a universal tool mount system to perform a broad range of tasks. An important guideline for the development of this system was to create a template for future users to develop new tools such as sensors, weed removal devices, and digger tools that Farmbot could use.

3.1.1. Universal Tool Mount Concept Development

A few of our first concepts for the universal tool mount are described below:

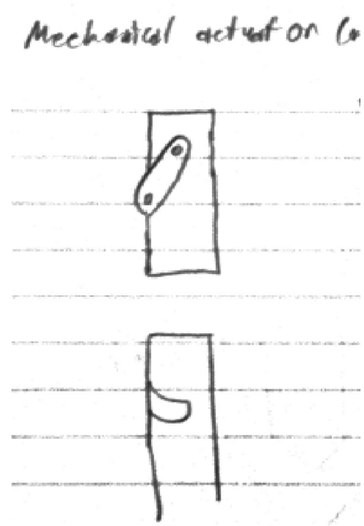


Figure 1: Early sketch of a lever actuation/release mechanism for the universal tool mount.

One of our first concepts was a lever style holder/release mechanism, which can be seen above in Figure 1. A tapered tool shaft was to push a lever out of the way as it was inserted into the tool mount. When

the tool reached a certain depth within the tool mount, the lever would fall back into a notch in the tool interface and lock the tool in place. This concept was not selected due to issues with releasing the tool.

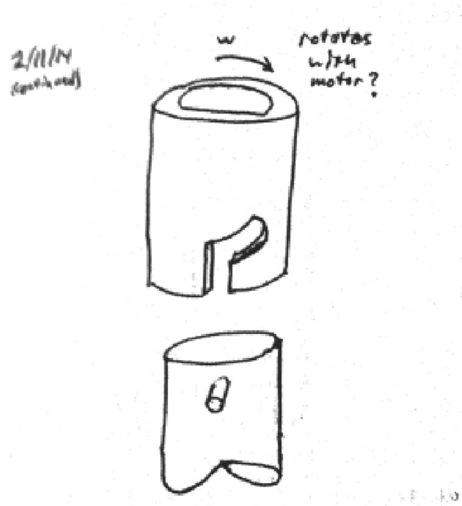


Figure 2: Early sketch for a rotating nub and slot mechanism for the universal tool mount.

Another one of our top concepts was a rotating nub and slot mechanism, which can be seen above in Figure 2. Each tool would feature a long shaft with a nub that fit into a slot in the tool mount. The system acted as an alignment guide, but it lacked a means of holding or releasing the tool.

We began developing several physical concept models for a universal tool mount system by using materials such as PVC pipe, foam core board, and screws. Some of these concepts included a lever system, a rotational nub and slot system, and others. All these concepts were put into a Pugh Matrix to determine how well the concepts satisfied our specifications. The lever system was one of the first concepts and seemed to be a reasonable standard, so this was set as the datum. The Pugh Matrix resulted in multiple concepts sharing the highest score and proved ineffective in leading us to the best conceptual design.

Next, we listed our concepts in a Decision Matrix to achieve more precise and distinct results. One additional concept for a tapered tool, nub, and solenoid actuator combination was developed from the previous concepts and added to the decision matrix. This new combined tapered tool system scored the highest on the decision matrix. Since the Pugh Matrix failed to determine a definitive concept, the Decision Matrix was our primary quantitative method to justify our selection of the top concept. The Pugh and Decision Matrices used for the initial tool mount are contained in Appendix A.

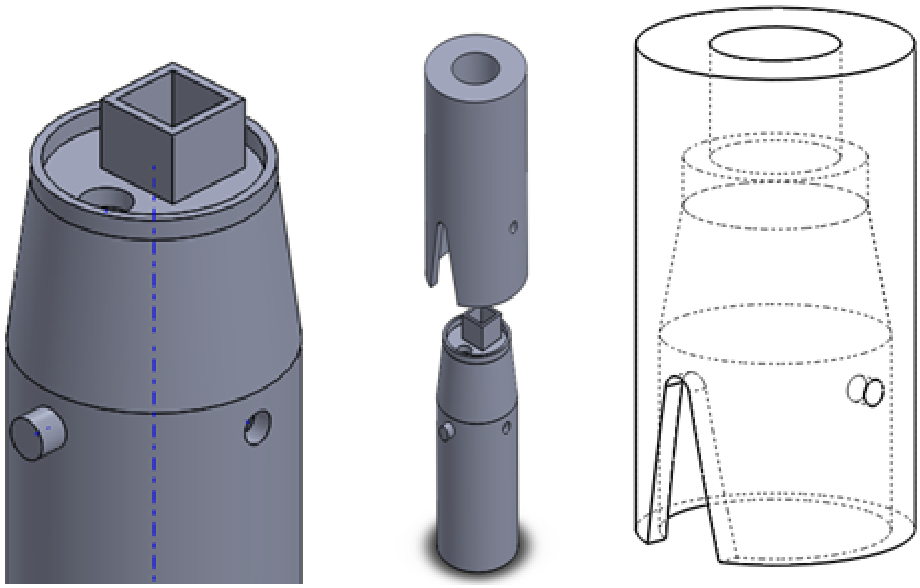


Figure 3: Solid model of our first top concept for the universal tool mount.

Our first iteration of the universal tool mount was conceived by combining elements from several previous concepts. A rendering can be seen above in Figure 3. The interface of the tool consisted of several elements. A protruding nub guided the tool into proper alignment into the tool mount. This was necessary to properly establish a USB power/data connection interface, as well as a possible internal air pressure line. There was a hole on the side in which a solenoid actuator rod would catch and hold the tool. The end of the tool shaft was tapered to ensure smooth guidance into the tool mount. The v-shaped notch was meant to guide the nub from the tool shaft to properly align it with the tool mount. The tool shaft was hollow to accommodate wiring and air pressure lines, which would be developed in the future. Finally, a protruding lip on the tool shaft accommodated a spring to ensure its ejection when the release was activated. No definitive material was selected for this version of the universal tool mount, due to the uncertainty of the fabrication of the parts. Difficulties arose between reconciling the need for precision tolerances and alignment and the ability for consumers and tinkerers to create their own tools and attachments. These issues were resolved through each of the next iterations.

The next iteration, seen in Figure 4, fixed a few of the problems we saw from our first design. The first problem was allowing for easier data and electrical contact between the tool shaft and the tool mount. We originally planned to use a USB 2.0 interface, but Rory wanted to create a system that would allow for some tolerance when interfacing. Because of this, we developed an idea to use machine screws combined with small springs to serve as our electrical contacts, which would fit into the four holes seen above the tool mount. The second problem was attaching the tool mount to the Farmbot arm. Since the new design featured a flat surface on one end, we were able to use metal brackets to secure the tool mount to the arm. Finally, the v-slot was revised to allow for better tool shaft alignment.

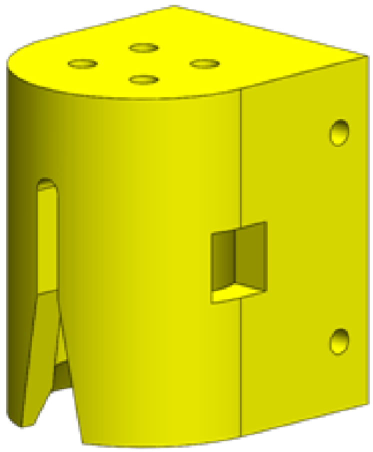


Figure 4: Solid model of second universal tool mount concept.
Figure 5: Picture of solenoid from Adafruit Industries

The solenoid actuator we used for this design was a lock-style 12VDC solenoid from Adafruit Industries, which can be seen above in Figure 5. It included mounting holes that allowed for easy attachment to the tool mount with M3 screws. When the tool shaft inserted into the tool mount, it pushed against the slanted face of the solenoid latch, causing it to retract. As the tool shaft slid further in, the spring-loaded solenoid latch would pop into the square cut in the tool shaft to lock it in place. To release the tool, current would be run through the solenoid to retract the latch and release the tool.

The problem with this design was that there was no practical method of mounting the solenoid actuator, and so we built a new tool mount with a plate to mount the actuator. This new design can be seen below in Figure 6. Along with creating the bracket for the actuator, we added brackets above and below for easier attachment to the Farmbot arm. However, when we 3D printed this iteration, the top and bottom brackets broke off. Thus, we had to create a sturdier tool mount.

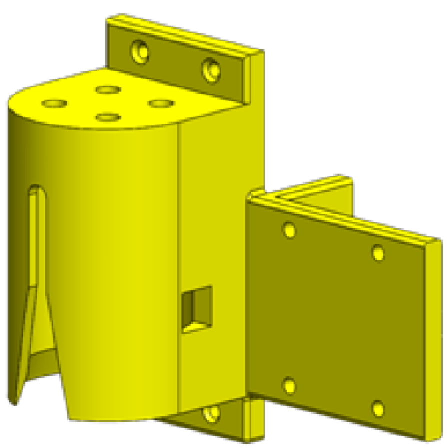
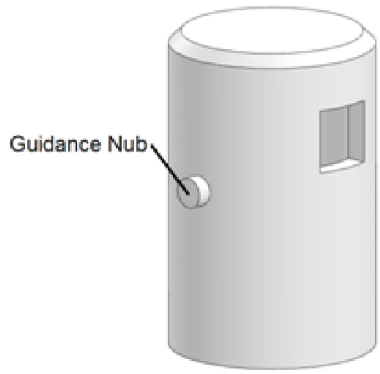


Figure 6: Solid model of our third universal tool mount concept.

The next concept included several additional features to accommodate mounting and fabrication considerations, and fixed many of the problems from our previous iteration. It integrated the fundamental features already described by our previous concepts: a solenoid actuator to hold and

release the tool, a v-notch to guide an alignment nub, and a tapered cylinder to ensure tool shaft insertion. This concept can be seen below in Figures 7 and 8.



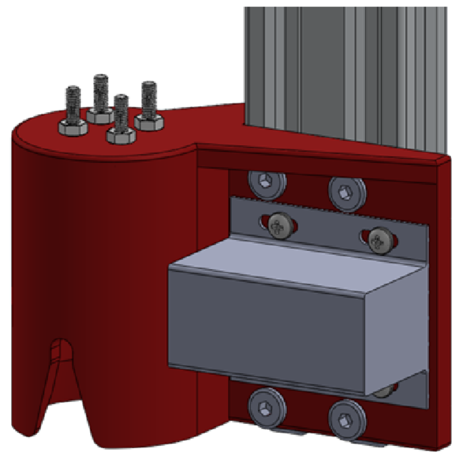
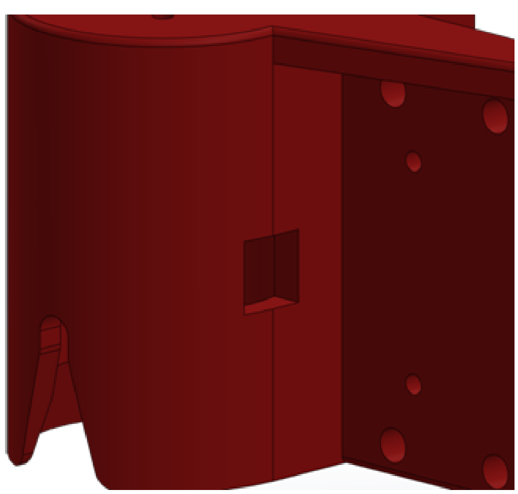


Figure 7 (left): Solid model of the tool shaft designed to fit into the universal tool mount.
Figure 8 (right): Solid model of the Universal Tool Mount subassembly shown mounted to the Farmbot Tool Mount extrusion arm.

The tool mount was designed to accommodate a variety of tools provided that each tool was fitted with the universal tool shaft we developed with it. Just like the previous iteration, the tool shaft featured a guiding nub that led the shaft into the correct orientation within the tool mount. This was especially important for aligning the electrical contact screws between the tool shaft and the tool mount. The electrical contact screws can be seen below in Figure 10. The square cut on the side of the shaft aligned with the square hole on the tool mount (seen in Figure 9), which allowed the solenoid latch to lock the tool in place. The top edge of the tool shaft was tapered to prevent snagging as it was inserted into the tool mount. The v-notch and guiding slot were optimized in this version to guarantee proper tool alignment through the following modifications: the corners were rounded to prevent the guiding nub from snagging; a short slot was added to the end of the v-notch to eliminate possible angular deflection of the tool shaft; the inner bottom edge of the tool mount was chamfered to prevent snagging as tools were inserted into the tool mount.



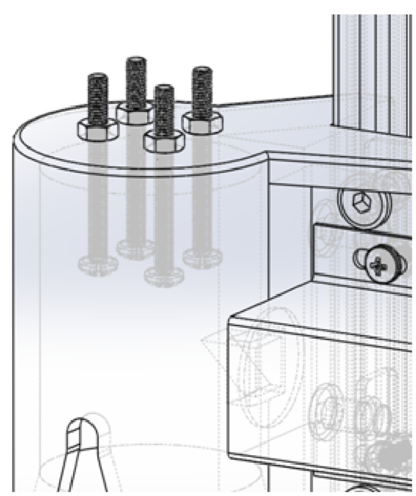
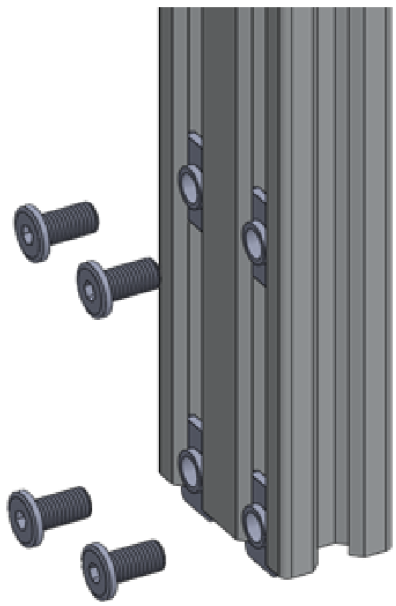


Figure 9: Square hole for the solenoid latch on the side of the tool mount cylinder.
Figure 10: Solid model of the universal tool mount transparent to show electrical contact screws.

The screws we specified for this version were M3 machine screws, with M3 hex nuts to prevent them from slipping out. Each screw-nut pair was fitted with a small spring; when a tool shaft was inserted into the tool mount, it would push the screw up, compressing the spring between the head of the screw and the ceiling of the cylinder within the tool mount. When the solenoid actuator was activated to release the tool, the compression springs would push the tool out of the tool mount, ensuring that the tool was released. The mounting hole and screw configurations can be seen below in Figures 11 and 12.



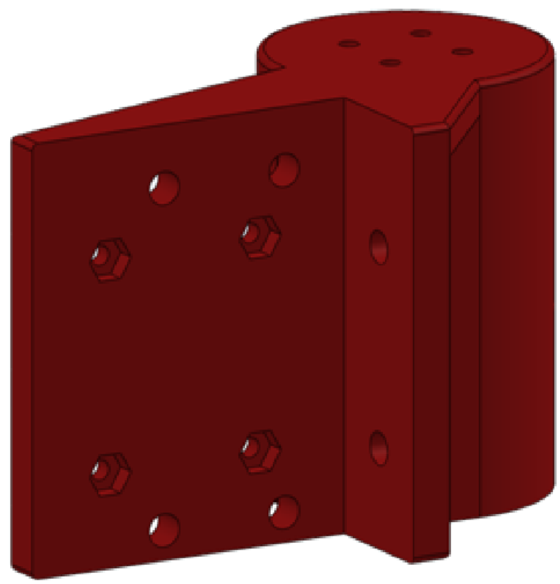


Figure 11: Solid model rendering showing tee joint and screw placement for 4th generation universal tool mount.

Figure 12: Solid model rendering of 4th generation universal tool mount showing mounting holes.

This version of the tool mount was designed with a mounting bracket, which was supported with ribs along the top of the tool mount. These added extra protection from stress concentrations along the common edges between the tool mount and the extrusion arm. The top edges were chamfered to reduce the number of sharp edges and improve user safety. This part was designed to be 3D printed upside-down to reduce the amount of support material required to form its shape.

After printing and preliminary testing, we found that the latch was less effective and bulkier than we originally anticipated. Because of this, we decided to investigate other interface methods. In a moment of sudden clarity during a sponsor meeting, we renewed our interest in using magnets for the tool interface, which our sponsor used to create his own conceptual model over the summer. When we returned to school in the fall, we used his model as a template to create our own version of a magnetic tool mount. This led to our final iteration, which is discussed in Section 4.

3.2. Water and Nutrient Delivery System

Water and Nutrients are obviously an essential aspect of growing plants, so it should be obvious that this was a portion of our project that we wanted to make as ideal as possible. Coincidentally, this also meant that we went through a lot of ideas, figured out how to improve them as much as possible, and scrapped previous ideas when we thought of new ideas that could achieve the objective better. Figure 13 below shows a drawing of one of our early water delivery and nutrient delivery systems, as well as a full assembly of a Farmbot.

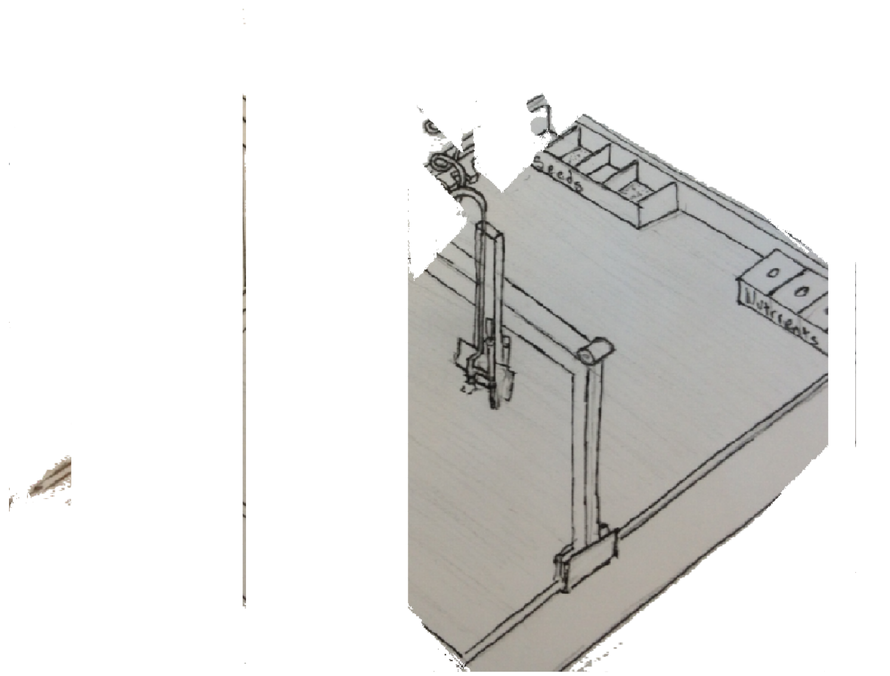
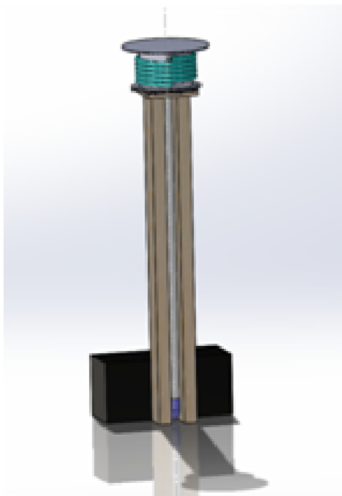


Figure 13: Drawing showing early water delivery design and full assembly.

3.2.1. Water Delivery Concept Development

In our Concept Design Report, we presented an idea for getting water from a gardening hose to the tool head used a retractable hose on top of a tower, which can be seen below in Figure 14. The idea was that the hose could expand or contract however much necessary for wherever the vertical tool arm moved around the plot by turning a coil. This idea was quickly scrapped due to feasibility issues for a modification which featured an expanding coiled hose on a similar tower over the system as shown below in Figure 15. This idea seemed good enough in function, but we eventually scrapped this idea as well due to aesthetics and “coolness” factor.



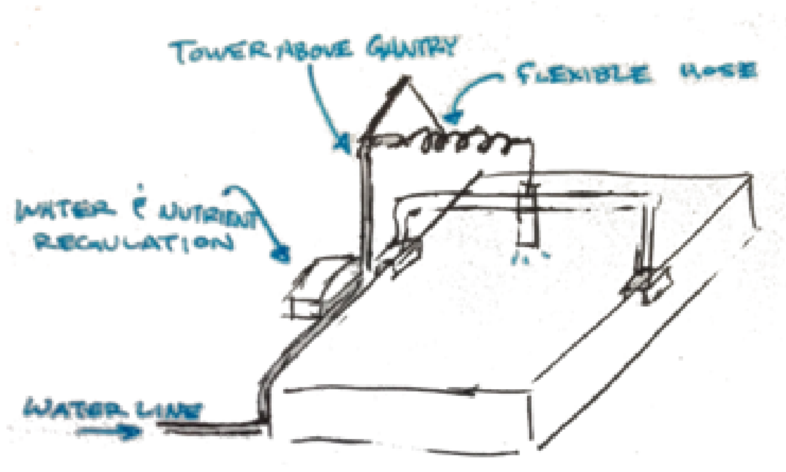


Figure 14: Solidworks model of retractable hose tower design.
Figure 15: Drawing of extendable hose design.

Our next idea, which Rory actually contributed, was a cable trolley system, similar to the one as shown below in Figure 16. Instead of using a fully assembled system, which would have been very costly, we planned to make a 'hacked together' version. This version featured PVC trolleys connected to the hose using zipties, eyebolts, and a pulling cable. We thought that because the machine incorporated this concept better than a huge boom hanging over the top, it better met our customer requirement of "must not look ugly," and the simple design would be easy for customers to manufacture on their own.

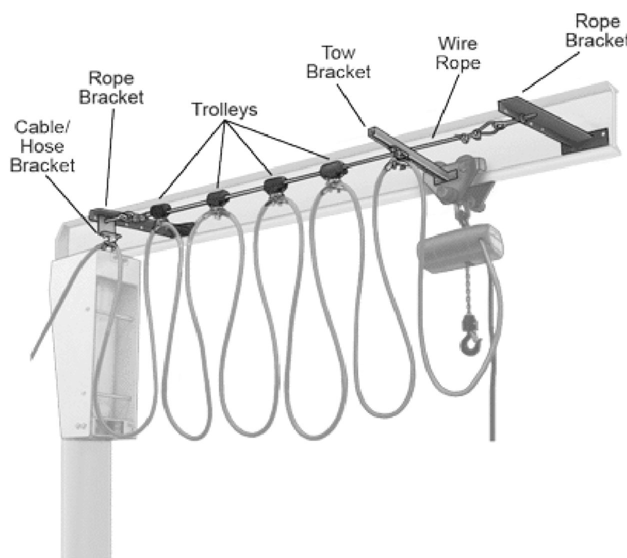


Figure 16: Picture of cable carrier concept from McMaster Carr.

Throughout the course of our brainstorming and design phases, we considered using a cable carrier system similar to those used in CNC machines, but initially ruled it out due to cost. However, Rory discovered a cheaper version of a smaller cable carrier chain, which he purchased and tested independently. After discussing more with him, we decided to pursue this as the final solution for holding the tubes that transport fluids to the tool mount. A picture of the cable carrier chain we opted to use can be seen below in Figure 17.

Figure 17: Picture of the cable carrier product used to house tubing and wires.
3.2.2. Nutrient Mixing Concept Development

3.2.2. Nutrient Mixing Concept Development

Different plants require different ratios of Nitrate, Phosphate, and Potassium to grow optimally. In order to feed our plants essential nutrients, we needed to develop a method of delivering custom nutrient mixtures to each individual plant.

The development of our final design for nutrient mixing was just as dynamic of a process as our other systems. At the beginning of our project, our design featured a peristaltic pump that would draw precise amounts of different concentrated fertilizers from a row of reservoirs to mix back into the water stream to feed the plants. We were convinced that there was a better, cheaper solution to perform the same function, which eventually led us to the idea of using a syringe pump.

Figure 18: Drawing of peristaltic pump concept.

The first issue with the development of the syringe pump was to determine how to automate vertical motion for the syringe stopper. We noticed that a lead screw sufficiently performed vertical motion on the tool arm of Farmbot, so we decided to implement the idea on a smaller scale into our syringe pump. Our first syringe pump design, shown in Figure 19, featured a collar for the lead screw, which protruded from the side of the top of the plunger.The end of the lead screw would then fit into an extended flange at the top of the syringe barrel. We figured that this piece would be hard to manufacture and attach to the syringe, and that the lead screw would create a moment that would not pull the plunger effectively.

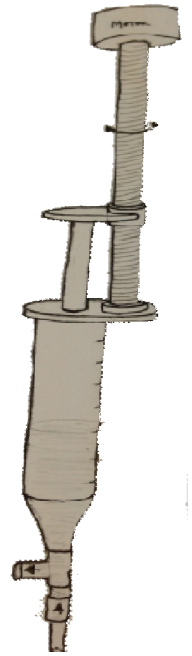


Figure 19: Drawing of original syringe pump concept.

The next syringe pump design incorporated the lead screw collar directly into the end of the plunger, which can be seen below in Figure 20. With this design, the lead screw motion was directly in line with the motion of the syringe plunger, but once again this concept would have required complicated custom parts in order to work, and so we opted for a simpler design.

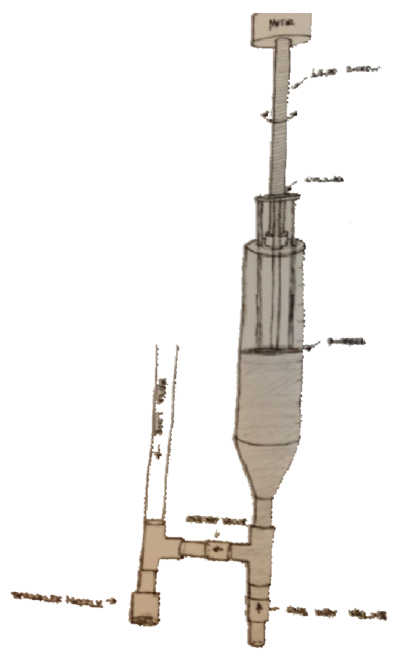


Figure 20: Drawing of second syringe pump concept.

Our third design of the syringe pump was a drastic improvement, and was inspired by interacting with real-life syringes. This idea used an adapting cap on the top of the plunger, which fit around the lead screw. The electric motor we chose had a lead screw that traveled through the motor, eliminating the

need for a riding collar attachment on the syringe. This iteration also featured two one way valves: one at the junction of the syringe pump and watering hose, and one at the syringe pump tip. These prevented air from being drawn from the water nozzle into the syringe, and prevented nutrients from being sprayed out of the syringe pump tip.

Our fourth and final design as of our critical design report can be seen below in Figure 21. It featured a 20 mL syringe, electric motor/ lead screw assembly, pull cap adapter, one way valve, and some tubing. The best part of this concept was the simplicity and feasible for anyone to make a similar version. The syringe pump was connected to a main water line with standard garden hose pressure. A solenoid valve was used just before the junction shown below to regulate the stream of the water.

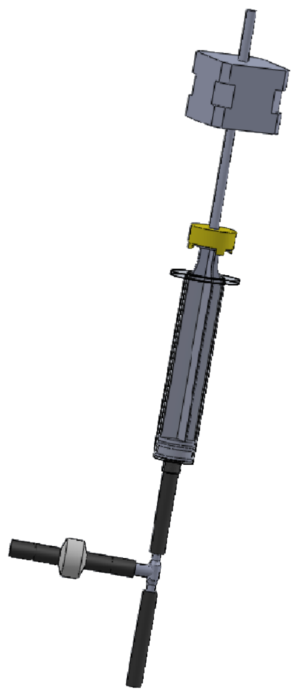


Figure 21: Old complete syringe pump design.

The 20mL plastic syringe was used because we found a fertilizer company, Urban Farms, that sold assorted concentrated fertilizers with a mixing ratio with water of 256:1. With this mixing ratio, a single syringe-full of concentrated solution would mix with water to produce 5.12 liters of nutrient-water mixture. We decided this was a sufficient amount to give Farmbot the ability to feed an entire gardening plot without having to stop to refill the syringe. The total travel of the syringe plunger from empty to full was 7 centimeters.

The electric motor used in our design was a 12 volt stepper motor with an integrated lead screw, which was found on Sparkfun.com. The lead screw had a total length of 10 cm, making it a perfect fit for our syringe. Each step was calibrated to move the lead screw 0.01 millimeters, which allowed for accuracy when measuring nutrients. The end of the lead screw was keyed, so we used a set screw to attach our syringe pull cap and hold it in place. Figures 22 and 23 below show pictures of our chosen motor and the keyed end of the lead screw. This lead screw was also used in our final iteration of the syringe pump design.

Figure 22 (left): Picture showing keyed end of lead screw.
Figure 23: Picture of lead-screw stepper motor from Sparkfun Electronics.

The only part that was not purchased off the shelf for this syringe pump design was the pull cap adapter, which can be seen below in Figure 24. We 3D printed this part at the SLO Maker's Space. It was designed to snap onto the end of the syringe plunger, with the lead screw fitting into the hole on the top. The hole on the side of the part allowed for a set screw to secure the keyed end of the lead screw in place. The 3D printed tabs proved too weak for our purpose, and snapped off immediately when we tried to fit the cap on to the top of the plunger. This led us to create a different version for our final design, which will be discussed in Section 4.

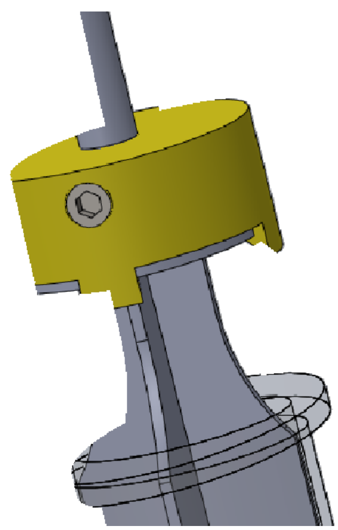


Figure 24: Solidworks model showing pull cap design.

The nozzle of the syringe easily fit ⅜ inch vinyl tubing, which we were able to find locally at a hardware store. We originally planned on using ¼ inch hose throughout our design process because it was standard size. We were also able to find properly sized one way valves to prevent flow in the wrong direction up the hose, as well as a tee-joint designed for ¼ inch hose on one branch, and 8 millimeter tubing on the other branches. Except for the tubing, all of these components were scrapped in our final design, which will be discussed in further detail in Section 4.

3.3. Seeding Tool

As part of the project objectives, we had to develop a system to deliver and plant seeds to a specific location. It had to be an independent tool that interfaced with the universal tool mount. Because of the ambiguity of this problem, we brainstormed many different concepts before determining our final design.

3.3.1. Seeding Tool Concept Development

Most of our initial concepts consisted of modified versions of the designs found from the background information. Two of our first designs used modified versions of the Precision English Seeder seen in Figure 25. Our options were to have the seeder suck and hold a seed using suction or to feed seeds through the seeder when the desired location was reached. In any case, there had to be a separate component on the seeder system in order to achieve its function. These two designs can be seen in Figure 26.

Figure 25: Precision English Seeder used for initial ideation of seed delivery tool

Another design was a scaled down version of the Syringe-Powered Universal Gripper that would be mountable to the gantry system. Essentially, a servo motor would be attached to the end of a syringe, which would be attached to a membrane similar to a balloon with coffee grounds in it. The idea is that the servo pulls on the syringe, sucking up air and causing a vacuum. The vacuum then would then cause the membrane with coffee grounds to tighten, forming around whatever the membrane was trying to pick up. In our case the item to be picked up would be a seed. Finally, another idea we explored was the Stand-and-Plant seeder, which was mentioned in the background section.

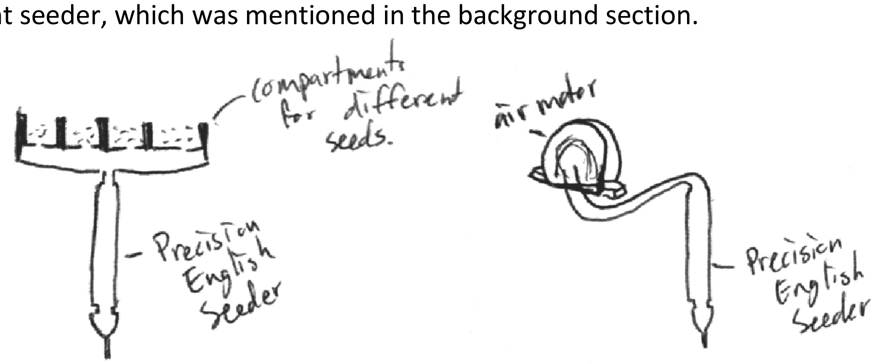


Figure 26: Initial concepts that used a modified Precision English Seeder

In order to determine the proof of concept of many of our designs, we investigated videos and other research. The most notable was the Syringe Powered Universal Gripper, which had videos describing the

proof of concept through a functional prototype. In order to determine if the air seed injector would work, our sponsor Rory bought a vacuum air pump from Sparkfun, and built a very simple prototype. He created a 3D printed seed tip to attach to the vacuum pump, and managed to pick up a small rock by using only the inward air flow.

After boiling down our ideas to the most feasible, we started to analyze how each concept compared to each other by using Pugh Matrices. The first iteration of the Pugh Matrix confirmed our initial thoughts of which designs would be better. We set a datum of the seed injector with compartments, because we thought that it would be a fairly common concept in agriculture. After the first iteration, we eliminated the concept that did the worst, and combined two concepts to create a new one. Additionally, we found one more mechanism that we decided to consider as well. After the second iteration, we found that our top concepts involved either a modification of a seed injector, or the Stand & Plant mechanism. However, we eventually scrapped the idea due to its lack of feasibility. These Pugh Matrices can be seen in Appendix A.

Our next step was to put our top concepts into a decision matrix. Our two highest weighting factors were cost and precision, followed by versatility and weather resistance. This Decision Matrix can be seen in Appendix A. After weighing all the factors, there was no clear winning concept. However, we did note that one concept was better for small seeds, while the other was better for larger seedlings or bulbs. At this point we decided to go with the Air Seed Injector for small seeds. While we wanted to implement the Stand & Plant Seeder for larger bulbs, Rory recommended focusing on creating a single tool for planting small seeds. This allowed us to focus on developing the first quality tool for Farmbot.

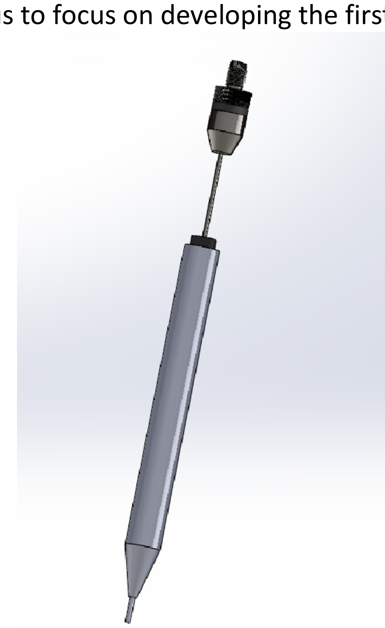


Figure 27: Preliminary design for seeding mechanism from the Concept Design Report

Our first design for the Air Seed Injector can be seen above in Figure 27. As seen, the seeder itself is modeled off of the bottom portion of a Precision English Seeder. A rubber stopper is fitted at the top in order for a ball needle to stay in. The rubber stopper would create a seal around the air needle so that air would not escape. The top of the needle would be connected to a tube, which would be connected to an air pump that created suction. The whole mechanism would move to a bay of seeds, and be able to pick up an individual seed by sucking air and holding on to the seed at the tip. The seed injector would

then move to the desired position, force the seed into the ground, and release the air pressure. The ball needle was designed to fit into the first iteration of the Universal Tool Mount seen in Figure 3.

After determining our concept design, we met with Rory to reiterate and improve upon our design. The first suggestion Rory gave us was to separate the air supply from the gantry system. Since seeding is merely an occassional job, there was no reason to have a semi-constant air supply. By removing the air supply from the seeding tool itself, the gantry would be less heavy and more mobile. He also already had an idea for the type of air supply needed: a Sparkfun vacuum pump that ran on 12 volts. This pump would supply enough air flow to be able to suck and hold a seed on the seeding tool tip.

Using Rory's suggestions, we developed a new design. We originally looked into modifying the direction of flow of an aquarium air pump. We saw many resources online that showed modifiable aquarium air pumps. After buying a few aquarium air pumps and opening them up to determine the feasibility, we realized that these air pumps were designed to only have air flow outwards. The cost to buy the correct air pump, as well as the time required to modify it was more than just buying a vacuum pump. We also looked into finding cheaper and smaller vacuum pumps than the one Rory had been using, yet they all came from what we judged to be questionable overseas suppliers.

We opted to use the 12 volt vacuum pump from Sparkfun. In order to determine whether or not this vacuum pump was sufficient to pick up a single seed, we did a very quick pressure and flow analysis. Table 2 summarizes the results for a 4mm diameter seed, where 1000 seeds weigh 6 grams.

Table 2: Flow analysis summary of requirement to pick up 4mm diameter seed.

Weight/seed	5.89E-5 N
Area of seed	1.26E-6 m^2
ΔP needed (Statics)	4.6839 Pa = 6.79E-4 psi = 0.00138 in Hg
Velocity of air needed (Bernoulli's)	2.7893 m/s
Area of nozzle (3mm diameter)	7.07E-6 m^2
Flow needed	1.97E-5 m^3/s = 1.1830 LPM

Using concepts learned in Statics, we calculated the pressure needed to keep the seed in static equilibrium. We then used Bernoulli's equation to determine the velocity of the air. Assuming the diameter of the seeder nozzle was 1 mm less than that of the seed, we were able to calculate the flow needed to pick up an above-average sized seed. Based on this, we were able to determine that this was more than feasible, especially with Sparkfun pump Rory recommended. Once we determined the pump would work, we were able to design all other aspects of the seeder around it.
The design of our seeding tool presented in our Critical Design Report was an iteration of our conceptual design. The seeding tool attached to the universal tool shaft through a coupling, allowing it to connect easily to the Universal Tool Mount.

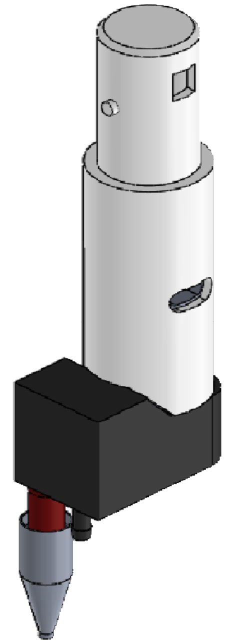



Figure 28 (left): Picture of the 12V vacuum pump.
Figure 29 (right): Assembly model of the full seeding mechanism/tool with the tool shaft attached.

The motor for the vacuum pump was housed inside the coupling, which connected the pump to the tool shaft. The metal tip for seeding fit right over the inlet of the vacuum pump, and was interchangeable. Two magnets allowed the seed tip to stay onto the pump, without it coming off during use. A picture of the motor we used can be seen in the figure above and to the left. We planned to take off the metal sleeve from the motor, as well as rotate the inlet-outlet cap 180 degrees in order to obtain the orientation as seen in the solid model on the right.

The vacuum pump was rated at 12 volts, just like the solenoid actuator we had originally planned to use. Additionally, the maximum allowed flow was up to 15 liters per minute. As seen from our preliminary analysis, a general seed would only need about 1.18 liters per minute of flow in order to be picked up using suction. Also, the vacuum created from the pump was about 16 inches of mercury, while the rated pressure was 16 psi. From our analysis, we concluded that the pressure differential plenty strong to lift seeds of different sizes.

The vacuum pump used a custom coupling to fit with the universal tool shaft. The motor from the vacuum pump fit inside the coupling, and was to be glued securely. Holes were designed into the sides of the coupling to allow for motor ventilation. A gap inside the tool shaft allowed space for the electrical contacts. This system is seen below in Figure 30. We designed the coupling and tool shaft to either be 3D printed or manufactured with off-the-shelf PVC parts. The tool shaft had 1 inch PVC pipe dimensions, while the coupling had 1 inch PVC coupling dimensions so that anybody could buy the standard material and create their own tool shaft and coupling. By buying the off-the shelf parts, cost could be reduced in terms of manufacturing and prototyping. The parts were also designed to be easily 3D printed.

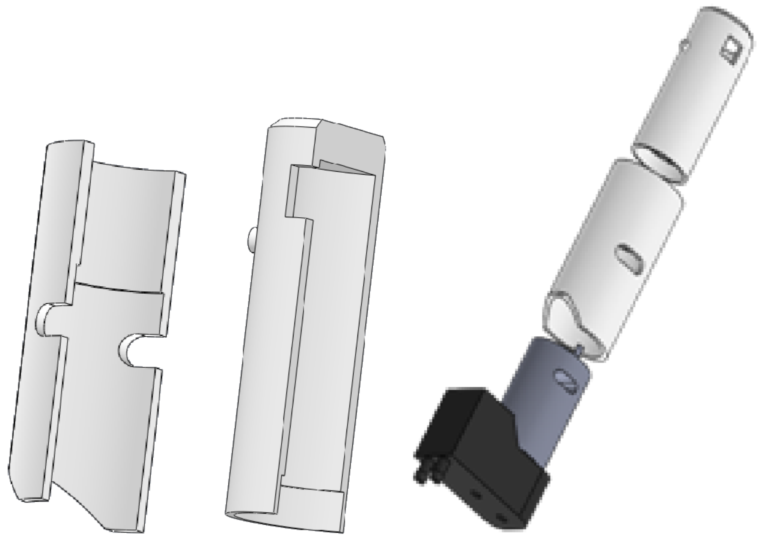


Figure 30: Renderings showing vacuum pump to tool shaft interface.

One of the key features of this seeding tool was that it used interchangeable tips. In order to achieve this, a few different tips with different cross sectional inlets would be made that could detach from the seeding tool. The mechanism is shown below.

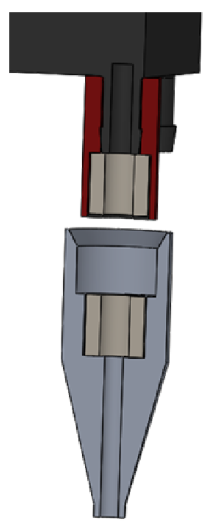


Figure 31: Cross sectional view of the seeder tip and coupling system.

A plastic seed tip coupling (seen in red) was designed to attach to the inlet nozzle, and was to be secured using the same glue as the universal tool shaft coupling. A ring magnet was to be attached at the inlet, with a thin polyurethane gasket glued on top of the magnet in order to create an air-tight seal between the interfacing magnets. Another ring magnet would sit securely inside the interchangeable tip in order to interface and connect to the inlet of the vacuum pump. The chamfer inside the interchangeable tip would guide the vacuum pump inlet nozzle into the tip. In order to take off the tip, flanges were to be added to the sides of the design. The flanges would allow the tip to remain stationary on the tool rack while the Farmbot arm lifted up. An exploded view of the different components included in the seeder tip can be seen below. All of the custom parts could have been easily manufactured using a lathe or 3D printing.

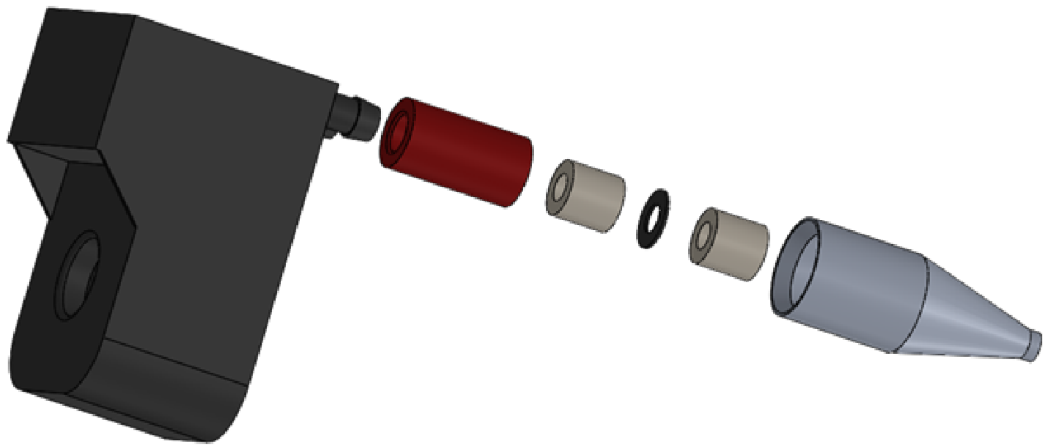


Figure 32: Exploded view of the seeder tip and coupling system.

After showing Rory this design, he expressed concern that the vacuum pump would draw in dust particles and potentially clog it, so he wanted us to incorporate some form of intermediary chamber between the pump inlet and the seeder tip. This would be similar to a vacuum cleaner, where the intermediary chamber allows dust to stay in the chamber without continuing into the rest of the piping system. However, our final iteration of the tool mount required us to completely redesign the seeding tool. In order to incorporate the new tool base design with the idea of an intermediary chamber to prevent dust build-up, we designed a big cone seeding tool, which can be seen in Figure 33 below. This tool was meant to interface with the final tool mount design, which is detailed in section 4.

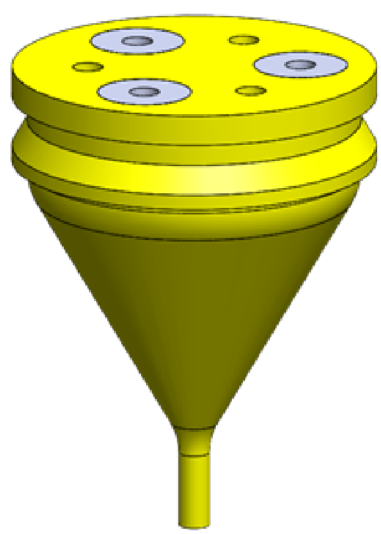


Figure 33: Solidworks rendering of our big cone seeding tool.

While the large cone prevented dirt build-up in the pump, it also created too many pressure losses, which proved to be ineffective in picking up seeds. From an analytical standpoint, we expected small pressure losses due to the change in internal cross sectional area within the seeding tool, yet we did not expect the pressure losses to be as significant as they turned out to be. Another issue with this design was the long narrow tip, which not only printed poorly with the low-resolution 3D printer, but also

broke easily. Each of these issues were addressed as we came to our final design, which is discussed in Section 4.

This tool was also meant to be used as a mixing chamber for nutrients and water. However, we quickly realized that this tool would not work for nutrient mixing because of two main reasons. The first was the significant pressure loss from the large change in internal area, which had similar effects as mentioned above. The second was as the syringe pump would try to draw nutrients, it would draw air from the vacuum pump instead. This was due to the fact that the least resistive fluid would be drawn, which in this case would be air. This led us to re-isolate the seeding tool from the nutrient mixing function.

4. Final Design Details and Analysis

As we finalized the designs for each system, we added them to an aluminum extrusion identical to those used on Farmbot to test their compatibility with each other and their functionality. This led us to create a testing apparatus that included all of our functions, which can be seen below in Figure 34.

Figure 34: Picture of our full testing apparatus.

The testing apparatus consisted of all of our functions attached to an aluminum extrusion for easy testing. The universal tool mount can be seen in yellow with the Farmbot sticker. The water, nutrient, and air lines connect directly into 3D printed barbs in the tool mount. The nutrient syringe pump was placed above the tool mount to facilitate the nutrient line connection. The stepper motor was attached directly above the syringe pump, with the lead screw interfacing onto the syringe pull cap. The vacuum pump and water lines were arbitrarily attached to the sides of the extrusion in order keep all the functions on one easily-tested system.

4.1. Final Design for the Universal Tool Mount System

The final design of the tool mount incorporated some aspects of our previous design, but completely changed interface method between the tool mount and the tool. Additional features were added to simplify our three different function into one tool. Because of the drastic change in shape and interface method, we also steered away from the tool shaft. Instead, we opted to create a tool base that would be used to create a tool. A real picture, as well as a Solidworks rendering can be seen below in Fiugres 35 and 36, respectively. The detailed drawings of both these parts can be seen in Appendix B.

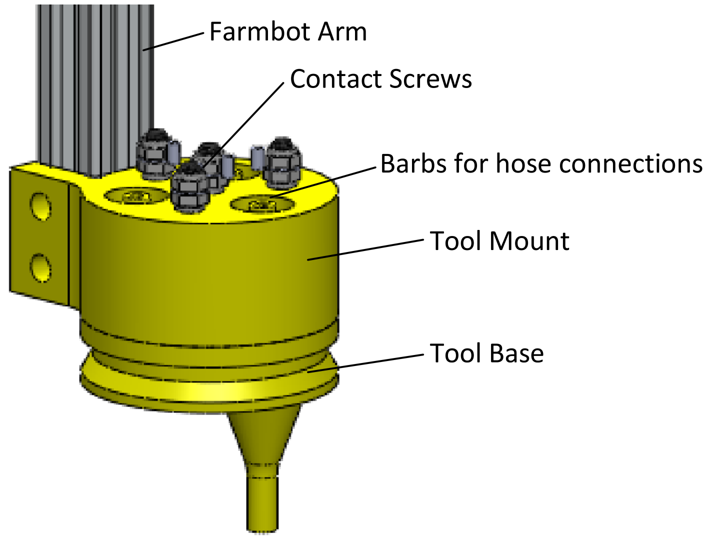


Figure 35 (left): Picture of our final universal tool mount next to a sweet pea seed (left) and a squash seed (right).
Figure 36 (right): Solidworks rendering of universal tool mount with seeding tip attached.

4.1.1. Universal Tool Mount

The final design for the universal tool mount was a cylindrical housing that incorporated all of the functions of our scope into one design. Three holes with barbs served as passageways for air, water, and liquid nutrients to the tools, with a counterbore on the other side of each hole to accommodate a ring magnet. The tool mount attached to the aluminum extrusion by use of the side bracket and two M5 screws, similarly to our previous design. Additionally, the concept of creating four through-holes to allow for the use of four screws as electrical and data contacts was kept. This design can be seen below in Figures 37 and 38.

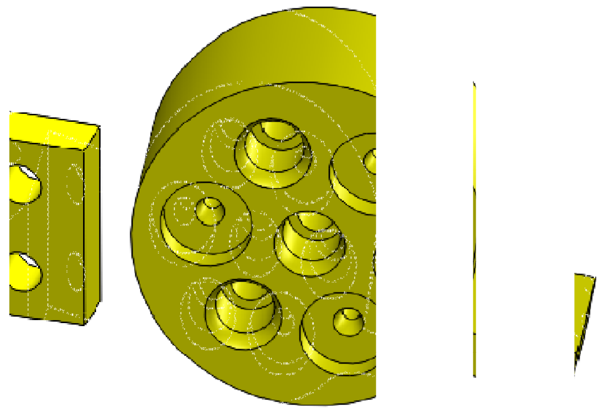


Figure 37: Solidworks rendering showing the top of the universal tool mount with tube barbs exposed.
Figure 38: Solidworks rendering showing the bottom of the universal tool mount exposing the magnet holes.

Each fluid passageway incorporated a barb built into the model in order to attach the various different lines of fluid easily. The idea was that each hole would interface with another hole on the tool base to perform the desired function. We assigned each barb a function as follows: the two passageways closest to the side bracket were to be used for water and nutrients; the passageway to the left of those were to be used for air. After assigning a function to each barb, we attached the water, nutrient, and air lines, which consisted of ⅜ inch nominal diameter tubing.

The ring magnets were glued into the counterbored holes on the bottom of the tool mount using plastic epoxy. The magnetic polarities were arranged in a pseudo-alternating fashion, according to the previously defined function of each barb. The magnets corresponding to the water and nutrient passageways were epoxied with positive polarity facing out, while the magnet corresponding to the air passageway was aligned with negative polarity facing out. This allowed for the proper alignment of each tool with their respective passageways.

Finally, we attached the contact screws very similarly to the previous design. However, we increased the size of the screws and added a nut to each contact screw in order to lock a ring terminal onto the screws for future use. On the inside of the tool mount, larger diameter springs were used to help push out the too base.

4.1.2. Universal Tool Base

Since our final tool mount design was completely different than the previous iteration, we scrapped the idea for a tool shaft, and instead created a tool base as the foundation of the tools. The tool base we created was specifically designed for the seeding tool and the nutrient mixing tool, and can be seen in Figure 39.

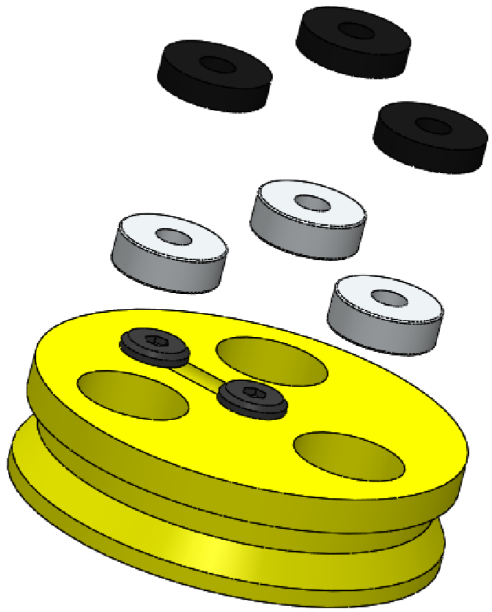


Figure 39: Solidworks rendering show the tool base.

Three counterbored holes, served as connections to the passageways, allowing for easy transfer of liquids or air. Glued into these holes were magnets with the opposite orientations from those mentioned in section 4.1.1 for the tool mount. This allowed for the proper alignment of each tool, and assured us that the tool base would connect to the tool mount. We glued a 4mm thick rubber washer on top of each magnet in order to help create a better seal between the tool base and tool holder interface. This also reduced the magnetic attraction between the base and the mount, allowing the base to be easily removed. For our two tools, we only needed two electrical contacts, which were connected to each other anyways. Thus, we created two holes that would allow the two contact screws to align with the tool mount.

4.1.3. Universal Tool Mount and Tool Base Interface

As mentioned before, the interface between the universal tool mount and the tool base was purely magnetic. A total of 6 magnets were used, and were orientated in such a way that the tool base could only attach to the tool mount in a single orientation. As seen below in Figure 40, the two contact screws on the tool base align exactly with the contact screws on the tool mount. The contact screws move up so that the top face of the tool base mates with the bottom face of the tool mount, allowing the black rubber washers to create a seal to transfer water, nutrients, or air.

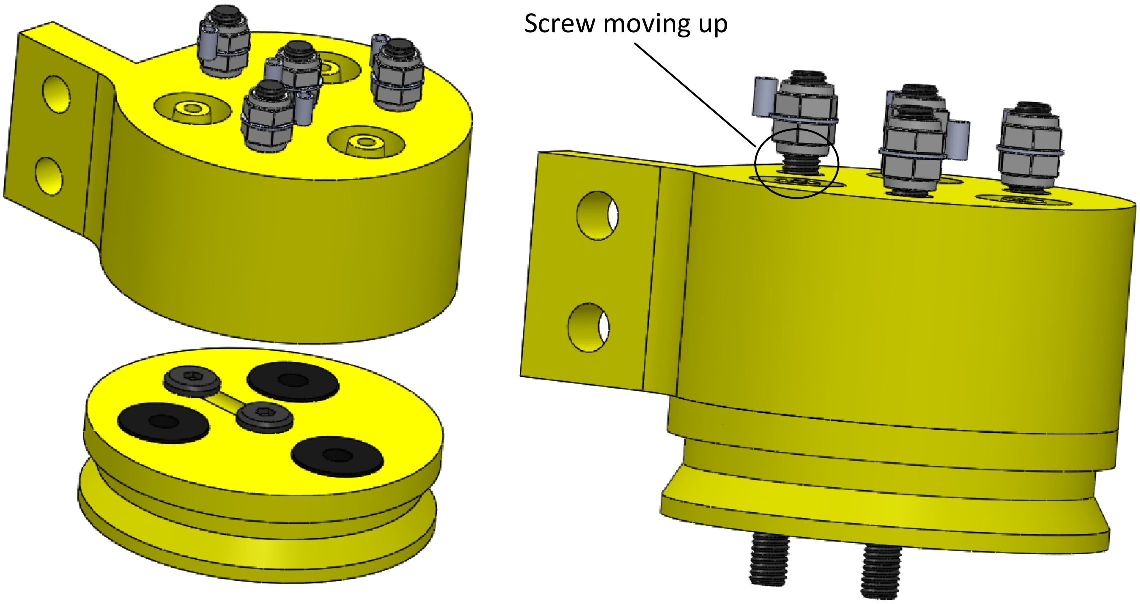


Figure 40: Solidworks renderings showing the magnetic interaction between the tool mount and tool base.

4.1.4. Parts Vendors and Cost Analysis

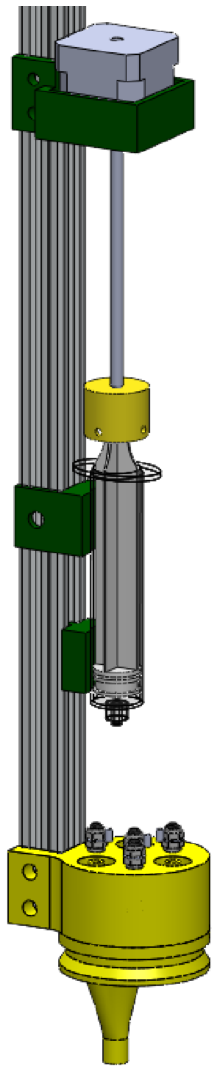
Our final tool mount also incorporated the contact screws developed in previous iterations. The screws within the tool mount were oriented with the head facing down and a combination of hex nuts and ring terminals on the threaded portion of the screw prevented them from falling out of the holes. The contact screws also kept the compression springs from the previous design to ensure that the electrical contact screws on the tool mount and the tools maintain physical contact. Table 3 summarizes the overall cost of the universal tool mount only.

Table 3: Breakdown of costs for universal tool mount.

Description	**Quantity**	**Cost**
Tool Mount	4.33 in^3	3D Printed ($7.28/$in^3$) = $31.52
Electrical Contact Screws (M5x25mm)	4	$0.96
M5 Hex Nuts	8	$0.32
Ring terminals	4	Provided by sponsor
M5 Mounting Screw	2	$0.48
	Total:	$1.76 + 3D Printing = $33.28

4.2. Watering and Nutrient Mixing System

The watering system consisted of a solenoid valve, a series of reducer couplings and adapters, a series of connecting tubes, and the universal tool mount with the the water and nutrient mixing tip. A standard garden hose was connected directly to the solenoid valve through a female to female threaded adapter. A barbed adapter attached to the solenoid valve allowed for the connection of a ⅝” vinyl tube. Using a series of barbed reducer couplings, the diameter of the vinyl tubes were reduced from ⅝” to ½” to ⅜”. The ⅜” tube connected to the water line barb on the universal tool mount. The syringe pump was connected to the nutrient line barb on the tool mount via a short ⅜” tube, and attached directly above it on the aluminum extrusion. A rendering of the full system without the connecting tubes can be seen below in Figure 41. Below on the right, a rendering of the watering and nutrient mixing tip can be seen in Figure 42.



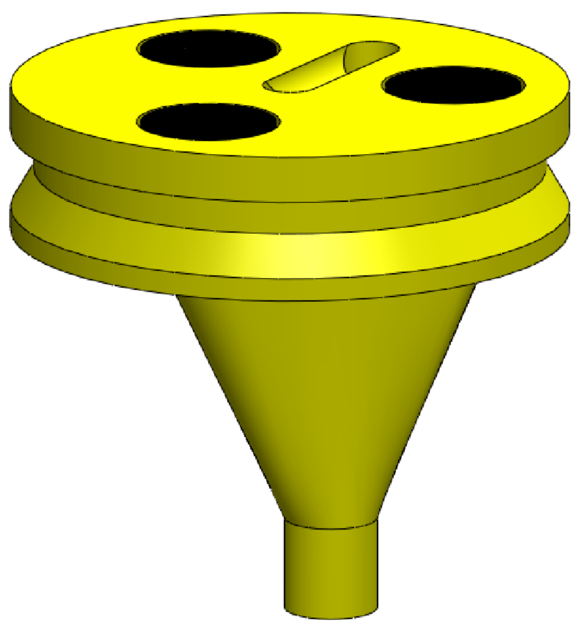


Figure 41 (left): Solidworks rendering of full watering and nutrient mixing testing apparatus.
Figure 42 (right): Solidworks rendering of the nutrient mixing tool.

4.2.1. Nutrient Mixing

The nutrient mixing function was incorporated into the interchangeable tool by combining the streams from the water line and from the syringe. A cross-sectional rendering of our nutrient mixing tool, showing the combination of the two streams, can be seen below in Figure 43. The orientation of the magnets glued into the counterbored holes of the nutrient mixing tip would only allow for the water and nutrient passageways on the tool mount to be aligned with each of the branches of the Y-channel on the mixing tool. The counterbored holes were also deeper in order allow room for the 4mm thick rubber washers.

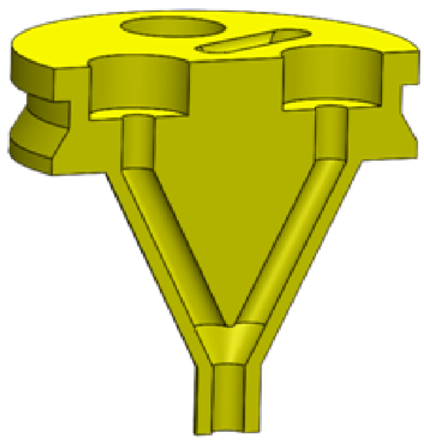


Figure 43: Solidworks rendering showing a cross section of the nutrient mixing tip.

This design was ultimately implemented in order to eliminate the use of t-joints and one-way check valves. One of the holes led to the nutrient pump, while the other led to the water supply. A solenoid valve was attached at the entrance of the water supply, which prevented air from being drawn by the nutrient pump when the valve was closed.

4.2.2. Syringe Cap

The syringe cap was also modified a few times to fix issues we encountered with previous versions. First, we replaced the tabs for a lip with holes for screws. We used four M3x5mm screws to hold the cap onto the top of the plunger. We also eventually made the screw hole lip thicker after we encountered a problem where the 3D printed layers were pulled apart by the axial force of the motor. A picture of the final syringe cap being attached to the top of a syringe plunger can be seen below in Figure 44.

Figure 44: Picture showing assembly of the syringe cap to the top of the syringe plunger.

4.2.3. Stepper Motor Bracket

The stepper motor for the syringe was attached to the aluminum extrusion with a 3D printed bracket, which was designed so that the lead screw aligned directly with the center of the syringe cap. The bracket included four holes that matched the mounting holes on the stepper motor, and we used M3x8mm screws to secure the motor and bracket together. The bracket attached to the extrusion using two M5 screws, similar to how the universal tool mount was attached to the extrusion. A picture of the stepper motor bracket being secured to the extrusion can be seen below in Figure 45.

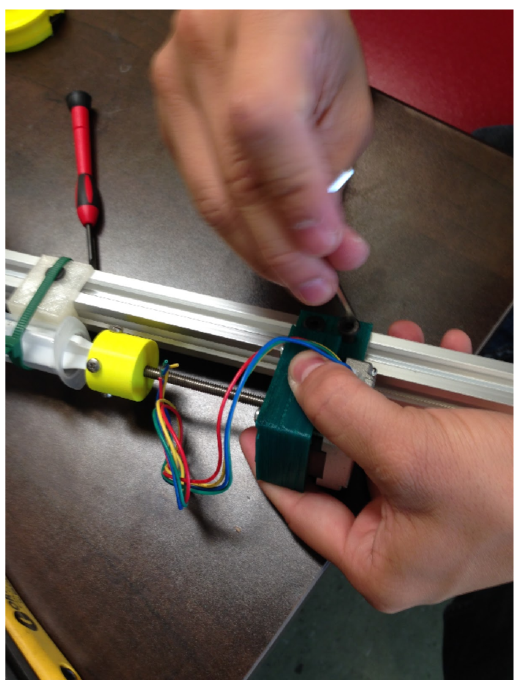


Figure 45: Picture showing assembly of the stepper motor to the aluminum extrusion.

4.2.4. Description of Operation

When the water and nutrient mixing tool is connected to the tool mount, the nozzle of the tool leads to both the nutrient and water passageways, which are connected to their respective lines. When the nozzle is placed in a reservoir of liquid nutrients, the stepper motor retracts the lead screw and pulls the syringe plunger up. This creates suction and fills the syringe with the liquid nutrient solution. If required, the user is then also able to read the mount of nutrients drawn by the syringe in mL. Because the solenoid valve at the beginning of the watering system is kept closed during the acquisition of nutrients, the liquid concentrated nutrients are the only fluid drawn into the syringe. Nutrients are dispensed when the stepper motor runs in the opposite direction to push the plunger into the syringe to expel the nutrients. This is intended to occur while the water is flowing at a calibrated flowrate for the proper mixing ratio.

4.2.5. Cost Analysis for the Watering and Nutrient Mixing System

Table 4 below shows a breakdown of the costs associated directly with the Mixing System:

Table 4: Breakdown of Costs for Water and Nutrient Mixing System.

Description	**Quantity**	**Cost**
Water/ Nutrient Mixing Tool	2.32 in^3	3D Printed ($7.28 /$in^3$) = $16.89
Contact Screws (M5x10mm)	2	$0.32
Vinyl Tubing	3 ft	$1.80
Stepper Motor	1	$17.22
Motor and Syringe Brackets	1	3D Printed by Sponsor
Stepper Motor Screws (M3x8mm)	4	$0.32
Syringe	1	$0.64
Solenoid Valve	1	$7.95
Zip-ties	3	$0.30
Syringe Cap	0.485 in^3	3D Printed ($7.28 /$in^3$) = $3.53
Misc. tube couplings & adapters	4	$4.53
Syringe cap screws (M3x4mm)	4	$0.28
Ring magnets	3	$1.62
Rubber washers	3	$1.83
	Total:	32.72 + 3D Printing = $57.23

4.3. Final Design for the Seeding Tool

The seeding tool is similar to the nutrient mixing tool, except that it only uses a single air line. As with the watering tip, the holes for the magnets are extra deep to allow space for rubber washers, which decrease the strength of the attraction between magnets and create a tighter seal for fluid flow. The orientation of the magnets glued into the counterbored holes of the seeding tool would only allow for the air passageway on the tool mount to be aligned with the seeding tool tip hole. The size of the cone was greatly reduced, which decreased pressure losses within the cone, and facilitated picking up seeds. The seeding tip is connected to the vacuum pump with a ⅜" vinyl tube attached to the designated barb on the tool mount. We used the same vacuum pump as the one described in the Design Development section, as it performed wonderfully. A rendering of the seeding tool can be seen in Figure 46 below. The seeding tool is assembled exactly like the mixing tool. Additionally, a cost summary for the seeding tool can be seen in Table 5 below.

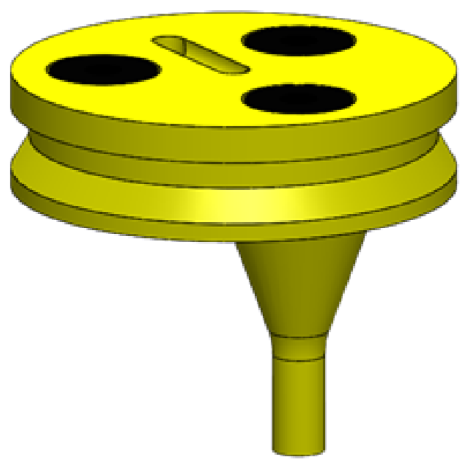


Figure 46: Solidworks rendering of the seeding tool.

Table 5: Breakdown of Costs for Seeding Tool

Description	Quantity	Cost
Seeding Tool	2.08 in^3	3D Printed ($7.28/$in^3$) = $15.14
Contact Screws (M5x10mm)	2	$0.32
Ring magnets	3	$1.62
Rubber washers	3	$1.83
Vinyl Tubing	2 ft	$1.20
Air Vacuum Pump	1	$14.95
	Total:	$19.92 + 3D Printing = $35.06

5. Product Realization

Just like our design process, we went through an iterative process on our product realization. Initially, we were having our custom-designed parts 3D printed at the SLO Makerspace with a Makerfarm 8" Prusa 13V PLA built from a kit, which can be seen below in Figure 47. Although this printer was extremely convenient for us to use, the parts it produced were pretty poor resolution, and we were required to use a dremel to remove unwanted support material, which was the same PLA as used on the actual parts. In what turned out to be incredibly convenient timing, this machine broke, which led us to using the 3D printer available through the Mechanical Engineering department, a Stratasys 1200es, shown below in Figure 48. This printer used ABS plastic and dissolvable support material.

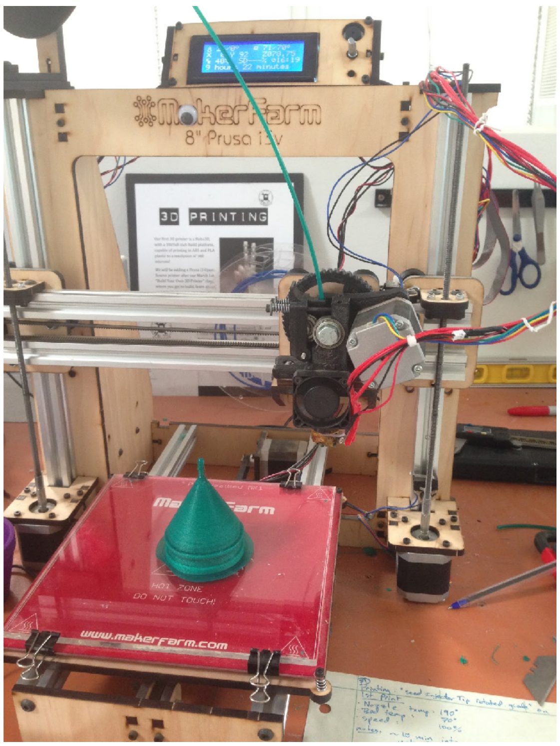


Figure 47: Picture of the Makerfarm Prusa 3D printer. (Left)
Figure 48: Picture of the Stratasys 3D printer. (Right)

While this process required more paperwork, the printer performed spectacularly, and we were very pleased with the final product. Each of the parts were printed solidly with resolution so fine it was nearly impossible to see, and they were even sturdy enough to handle a few unintentional drops onto hard surfaces. Pictures of the parts produced by the Makerfarm 3D printer and the Stratasys 3D printer can be seen below in Figures 49 and 50.


Figure 49 (left): Parts produced by the Makerfarm Prusa 3D printer.
Figure 50 (right): Parts produced by the Stratasys 3D printer

Keeping assembly simple was a key goal for us. For the assembly of our testing apparatus, we used a combination of plastic epoxy, screws, and zip-ties. We had previously tried other adhesive methods to hold the magnets on to the parts, but each failed until we resorted to the plastic epoxy. The screws, brackets and zip-ties performed their respective applications as expected.

In the fast moving, iterative fashion of this project, there have already been new versions of the parts we've designed produced, using what we learned from our designs. The later tool-holder features screwed-in stainless steel hose barbs, screwed in magnets, and chamfered holes for the tool tips. The latest tool tips have chamfered male-end connections to the tool-holder, which help guide the tool into alignment. The connections also feature removable o-rings for creating seals for passing fluids.

6. Design Verification and Testing

Most of our tests were functional tests. Because of how easily we were able to have early prototypes of our tool mount and seeder tips 3D printed, testing started at the same time as manufacturing. Later, the water and nutrient mixing system became a 3D printed part, which once again allowed for functional testing to be performed as soon as the part was printed and assembled. A testing apparatus was created from all of our functions in order to complete the final functional and flow tests, which can be seen in Figure 51.

Figure 51: Picture of full testing apparatus with nutrient mixing tool attached.

6.1. Tool Mount Testing and Results

The interaction between the tool mount and the basic tool was tested throughout our iterations. However, we did not test the picking up, holding, and releasing of the tools until the final iteration. Because the Tool Mount 5.0 used magnets to hold the tool, it was easy to test its functionality.
To test picking up tools, we held the seeder tool vertically so that the magnets were facing up. We then manually moved the testing apparatus towards the seeder tool until the magnets were attracted to each other and the tool attached to the tool mount. We tested picking up the tools with different magnet orientations, and with and without the electrical contact screws. The first pick-up test trials were done with a magnet-on-magnet interface and without the electrical contact screws. All tests passed during this iteration. Then, we added the electrical contact screws, which proved to be problematic when trying to align the magnets between the tool and the tool mount. The problem here was that the magnets on the tool were also attracted to the screws, which made alignment much more difficult. At one point, we replaced the magnets with metal washers, because the magnet-on-magnet attraction was excessively strong. Unfortunately, the magnetic attraction between the magnets and washers was not sufficient to grab and hold the tool with the opposing force of the springs from the electrical contact screws. After that, we switched back to a magnet-on-magnet interface, with at least one magnet facing the opposite direction. This proved to be effective in aligning the tool correctly to the magnets and the proper holes. All the trials passed alignment and picking up the tool for this iteration of the test.

After the pick-up test, we tested the hold duration of the tool. This was done by just leaving the seeding tool indefinitely on the tool mount. We left the seeding tool attached to our tool mount for a few days, and the tool continued to be on the tool mount. This was expected since there wasn't any reason for the magnets to become demagnetized.

Next, we tested the tool release of the tool mount. Since our tool release mechanism changed from the previous tool mount iteration, we decided to manually test the tool release. In order to do this, we manually pulled on the tool vertically with our fingers in the slots to simulate the tool rack. The first trials of this test were done by using the third seeding tool, with a magnet-on-magnet interface. This proved to be too strong to be pulled apart vertically, so these trials failed. A mechanical moment was needed to easily pull of the tool, which was not realistic when put on Farmbot. From this, the magnets on the tool were replaced for metal washers in order to reduce the magnetic attraction. However as mentioned above, the tool mount wouldn't even pick up the tool well, and so we were unable to test this. Next, we switched back to using only magnets, but with at least one facing the opposite direction. We added 4mm-thick rubber washers between the magnets in order to reduce the magnetic attraction and ensure tighter seals. Tests with this version showed that it was much easier to pull off the tool vertically.

The final tool mount test was for the functionality of the electrical contact screws. This was performed with a voltmeter, by using the audible continuity test setting. First, the continuity of the screws was tested. Next, the continuity was tested of the electrical screw interface between the tool mount and the tool. Both tests revealed that there was continuity with the screws, which meant that they could definitely be used for data and power connections.

Overall, our tests showed that the best assembly to pick up, hold, and release tools is to use magnets on the tool mount, with one facing the opposite direction to ease alignment. Additionally, only washers on the tool proves to be ineffective in picking up the tool, and so at least one magnet is required. Additionally, the use of rubber washers between magnets not only creates a better seal for the water

and air, it reduces the magnetic attraction in order to ease the release of the tool. Continuity tests passed as well, opening the gateway to power and data transfer through the tool mount to tool interface.

6.2. Seeder Testing and Results

Testing for the seeder was also only performed for functionality. We ran preliminary functional tests on the last two seeder tool iterations. This consisted of connecting the seeder to the tool mount, which already had the vacuum pump attached, and trying to pick up a small rock with the suction. The preliminary testing showed us that the large hollow cone before the inlet for the 3rd seeder had too many pressure losses to pick up a small rock. From this, we designed a new seeder with a smaller chamber, which passed the preliminary pick-up test. After solidifying our seeder design, we proceeded to the final testing stage, which used the testing apparatus.

We tested picking up and releasing both small seeds and large seeds, creating four different tests. We used the testing apparatus to run each test for 10 trials. We used sweet pea seeds for the small seed tests and squash seeds for the large seed tests. For both of the seed pick-up tests, all trials passed the functional tests, but we noticed the seeder would sometimes blow a seed away before picking it up when on an open table top. This was a more common trend for smaller seeds, but the pick-up was always eventually successful. This problem could be alleviated by having a large amount of seeds in a small cup, as Farmbot will use in reality. While the seed was being suspended vertically, we moved the testing apparatus about a foot, then cut the power to release the seed. Both seed sizes passed the seed-release functional tests. A picture of our testing apparatus holding a squash seed can be seen below in Figure 52.

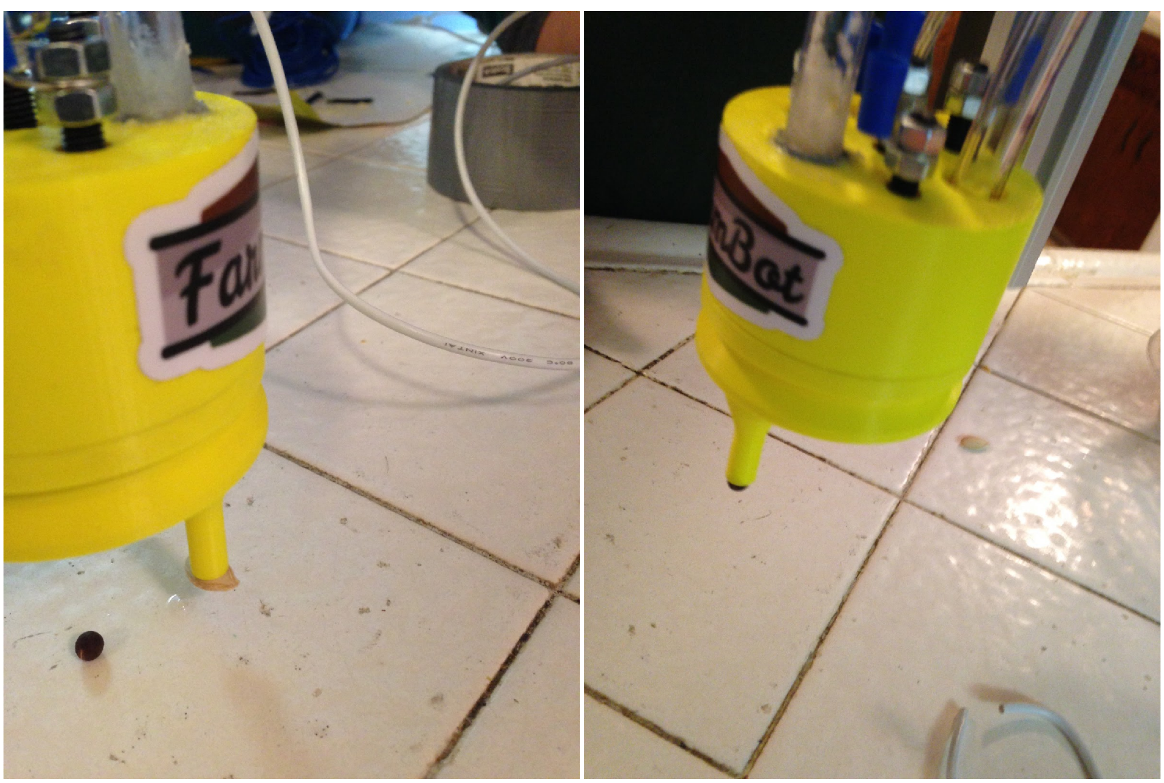


Figure 52: Picture of the seeding tool holding a squash seed (left) and a sweet pea (right) during testing

6.3. Water/Nutrient Mixing Testing and Results

Testing for the water and nutrient mixing did not begin until the final iteration, which consolidated the functions of water delivery with nutrient mixing into one tool. For the water and nutrient mixing tool, we intended to test four different aspects. The first was a visual inspection of water coming out of the mixing tool. The second test was a flow rate test of the flow of water through the mixing tool. The third was a functional test of the nutrient syringe pump, assuring us that the syringe would suck up and release nutrients through the mixing tool. The final test was a calibration test of the flowrate, given a specific and constant stepper motor speed.

Both functional tests of the flow through the mixing tool passed our visual inspection; water was able to flow through the mixing tool, and the nutrient pump was able to suck and release water-soluble nutrients, as seen in Figures 53 and 54. Figure 54 shows the testing process for the visual inspection of the flow of water through the mixing tool. One thing we noticed was that the flow from the water created too much pressure to measure and control the flow efficiently, due to the step downs of the tube sizing. Additionally, we found out that the solenoid valve we used to control the water coming in from the hose attached to the water spigot only allowed for on or off, which made it very difficult to change flow by using a controller. Because of this, our water mixing failed the flowrate test. However, this showed us that despite opening the water spigot to its minimum, the pressure build-up over time at the entrance of the solenoid valve was too much for the system to handle.

The final test was a calibration of the syringe pump flowrate. In order to do this, we programmed the stepper motor to move at a constant speed and adjusted the amount of time, in seconds, the stepper motor was on. Because our syringe pump has measurement lines on it, we were able to measure how much volume, in mL, was sucked up by the syringe pump. Knowing that the in-flow would be the same as the out-flow, we created a Volume of Water vs. Time plot in order to find the flowrate of the syringe pump at the specific speed, which can be seen in Figure 55. The slope of the line yielded a flowrate of 0.1675 LPM. Below is a figure of our testing process to determine the flowrate of the nutrients, as well as a graph summarizing our test.

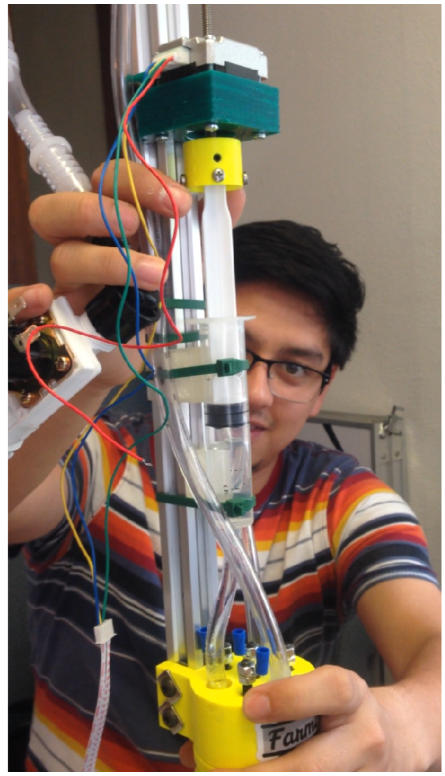


Figure 53: Picture of the nutrient mixing tool spraying water from a connected garden hose during testing.
Figure 54: Picture of syringe pump drawing "nutrients" during testing.

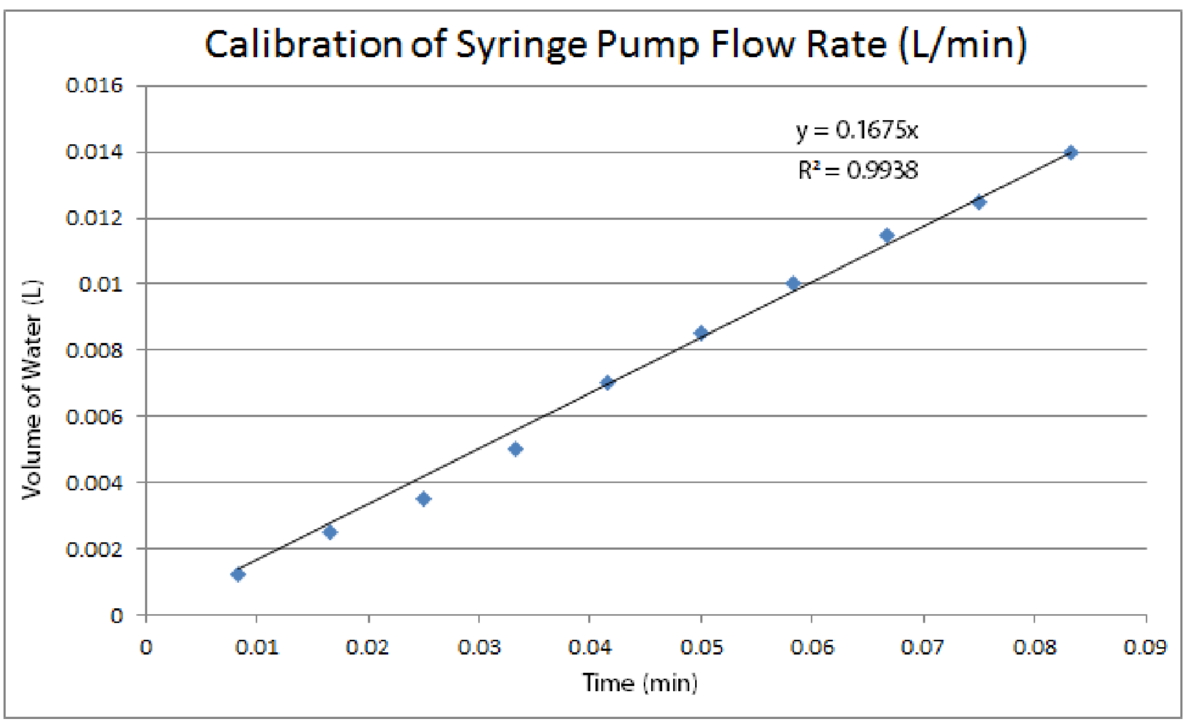


Figure 55: Calibration curve of the syringe pump flow rate at a constant motor speed

6.4. Specification Verification Checklist (DVPR)

The design verification plan and report is attached in Appendix _. Overall, 11 out of 12 tests passed. The first few trials that didn't pass gave us valuable input to redesign our prototypes.

Table 6: Summary of test results

Functional Test	Pass	Fail
Watering nozzle sprays water	X	
Water flow rate can be controlled		X
Syringe pump holds and dispenses fluid	X	
Seeder picks up, carries, and releases seeds	X	
Tool mount picks up and holds tools	X	
Told mount releases tool	X	
Tool mount continuity test	X	

7. Conclusion and Recommendations

Working on this project over the past year has been an awesome experience. Each of us have learned immeasurable amounts about taking on a design project from start to finish, working with teams, and being adaptive to do whatever it takes to get the job done. We learned extensively about what worked and didn't work, specifically with regard to Farmbot, and each day was a valuable step toward accomplishing our goal of creating functional tools for Farmbot. All of our learning experiences and recommendations have already been covered previously in the product realization section of this report. While this marks the end of our journey with Farmbot for our team, it is by no means the end. Rory has plans to continue developing and improving the design, along with other volunteer developers he works with around the world, and isn't slowing down anytime soon. All information about the development of Farmbot is open to the public via the Farmbot Wiki page on the internet, and it will be exciting to track it's progress as it comes together to eventually fulfill the initial dream that Rory envisioned a few years ago. We are beyond proud to have such a significant role in the early stages of this project, and we can't wait to see how far Farmbot will go.

References

1. Aronson, Rory L. *Farmbot: Humanity's Open-Source Automated Precision Farming Machine*. Tech. Farmbot, 19 Sept. 2013. Web. 21 Jan. 2014.

2. Barker, Allen V., and D. J. Pilbeam. *Handbook of Plant Nutrition*. Boca Raton, FL: CRC/Taylor & Francis, 2007. Print.

3. Ford, Charles. "Universal Gripper - Syringe Powered." *Instructables.com*. Instructables, 2012. Web. 03 Mar. 2014.

4. "John Deere Products & Services." *John Deere Products & Services*. N.p., n.d. Web. 30 Jan. 2014. <http://www.deere.com/wps/dcom/en_US/regional_home.page>.

5. Lipson, Hod, John R. Amend, Jr., Heinrich Jaeger, and Eric Brown. Gripping and Releasing Apparatus and Method. Cornell University, assignee. Patent US20130106127A1. 2 May 2013. Print.

6. Occupation Safety and Health Standards for Agriculture, § 1928. Print.

7. "Precision English Seeder." *Amazon.com*. Amazon, n.d. Web. 27 Feb. 2014.

8. "Quick Release Couplings and Accessories for Compressed Air: Superior Safety and Performance." *Staubli.com*. Staubli International, n.d. Web. 27 Feb. 2014. <http://www.staubli.com/en/connectors/quick-couplings/compressed-air-coupling/>.

9. "Seeder." *Stand & Plant Seeder & Planter*. Stand 'N Plant, 2012. Web. 03 Mar. 2014.

10. "Silvery Air Inflation Sports Ball Point Needle 5PCS." *Amazon.com*. Amazon, n.d. Web. 27 Feb. 2014.

11. "UM10204 I2C-bus Specification and User Manual." *NXP.com*. NXP Semiconducters, 09 Oct. 2012. Web. 25 Feb. 2014. <http://www.nxp.com/documents/other/UM10204_v5.pdf>.

12. "USB 3.1 Specification." *USB.org*. Universal Serial Bus Implementers Forum, n.d. Web. 27 Feb. 2014. <http://www.usb.org/developers/docs/>.

Appendix A: QFD, Pugh, and Decision Matrices

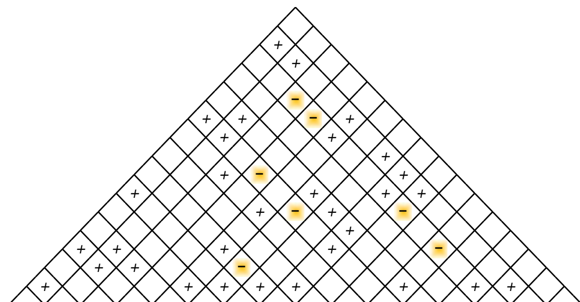
QFD: House of Quality

Project: Farmbot
Revision: 1
Date: 1/28/2014

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



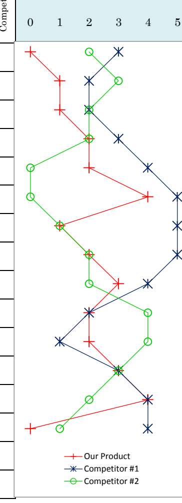
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of Improvement	▼	◇	▲	▼	▼	▼	▲	▲	▼	▲	▼	◇	◇	▲	▲	

WHO: Customers

HOW: Engineering Specifications

Row #	Weight Chart	Relative Weight	Rory Aronson (sponsor)	Home Garden Enthusiasts	Agriculture Sector	Farmbot Developers	Maximum Relationship	WHAT: Customer Requirements (explicit & implicit)	Total Weight	Dimensions	Minimum Endurance Life	Installation Time	Cost to Manufacture	Tolerance of Motion	Maximum Loading on Gantry	Performs Its Functions	Run/Work Time	Wear Resistance of Individual Parts	Track Deflection	Movement (XYZ)	Open Sourced	Percent of Customers Find it Appealing	Capacity for Different Plants and Nutrients		Current Product: Farmbot 1.0 (Prototype)	Competitor #1: *Traditional Gardening*	Competitor #2: *Precision Farming Machine*	Competitor #3: *Product Name*	Competitor #4: *Product Name*	Row #
1		11%	11	10	10	12	9	Dig Holes, Plant Seeds, Feed Plant	▽					○	○	●				○			○		0	3	2			1
2		9%	6	10	8	10	9	Easy to Operate									●								1	2	3			2
3		7%	6	7	9	5	3	Easy to Maintain			▽							○			▽				1	2	2			3
4		7%	8	7	8	5	9	Easy to Install	▽	▽		●													2	3	2			4
5		4%	3	4	4	3	9	Low Weight of Product	●	○					○								▽		2	4	0			5
6		6%	9	1	4	11	9	Modifiable		○											●				4	5	0			6
7		8%	6	11	11	5	9	Low Cost	○	○			●												1	5	1			7
8		4%	1	8	3	2	9	Nicer Aesthetics		▽												●			2	5	2			8
9		7%	9	2	10	8	9	Scalability	●	●			●		○				○	●					3	4	2			9
10		9%	9	9	9	9	9	Reliablility			●			○	●			●	●	○					2	2	4			10
11		8%	7	7	9	7	9	Weather Resistant					▽					●							2	1	4			11
12		8%	10	7	6	9	9	Precision						●		●							▽		3	3	3			12
13		6%	7	8	4	6	3	Safety	▽	▽					○										4	4	2			13
14		8%	8	9	5	8	9	Versatility of Plant Type													▽		●		0	4	1			14
15		0%																												15
16		0%																												16

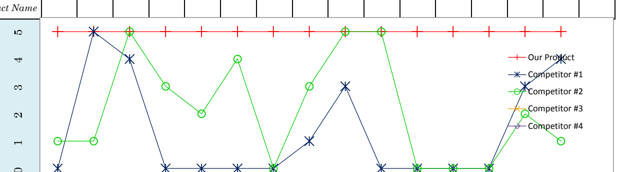
NOW: Current Product Assesment - Customer Requirements



100 100 100 100

HOW MUCH: Target	Total Weight	Dimensions	Minimum Endurance Life	Installation Time	Cost to Manufacture	Tolerance of Motion	Maximum Loading on Gantry	Performs Its Functions	Run/Work Time	Wear Resistance of Individual Parts	Track Deflection	Movement (XYZ)	Open Sourced	Percent of Customers Find it Appealing	Capacity for Different Plants and Nutrients	
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	
Technical Importance Rating	145.5	136	87.75	63	147	131.25	164.25	168.75	76.5	168.75	102.75	124.5	70.5	31.5	111.25	
Relative Weight	8%	8%	5%	4%	9%	8%	9%	10%	4%	10%	6%	7%	4%	2%	6%	
Weight Chart																
Current: Farmbot 1.0 (Prototype)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	
Competitor #1: *Traditional Farming*	0	5	4	0	0	0	0	1	3	0	0	0	0	3	4	
Competitor #2: *Precision Farming Machine*	1	1	5	3	2	4	0	3	5	5	0	0	0	2	1	
Competitor #3: *Product Name*																
Competitor #4: *Product Name*																

Current Product Assesment - Engineering Specifications



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Template Revision: 0.9 Date: 4/23/2010
Christopher Battles

ME 428 - Team Farmbot - James Cruz - 2/24/14 - Decision Matrix for the Universal Tool Mount

Design Criteria	Cost	Visual Appeal	Precision	Easy Installation	Mobility	Protection From Elements	Overall Satisfaction
Weighting Factor	0.15	0.10	0.20	0.15	0.20	0.20	1.00
Automatic Retractable Hose	70	50	85	100	75	75	77.5
	10.5	5	17	15	15	15	
Expanding Coiled Hose	90	50	85	100	70	10	66.5
	13.5	5	17	15	14	2	
Attached to Gantry w/ Side Re	55	50	90	45	60	0	50
	8.25	5	18	6.75	12	0	
Centralized Fountain	100	35	25	90	0	0	37
	15	3.5	5	13.5	0	0	
Refilling Watering Bucket	40	100	80	40	70	0	52
	6	10	16	6	14	0	
Flexible Housing	40	100	90	65	100	100	83.75
	6	10	18	9.75	20	20	
Side Tower With Retractable Hose	85	75	100	90	90	90	89.75
	12.75	7.5	20	13.5	18	18	

ME 428 - Team Farmbot - Pugh Matrix for Universal Tool Mount - James Cruz - 2/17/14

Concept	Hook and Lever	Puzzle Piece	Rotating Nub	Solenoid Actuator	Hook and Nub	Slot and Pin	Triangle Latch and Pin	Smoke Detector Lock	Magnet	Lever with Release Hook
Criteria	1	2	3	4	5	6	7	8	9	10
Cost	D	+	S	-	+	-	S	S	+	-
Actuation		-	S	+	+	-	S	-	+	+
Release		S	S	+	-	+	S	+	+	+
Ease of Operation	A	-	S	+	-	-	-	S	+	+
Size		S	S	-	S	-	S	-	+	-
Weight		+	+	+	+	-	+	-	-	-
Complexity	T	S	S	S	+	-	-	-	-	-
Rigidity		-	+	S	-	+	S	-	-	S
Power Consumption		S	S	-	S	S	S	S	S	S
Looks cool	U	+	S	S	S	S	-	+	-	S
Safety		+	S	+	+	-	+	+	+	-
Sum +		5	2	5	5	2	2	3	6	3
Sum -	M	3	0	3	3	7	3	5	4	5
Total		2	2	2	2	-5	-1	-2	2	-2

ME 428 - Team Farmbot - James Cruz - 2/24/14 - Decision Matrix for the Universal Tool Mount

Design Criteria	Safety	Cost	Actuation	Release	Size	Complexity	Holds tool firmly	Power Consumption	Looks Cool	Overall Satisfaction
Weighting Factor	0.12	0.12	0.15	0.15	0.12	0.10	0.15	0.05	0.04	1.00
Lever mechanism	75	75	90	25	75	75	90	100	90	73.85
	9	9	13.5	3.75	9	7.5	13.5	5	3.6	
Puzzle piece	90	90	50	50	90	90	50	100	75	71.9
	10.8	10.8	7.5	7.5	10.8	9	7.5	5	3	
Rotating nub in slot	75	75	75	50	90	75	90	100	75	76.55
	9	9	11.25	7.5	10.8	7.5	13.5	5	3	
Internal protruding nub	90	90	75	25	75	75	75	100	75	72.35
	10.8	10.8	11.25	3.75	9	7.5	11.25	5	3	
L-arm, slot, and pin	75	50	50	50	75	50	90	100	75	65.5
	9	6	7.5	7.5	9	5	13.5	5	3	
Rod and triangle latch	75	75	75	50	75	75	75	100	90	73.1
	9	9	11.25	7.5	9	7.5	11.25	5	3.6	
Rotating radial locks (smoke detector)	90	75	90	90	50	75	75	100	75	79.55
	10.8	9	13.5	13.5	6	7.5	11.25	5	3	
Solenoid Actuator	100	50	90	90	75	50	75	75	50	76
	12	6	13.5	13.5	9	5	11.25	3.75	2	
Electromagnet	90	75	90	90	90	90	25	50	50	74.85
	10.8	9	13.5	13.5	10.8	9	3.75	2.5	2	
Lever and actuator rod	25	50	75	75	50	75	90	100	50	65.5
	3	6	11.25	11.25	6	7.5	13.5	5	2	
Tapered tool extrusion with pin, and solenoid	90	75	90	90	75	90	75	90	90	84.15
	10.8	9	13.5	13.5	9	9	11.25	4.5	3.6	

Pugh Matrix for Seeding 1

Criteria \ Concept	Seed Injector w/ air	Seed Injector w/ compartments	Digger	Force Press	High Velocity Projectile	Through-Hole Auger	Universal Gripper
	1	**2**	**3**	**4**	**5**	**6**	**7**
Cost	-	**D**	+	+	-	-	-
Precision	S	•	-	S	-	S	S
Weight	+	**A**	-	S	+	-	+
Size	+	•	-	+	+	-	+
Mobility	+	**T**	-	S	S	S	+
Versatility of seeds	S	•	+	S	S	S	S
Versatility of depth	S	**U**	-	S	-	+	-
Injection force	S	•	+	-	-	+	S
Speed	-	**M**	-	-	S	-	-
Σ+	3		3	2	2	2	3
Σ-	2		6	2	4	4	3
ΣS	4		0	5	3	3	3

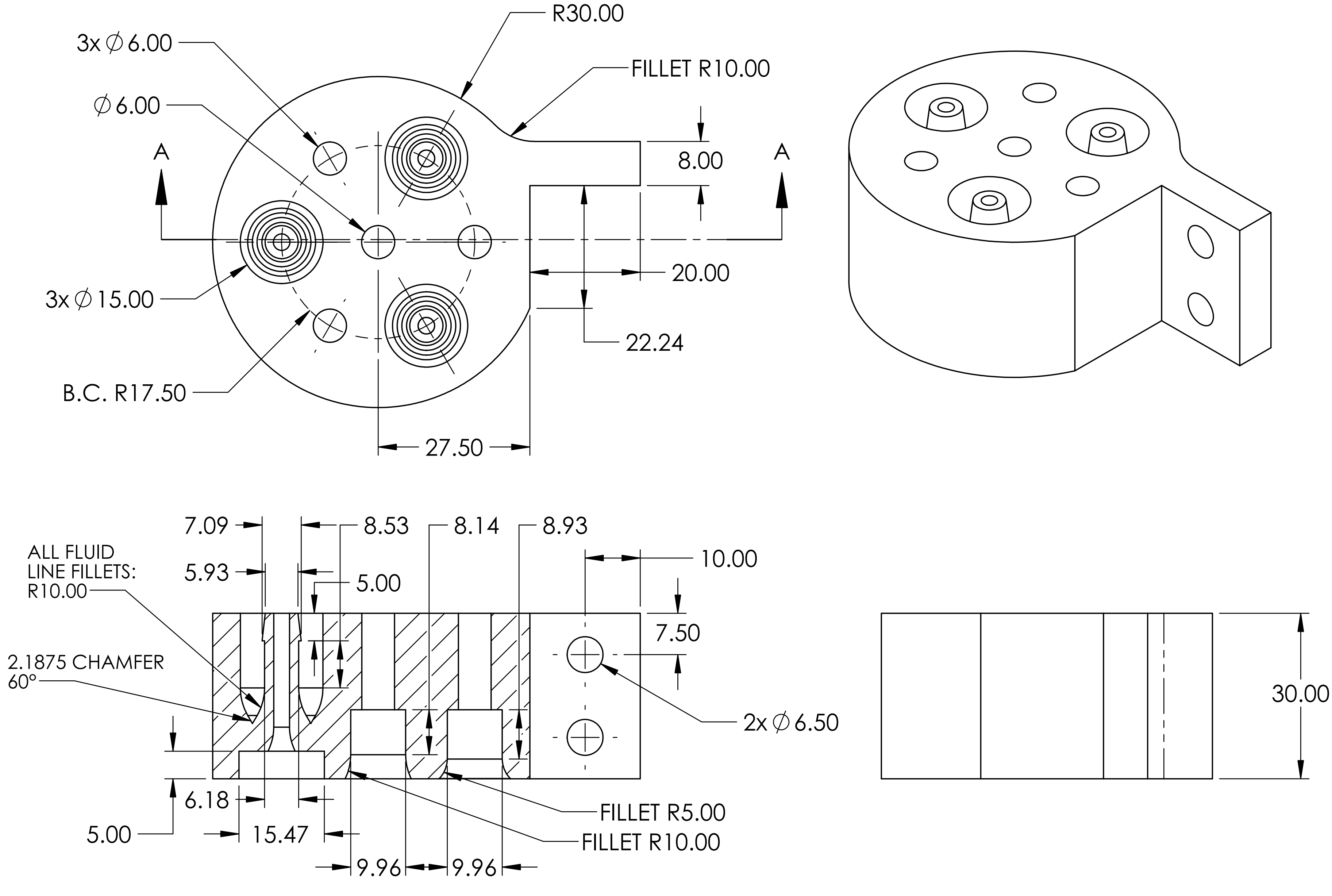
Pugh Matrix for Seeding 2

Criteria \ Concept	Air Seed Injector Change Tip	Vaccuum Seed Injector Uni Grip	Compartment Seed Injector	Digger	Place and Force Press	Through-Hole Auger	Stand & Plant Seeder
	1	**2**	**3**	**4**	**5**	**6**	**7**
Cost	**D**	+	S	+	+	-	+
Precision	•	S	S	-	-	-	S
Weight	**A**	S	-	-	S	-	-
Size	•	S	-	-	S	-	-
Mobility	**T**	S	-	-	S	-	S
Versatility of seeds	•	+	S	S	S	S	+
Versatility of depth	**U**	S	S	-	S	S	S
Injection force	•	S	S	+	+	+	+
Speed	**M**	S	+	-	-	-	S
Σ+		2	1	2	2	1	3
Σ-		0	3	6	2	6	2
ΣS		7	5	1	5	2	4

Decision Matrix for Seeding - Team Farmbot - Bryan Rodriguez - 2/25/2014

Design Criteria	Cost	Precision	Size	Mobility	Speed of Function	Safety	Weather Resistance	Nice Aesthetics	versatility	Overall Score
Weighting Factor	0.15	0.17	0.10	0.08	0.09	0.10	0.12	0.07	0.12	1.00
Seed Injector With Air	70	90	90	90	90	75	75	90	90	83.7
	10.5	15.3	9	7.2	8.1	7.5	9	6.3	10.8	
Seed Injector With Compartments	80	90	80	80	85	80	75	85	90	83.1
	12	15.3	8	6.4	7.65	8	9	5.95	10.8	
Digger	70	25	25	30	20	70	80	50	30	45.15
	10.5	4.25	2.5	2.4	1.8	7	9.6	3.5	3.6	
Force Press	75	75	50	50	75	50	70	80	80	68.35
	11.25	12.75	5	4	6.75	5	8.4	5.6	9.6	
High Velocity Projectile	50	10	50	50	80	10	50	80	75	47
	7.5	1.7	5	4	7.2	1	6	5.6	9	
Through-Hole Auger	25	75	30	60	65	50	70	70	75	57.45
	3.75	12.75	3	4.8	5.85	5	8.4	4.9	9	
Universal Gripper	50	75	60	90	90	75	65	90	90	73.95
	7.5	12.75	6	7.2	8.1	7.5	7.8	6.3	10.8	

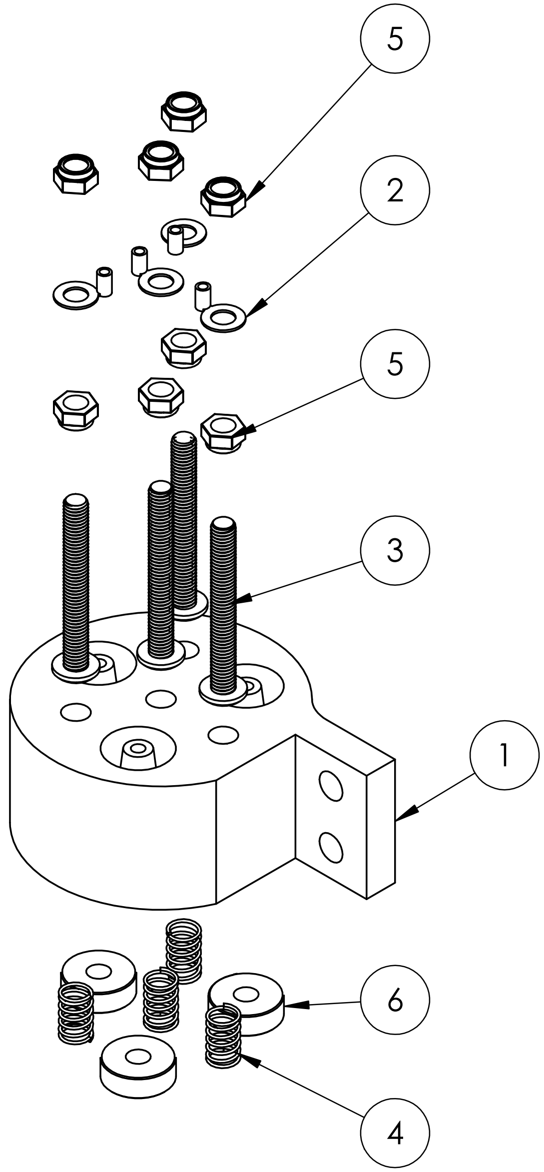
Appendix B: Part and Assembly Design Drawings



SECTION A-A

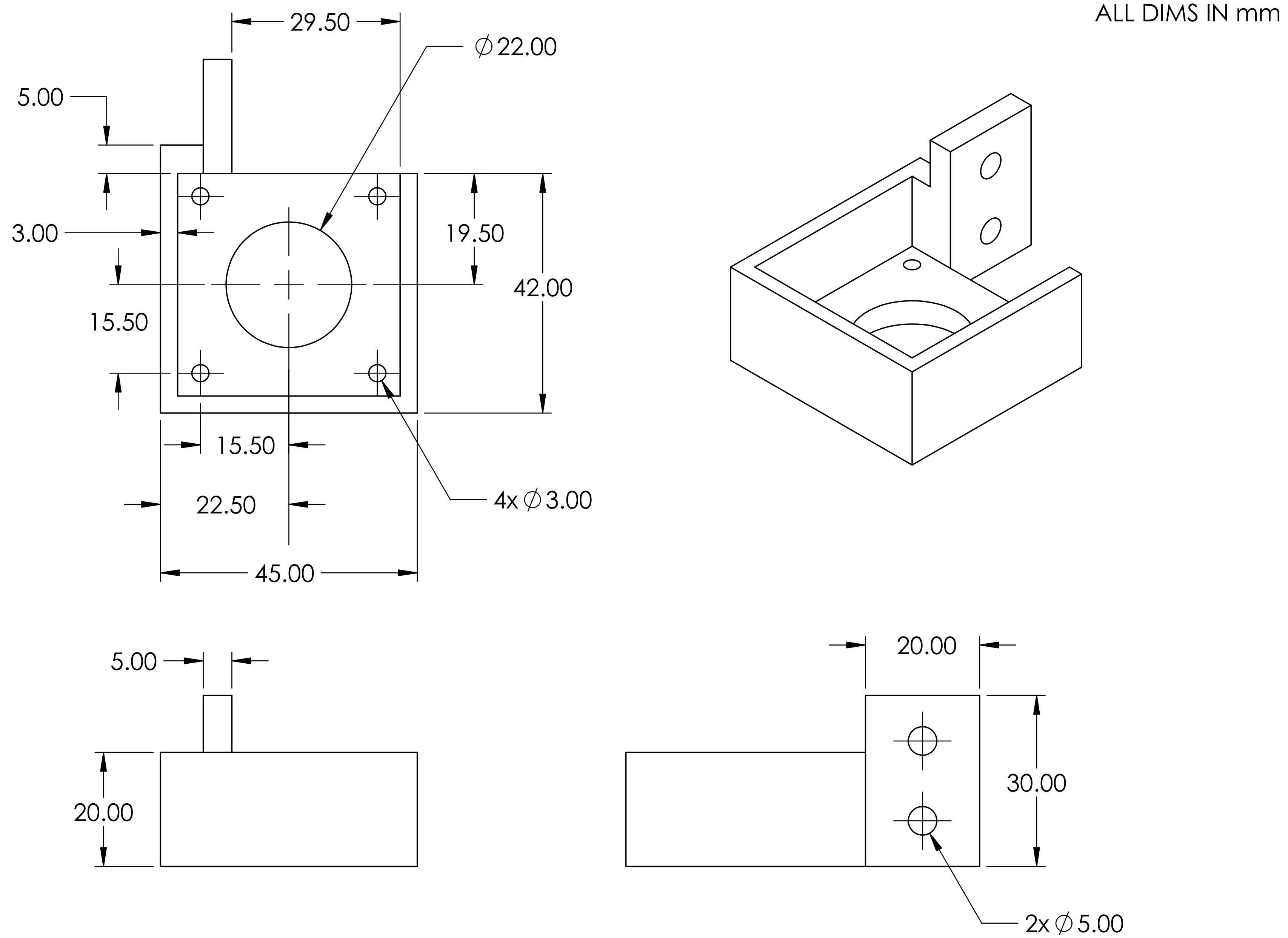
ALL DIMS IN mm

Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Universal Tool Mount	Name: James Cruz
Team Farmbot	Dwg. #: 11	Nxt Asb: 1-A	Date: 9/30/14 · Scale: 1:1	Sponsor: Rory Aronson

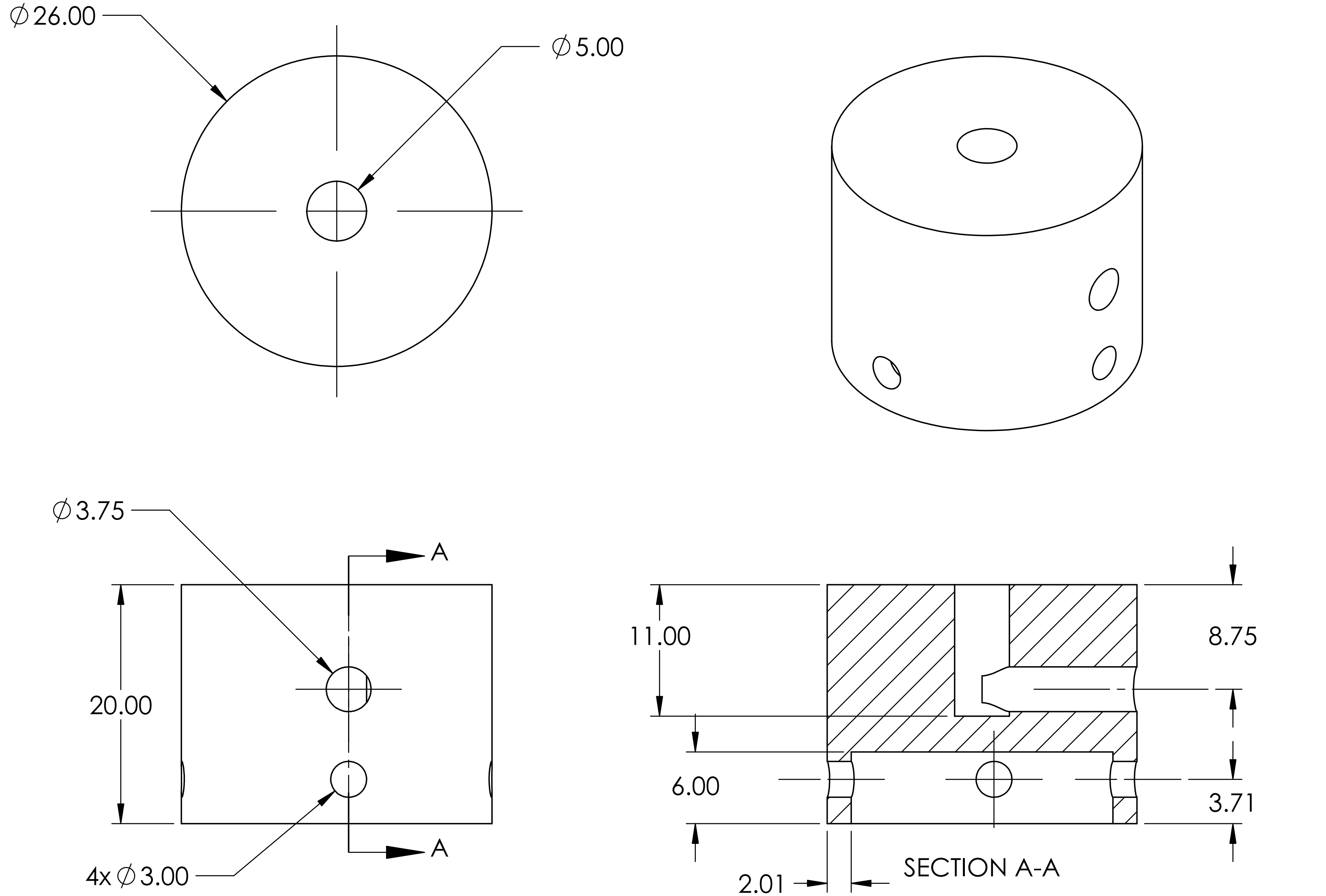


ITEM NO.	PART	QTY.
1	UNIVERSAL TOOL MOUNT	1
2	RING TERMINAL	4
3	LOW PROFILE SOCKET HEAD SCREW	4
4	COMPRESSION SPRING	4
5	NYLON INSERT HEX LOCKNUT	8
6	RING MAGNET	3

Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Universal Tool Mount		Name: James Cruz
Team Farmbot	Dwg. #:1-A	Nxt Asb: Tool Arm	Date: 9/30/14	Scale: 2:3	Sponsor: Rory Aronson

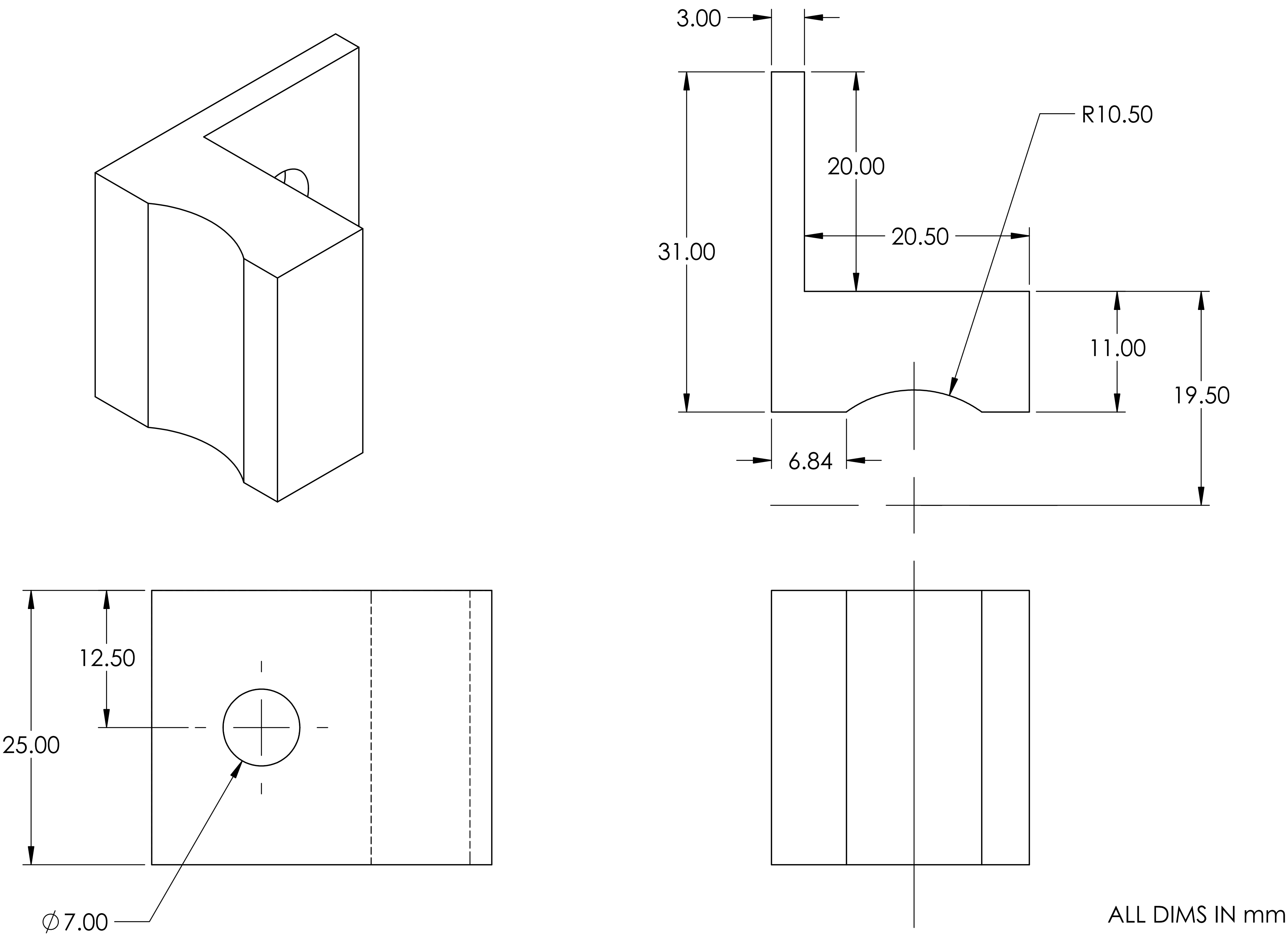


Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Stepper Motor Bracket		Name: James Cruz
Team Farmbot	Dwg. #: B1	Nxt Asb: Tool Arm	Date: 12/5/14	Scale: 2:1	Sponsor: Rory Aronson

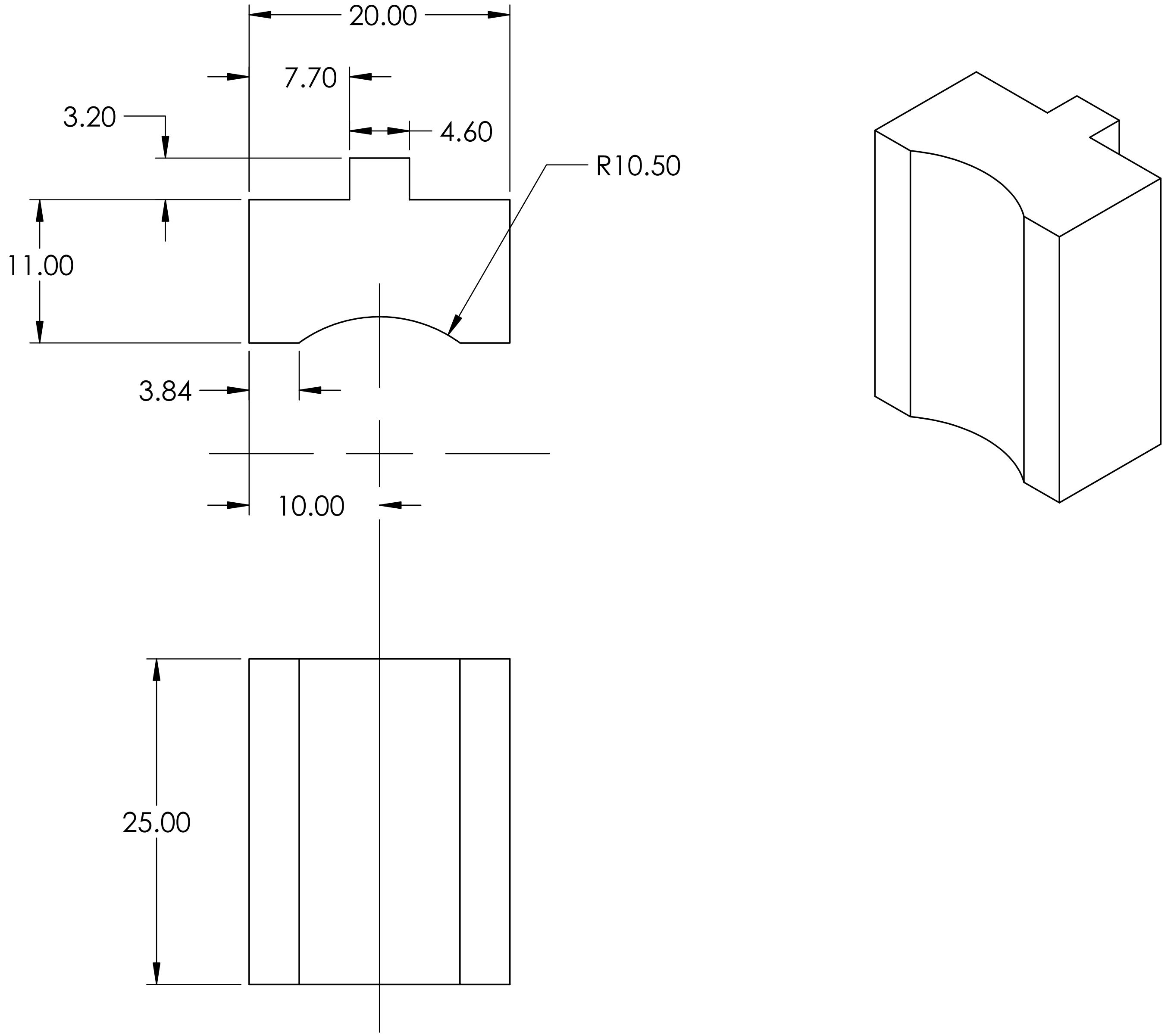


ALL DIMS IN mm

Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Syringe Cap		Name: Scott Herrington
Team Farmbot	Dwg. #: C1	Nxt Asb:Tool Arm	Date: 12/5/14	Scale: 2:1	Sponsor: Rory Aronson

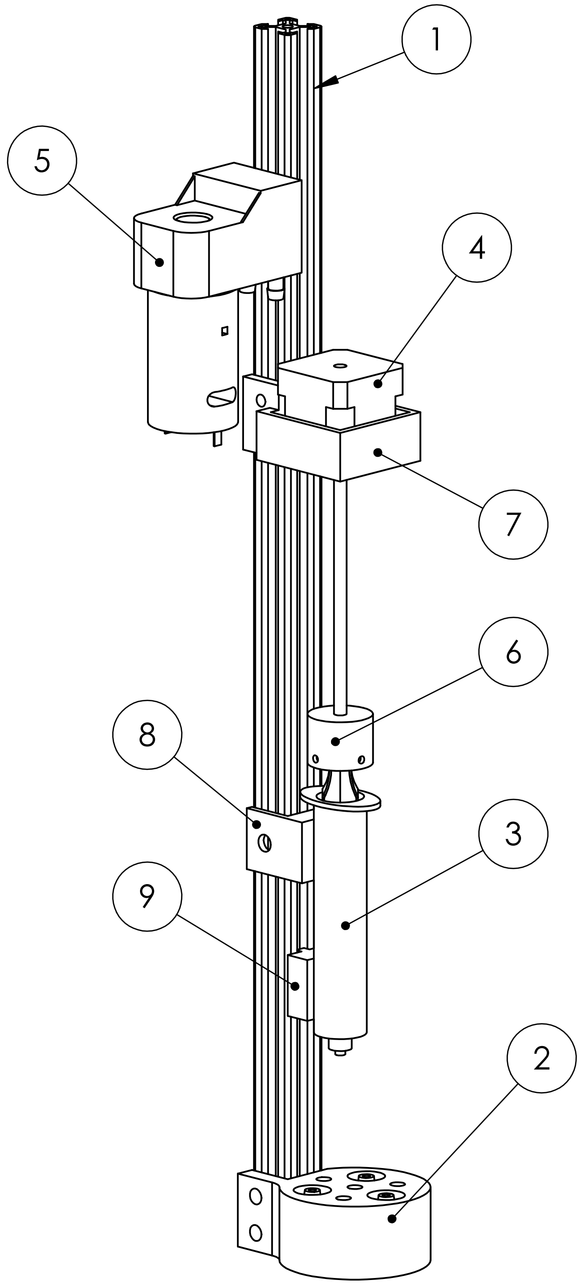


Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Top Syringe Spacer		Name: James Cruz
Team Farmbot	Dwg. #: B2	Nxt Asb: Tool Arm	Date: 12/5/14	Scale: 2:1	Sponsor: Rory Aronson



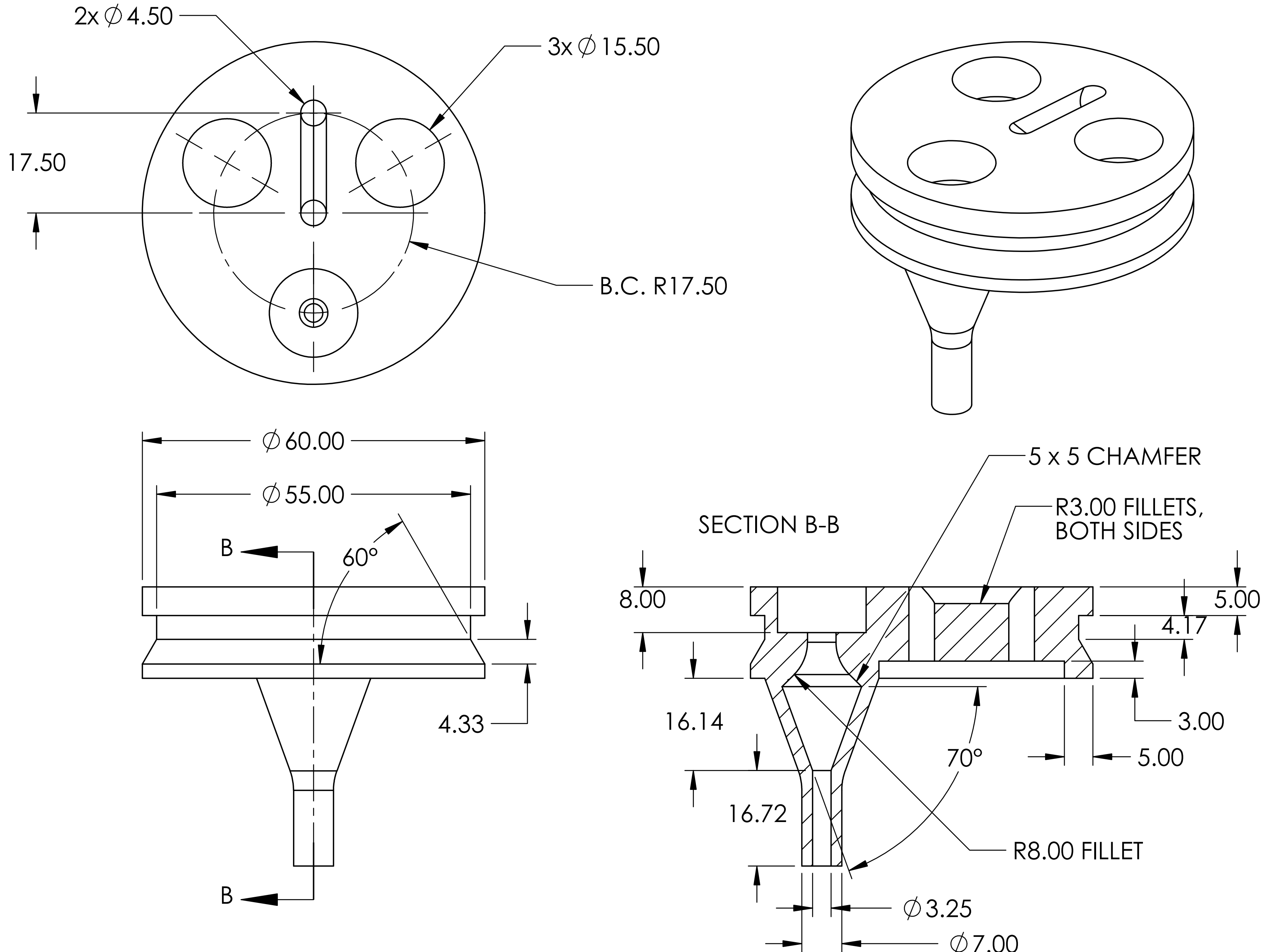
ALL DIMS IN mm

Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Bottom Syringe Spacer	Name: James Cruz
Team Farmbot	Dwg. #:B3	Nxt Asb:Tool Arm	Date: 12/5/14 / Scale: 2:1	Sponsor: Rory Aronson



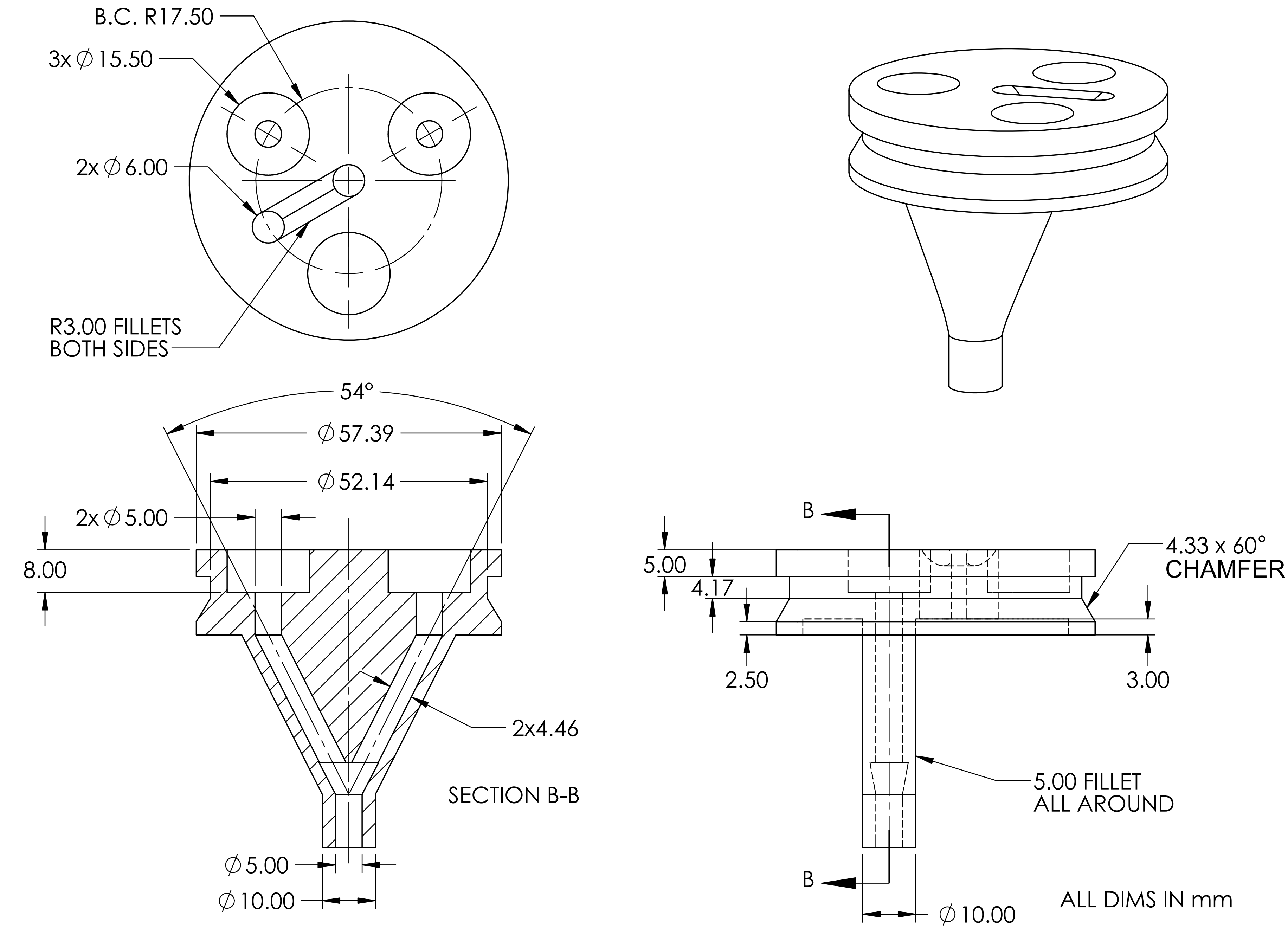
ITEM NO.	PART	QTY
1	EXTRUSION	1
2	UNIVERSAL TOOL MOUNT	1
3	SYRINGE	1
4	STEPPER MOTORW/LEAD SCREW	1
5	vACUUM PUMP	1
6	SYRINGE CAP	1
7	MOTOR BRACKET	1
8	TOP SYRINGE SPACER	1
9	BOTTOM SYRINGE SPACER	1

Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Prototype Assembly		Name: James Cruz
Team Farmbot	Dwg. #:Tool arm	Nxt Asb: Tool Arm	Date: 12/5/14	Scale:	Sponsor: Rory Aronson



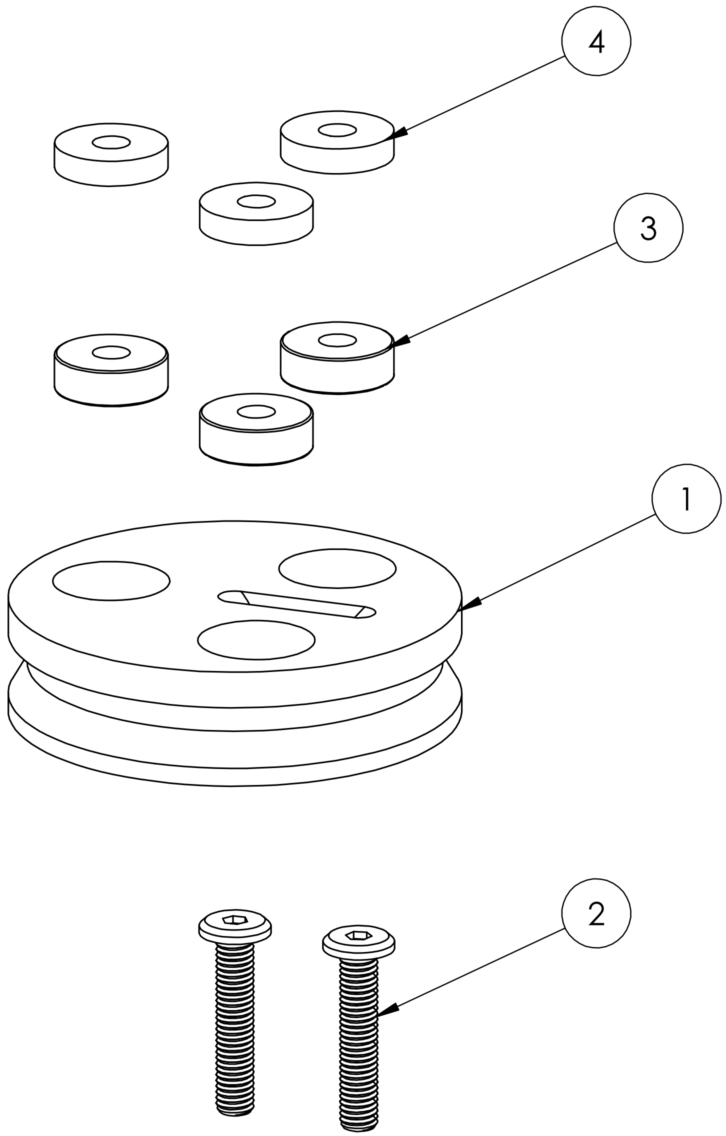
ALL DIMS IN mm

Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Seeder Tip		Name: James Cruz
Team Farmbot	Dwg. #:T1	Nxt Asb:	Date: 12/5/14	Scale: 1:1	Sponsor: Rory Aronson



Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Water and Nutrient Tip		Name: Bryan Rodriguez
Team Farmbot	Dwg. #:T2	Nxt Asb:Tool Arm	Date: 12/5/14	Scale:1:1	Sponsor: Rory Aronson

NOTE: SINCE SEEDING TIP AND MIXING TIP USE THE SAME TOOL BASE, ASSEMBLY OF EACH TOOL WOULD BE EXACTLY THE SAME AS THIS



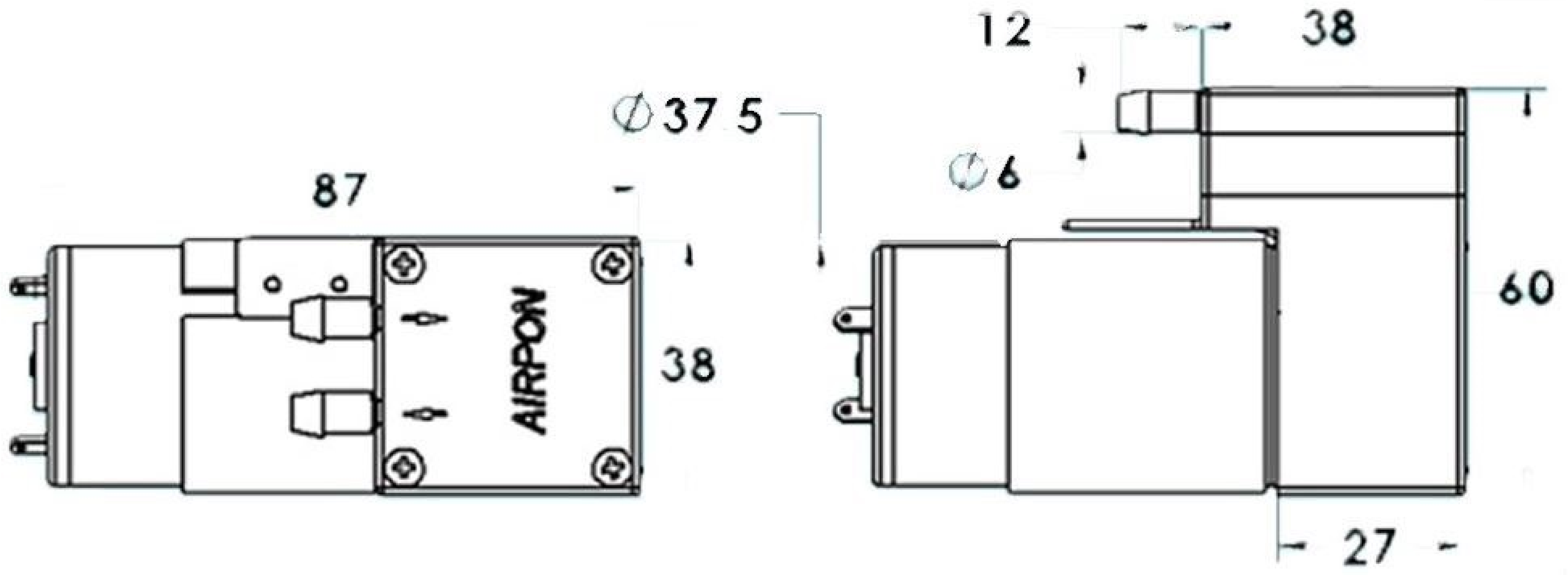
ITEM NO.	PART	QTY.
1	TOOL BASE	1
2	M5 x 20MM SCREW	2
3	RING MAGNET	3
4	RUBBER RING WASHER	3

Cal Poly Mechanical Engineering	Senior Project	Winter-Fall 2014	Part Name: Tool Base Assembly	Name: James Cruz
	Dwg. #: T1S	Nxt Asb:	Date: 12/5/14 / Scale: 1:1	Sponsor: Rory Aronson

Appendix C: List of Vendors and Prices of Commercial Parts

Part	Qty.	Potential Vendor(s)	Cost
M5 Screws, 10mm	5	Openbuilds	$4.50 (for 25)
M5 Tee-nuts	6	Openbuilds	$4.50 (for 25)
M5 x 10mm Contact Screws	4	Miner's Ace Hardware, SLO	$0.64
M5 x 25mm Contact Screws	4	Miner's Ace Hardware, SLO	$0.96
M3 Machine Screws, 6mm	4	McMaster-Carr	$6.76 (for 100)
M5 Hex Nuts	8	Miner's Ace Hardware, SLO	$0.32
Airpon Vacuum Pump	1	Sparkfun	$14.95
Ajax 20mL Syringe	1	Amazon.com LLC	$5.87 (for 10)
Stepper Motor w/threaded shaft	1	Sparkfun	$29.95
Silicone Tube - 4mm ID, 8mm OD, 1m	1	Ebay (ideal.car)	$5.99
Tee Shape Quick Joint 1/4" to 8mm	1	Amazon.com LLC (Amico)	$9.29 (for 10)
Solenoid Valve	1	Sparkfun	$7.95
1/2" Vinyl Tube	1 ft	Home Depot, SLO	$0.49
3/8" Vinyl Tube	2 ft	Home Depot, SLO	$3.00
1/4" Vinyl Tube	2 ft	Home Depot, SLO	$0.78
1/2" x 3/4" Coupling	1	Home Depot, SLO	$2.49
Rubber Washers	6	Home Depot, SLO	$3.63
M3 Washers	8	Miner's Ace Hardware, SLO	$0.64
M3 x 50mm Philips Screws	4	Miner's Ace Hardware, SLO	$1.28
M4 x 8mm Set Screw	1	Miner's Ace Hardware, SLO	$0.30
3D-printed			
Tool Holder	1	Rory Aronson	n/a
Syringe Pull Cap	1	Rory Aronson	n/a
Motor Bracket	1	Rory Aronson	n/a
Syringe Spacer Braket Set	1	Rory Aronson	n/a
Various parts (see below)	n/a	Cal Poly Mechanical Engineering	$164.00
Tool Holder	1		
Seeder Tip	2		
Watering Tip	2		
Provided by Sponsor			
M5 x 40mm Contact Screws	4	Openbuilds	
Electrical Ring Terminals	4	Home Depot	
20x20mm v-slot extrusion	1	Openbuilds	
Plastic Zip Ties	3	Home Depot	$0.30
Ring Magnets	6		$3.24

Appendix D: Vendor Supplied Component Specification and Data Sheets



Airpon Vacuum Pump

常州市万泰电器有限公司 Hybrid Linear Actuators

39BYGL

SERIES HYBRID STEPPING MOTOR(混合式步进电机)

General Specifications(详细说明):

Step Accuracy···±5%

Temperature Rise···80℃ Max

Ambient Temperature Range·····························-20℃~+50℃

Insulation Resistance··························100MΩ Min.500VC DC

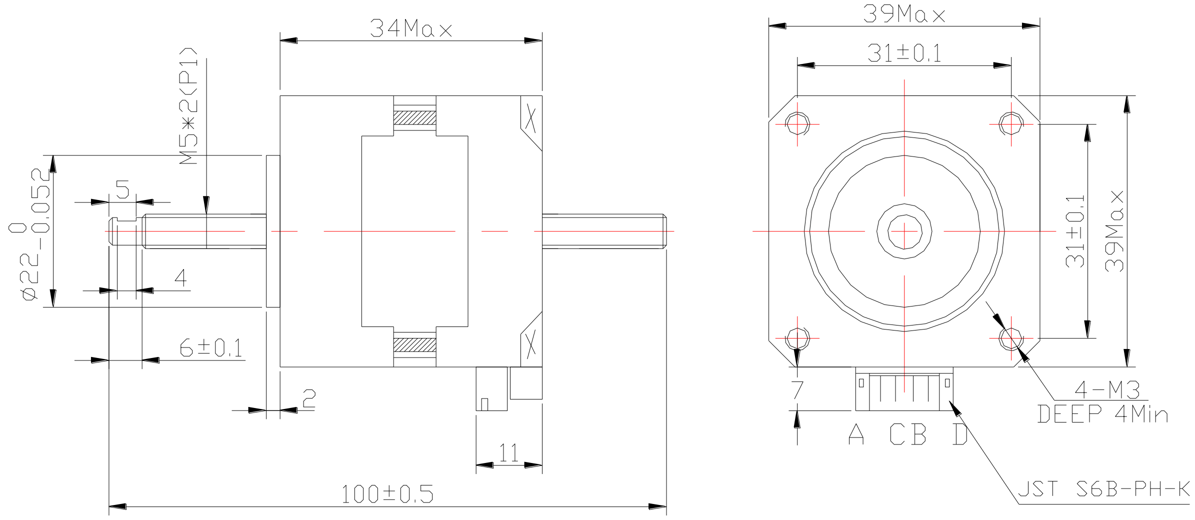
电机型号 Model	步长 Step distance mm/step	机身长 Motor Length L(mm)	相电压 Rate Voltage (V)	相电流 Rate Current (A)	相电阻 Phase Resistance (Ω)	相电感 Phase Inductance (mH)	静转矩 Holding Torque (N.m)	引线数 Lead Wire (NO.)	定位力矩 Detent Torque (kg.cm)	转动惯量 Rotor Inertia (kg.cm^2)	重量 Motor Weight (kg)
39BYGL215A	0.01	34	12	0.4	30	42	0.21	4	0.12	0.02	0.18

Dielectric Strength·································500V AC 1S

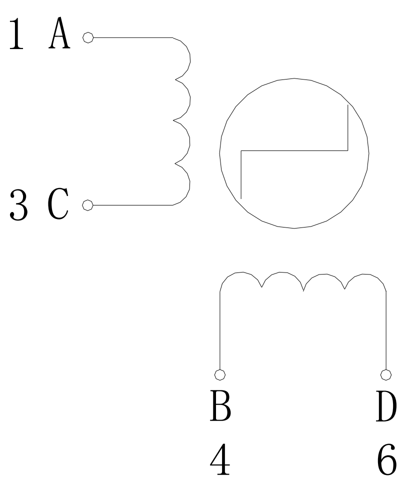
Electrical Specifications(技术数据):

*以上仅为代表产品，特殊产品可根据客户要求制作

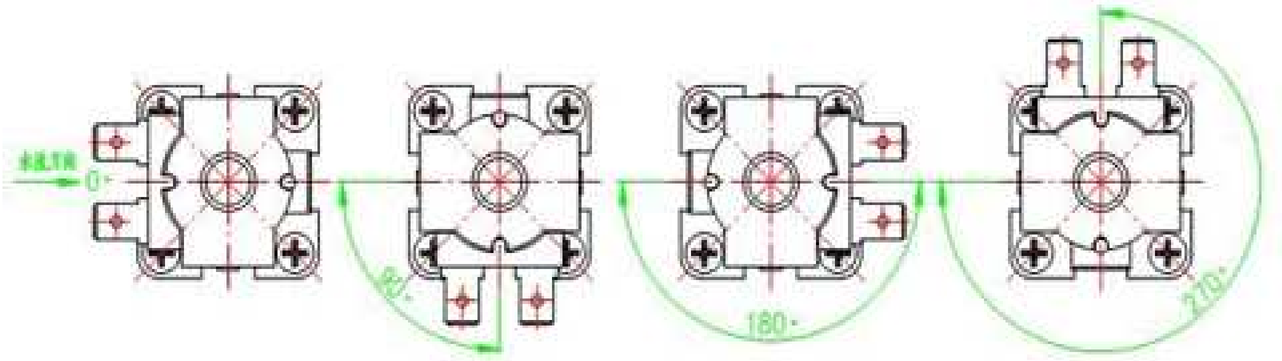
Mechanical Dimensions(外型图)



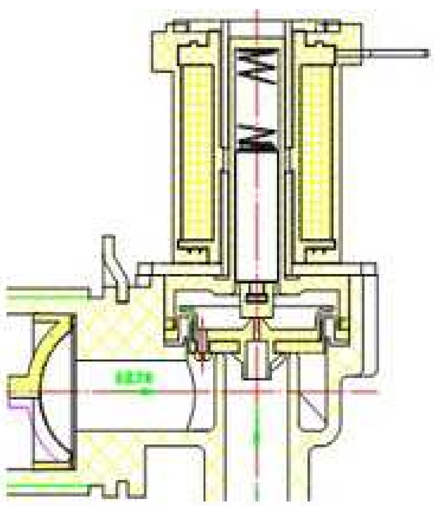
Wiring diagram(接线图):

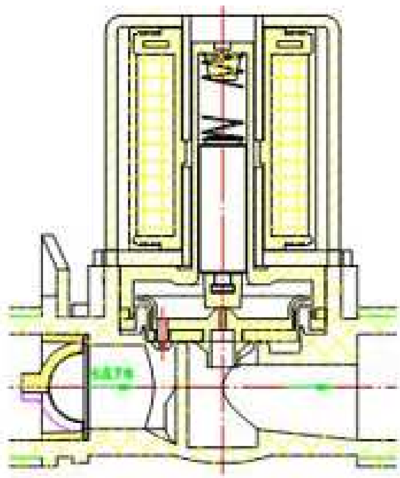


Usage: Specially working in low pressure environment		**Usage:** Specially working in low pressure environment	
			
Model No.	AQT15SCB	**Model No.**	AQT15SP
Thread Size	1/2"BSP inlet and let	**Thread Size**	1/2"BSP inlet and 12mm outlet
Material	Brass	**Material**	Plastic
Working Temp	0~100℃	**Working 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**	4.75KΩ ±0.25KΩ (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:





Appendix E: Support Analysis for Vacuum Pump Air Flow

Assumptions:

4mm diameter seed
1000 seeds is about 6 grams

d	4	mm
A	12.566	mm^2
A	1.26E-05	m^2
N	1000	seeds
mass N	6	g
m	0.0060	g/seed
m	6.00E-06	kg/seed
W	5.89E-05	N
P=ΔP	4.6839	Pa
ΔP	0.000679	psi
ΔP	0.00138	in Hg
ρ air	1.2041	kg/m^3
Velocity	2.7893	m/s
d nozzle	0.003	m
A nozzle	7.07E-06	m^2
AV	1.97E-05	m^3/s
AV	1.1830	LPM

Assumptions:

10mm diameter seed
1000 seeds is about 40 grams

d	10	mm
A	78.540	mm^2
A	7.85E-05	m^2
N	1000	seeds
mass N	40	g
m	0.0400	g/seed
m	4.00E-05	kg/seed
W	3.92E-04	N
P=ΔP	4.9962	Pa
ΔP	0.000725	psi
ΔP	0.00148	in Hg
ρ air	1.2041	kg/m^3
Velocity	2.8807	m/s
d nozzle	0.003	m
A nozzle	7.07E-06	m^2
AV	2.04E-05	m^3/s
AV	1.2218	LPM

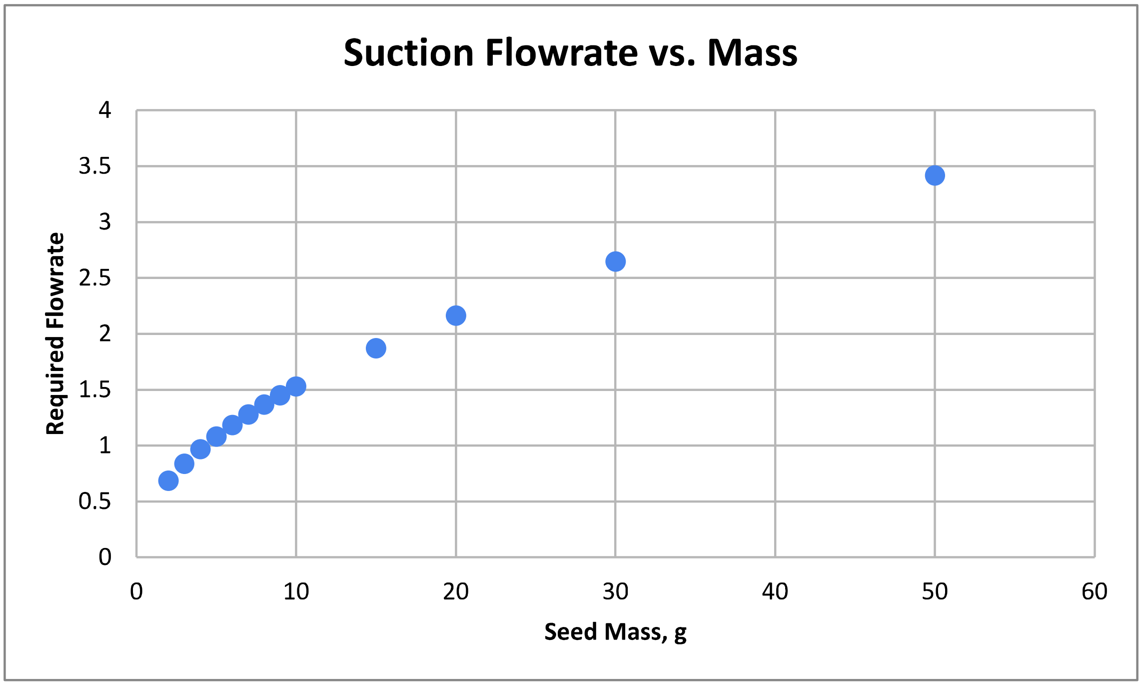
Assumptions:

1mm diameter seed
1000 seeds is about 2 grams

d	1	mm
A	0.785	mm^2
A	7.85E-07	m^2
N	1000	seeds
mass N	2	g
m	0.0020	g/seed
m	2.00E-06	kg/seed
W	1.96E-05	N
P=ΔP	24.9810	Pa
ΔP	0.003623	psi
ΔP	0.00738	in Hg
ρ air	1.2041	kg/m^3
Velocity	6.4415	m/s
d nozzle	0.003	m
A nozzle	7.07E-06	m^2
AV	4.55E-05	m^3/s
AV	2.7319	LPM

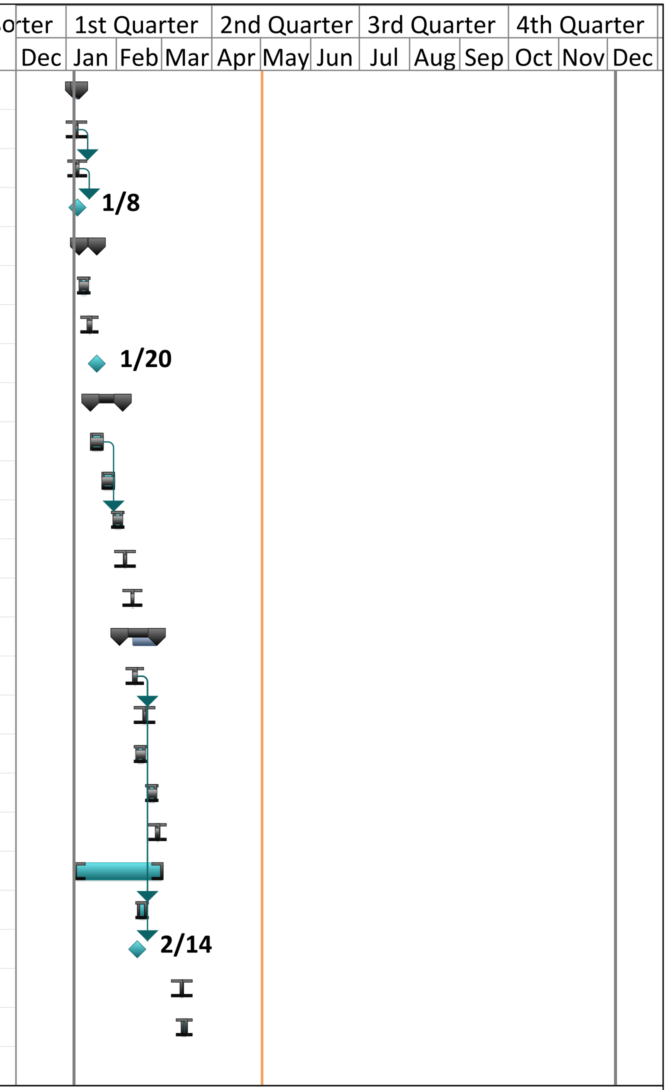
4mm diameter seed
1000 seeds is about 5 grams

d	4	mm
A	12.566	mm^2
A	1.26E-05	m^2
N	1000	seeds
mass N	5	g
m	0.0050	g/seed
m	5.00E-06	kg/seed
W	4.91E-05	N
P=ΔP	3.9033	Pa
ΔP	0.000566	psi
ΔP	0.00115	in Hg
ρ air	1.2041	kg/m^3
Velocity	2.5462	m/s
d nozzle	0.003	m
A nozzle	7.07E-06	m^2
AV	1.80E-05	m^3/s
AV	1.0799	LPM


Suction Flowrate vs. Mass
Required Flowrate
Seed Mass, g
0
0.5
1
1.5
2
2.5
3
3.5
4
0
10
20
30
40
50
60

Appendix F: Gantt Chart and Timeline for Project

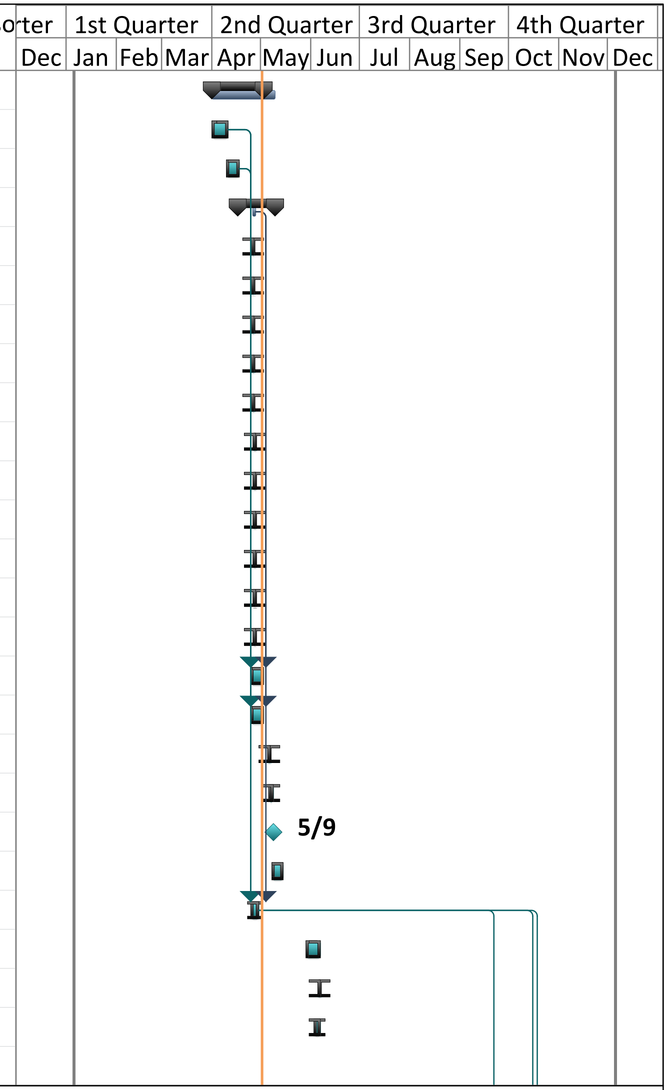
ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Project Selection**	**3 days**	**Mon 1/6/14**	**Wed 1/8/14**	
2		Watch Sponsor Presentations	1 day	Tue 1/7/14	Tue 1/7/14	
3		Turn in Preference Form	2 days	Tue 1/7/14	Wed 1/8/14	2
4		Receive Project Assignment	0 days	Wed 1/8/14	Wed 1/8/14	3
5		**Team Forming**	**7 days**	**Thu 1/9/14**	**Mon 1/20/14**	
6		Intro Letter to Sponsor	4 days	Thu 1/9/14	Tue 1/14/14	
7		Team Contract	3 days	Tue 1/14/14	Thu 1/16/14	
8		First Sponsor Meeting	0 days	Mon 1/20/14	Mon 1/20/14	
9		**Project Proposal**	**14 days**	**Thu 1/16/14**	**Tue 2/4/14**	
10		Problem Statement	6 days	Thu 1/16/14	Thu 1/23/14	
11		QFD	6 days	Thu 1/23/14	Thu 1/30/14	
12		Proposal Report	4 days	Thu 1/30/14	Tue 2/4/14	10
13		First Team Evaluations	1 day	Thu 2/6/14	Thu 2/6/14	
14		First Reflection	2 days	Mon 2/10/14	Tue 2/11/14	
15		**Brainstorming**	**17 days**	**Mon 2/3/14**	**Tue 2/25/14**	
16		Concept Modeling	3 days	Tue 2/11/14	Thu 2/13/14	
17		Present Concept Models	1 day	Tue 2/18/14	Tue 2/18/14	16
18		Pugh Matrices	4 days	Thu 2/13/14	Tue 2/18/14	
19		Decision Matrices	4 days	Thu 2/20/14	Tue 2/25/14	
20		Gantt Chart	3 days	Tue 2/25/14	Thu 2/27/14	
21		Finish All Yellow Tags	41 days	Mon 1/6/14	Sat 3/1/14	
22		**Concept Design Report**	4 days	Fri 2/14/14	Wed 2/19/14	16
23		**Preliminary Design Review**	0 days	Fri 2/14/14	Fri 2/14/14	16
24		Second Team Evaluations	1 day	Thu 3/13/14	Thu 3/13/14	
25		Second Reflection	3 days	Thu 3/13/14	Sun 3/16/14	
26						



Project: Senior Project Plan
Date: Fri 5/2/14

Task	External Milestone	Manual Summary Rollup
Split	Inactive Task	Manual Summary
Milestone	Inactive Milestone	Start-only
Summary	Inactive Summary	Finish-only
Project Summary	Manual Task	Deadline
External Tasks	Duration-only	Progress

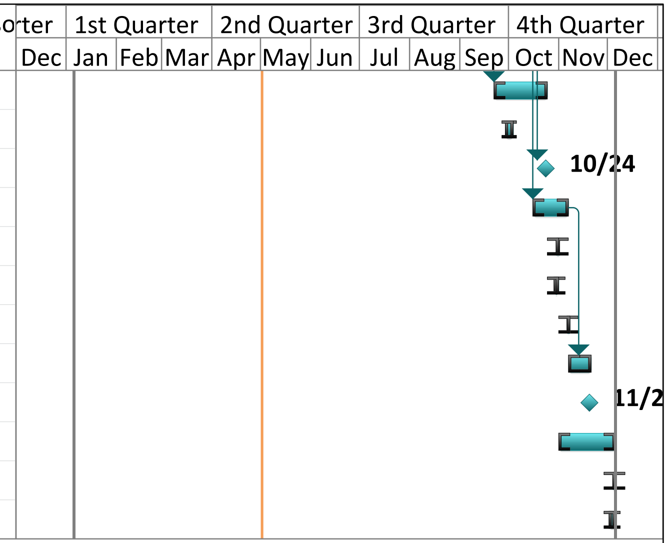
ID	Task Mode	Task Name	Duration	Start	Finish	Predecesso
27		**Final Design Report**	**24 days**	**Tue 4/1/14**	**Fri 5/2/14**	
28		Design	8 days	Tue 4/1/14	Thu 4/10/14	
29		Model	6 days	Thu 4/10/14	Thu 4/17/14	
30		**Analysis & Testing**	**17 days**	**Thu 4/17/14**	**Fri 5/9/14**	
31		Flow rate test	1 day	Sat 4/26/14	Sat 4/26/14	
32		water nutrient ratio test	1 day	Sat 4/26/14	Sat 4/26/14	
33		nutrient volume calibration	1 day	Sat 4/26/14	Sat 4/26/14	
34		flow rate calibration	1 day	Sat 4/26/14	Sat 4/26/14	
35		tool pickup test	1 day	Sat 4/26/14	Sat 4/26/14	
36		tool security test	1 day	Sun 4/27/14	Sun 4/27/14	
37		tool release test	1 day	Sun 4/27/14	Sun 4/27/14	
38		small seed suction	1 day	Sun 4/27/14	Sun 4/27/14	
39		small seed planting	1 day	Sun 4/27/14	Sun 4/27/14	
40		large seed suction	1 day	Sun 4/27/14	Sun 4/27/14	
41		large seed planting	1 day	Sun 4/27/14	Sun 4/27/14	
42		Schedule CDR w/ Sponsor	6 days	Fri 4/25/14	Fri 5/2/14	28,29,30
43		Complete and Format Report	6 days	Fri 4/25/14	Fri 5/2/14	28,29,30
44		Third Team Evaluations	1 day	Tue 5/6/14	Tue 5/6/14	
45		Third Reflection	3 days	Tue 5/6/14	Thu 5/8/14	
46		**Critical Design Review**	0 days	Fri 5/9/14	Fri 5/9/14	
47		Individual Ethics Memo	5 days	Thu 5/8/14	Wed 5/14/14	
48		**All Parts & Materials Ordered**	3 days	Fri 4/25/14	Tue 4/29/14	28,29,30
49		End of Quarter Report	7 days	Thu 5/29/14	Fri 6/6/14	
50		Fourth Team Evaluations	1 day	Fri 6/6/14	Fri 6/6/14	
51		Fourth Reflection	4 days	Tue 6/3/14	Fri 6/6/14	
52						



Project: Senior Project Plan
Date: Fri 5/2/14

Task		External Milestone		Manual Summary Rollup	
Split		Inactive Task		Manual Summary	
Milestone		Inactive Milestone		Start-only	
Summary		Inactive Summary		Finish-only	
Project Summary		Manual Task		Deadline	
External Tasks		Duration-only		Progress	

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
53		**Prototype Construction**	25 days	Mon 9/22/14	Fri 10/24/14	48
54		Project Memo Update to Sponsor	5 days	Mon 9/29/14	Fri 10/3/14	
55		**Project Hardware Demo**	0 days	Fri 10/24/14	Fri 10/24/14	48
56		Project Testing	16 days	Thu 10/16/14	Thu 11/6/14	48
57		Fifth Team Evaluations	1 day	Fri 10/31/14	Fri 10/31/14	
58		Fifth Reflection	3 days	Wed 10/29/14	Fri 10/31/14	
59		Complete Senior Survey	2 days	Thu 11/6/14	Fri 11/7/14	
60		Prepare for Senior Design Expo	10 days	Fri 11/7/14	Thu 11/20/14	56
61		**Senior Design Expo**	0 days	Thu 11/20/14	Thu 11/20/14	
62		Final Project Report	26 days	Sat 11/1/14	Fri 12/5/14	
63		Sixth Team Evaluations	1 day	Fri 12/5/14	Fri 12/5/14	
64		Sixth Refletion	4 days	Tue 12/2/14	Fri 12/5/14	



Project: Senior Project Plan
Date: Fri 5/2/14

Task	External Milestone	Manual Summary Rollup
Split	Inactive Task	Manual Summary
Milestone	Inactive Milestone	Start-only
Summary	Inactive Summary	Finish-only
Project Summary	Manual Task	Deadline
External Tasks	Duration-only	Progress

Appendix G: Failure Modes and Effects Analyses (FMEA) and Design Verification Plans and Reports (DVP&R)

Potential
Failure Mode and Effect Analysis
(Design FMEA)

X System
___ Subsystem
___ Component

Model Year(s)/Vehicle(s): Farmbot 2.0
Core Team: Farmbot Farmboys

Design Responsibility:
Key Date: 11/20/2014

FMEA Number: 1
Page 1 **of** 1
Prepared By: Scott, James, Bryan
FMEA Date (Orig.) (3/11/2014

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Sev	Action Results: Occur	Action Results: Crit
3D movement	goes to wrong position	disrupted garden layout,	7	frame deflection	4	28	Reinforced Frame		consult Rory	7	2	14
		improperly maintained		motor miscalibration	3	21	Proper Programming		consult programmers		2	14
		plants		data loss	1	7	Keep track of memory		consult programmers		1	7
				forced movement	7	49	surrounding fence		consult Rory		5	35
				timing belt stretches	4	28	stronger belts		consult Rory		2	14
	doesn't move	loss of primary function	8	obstruction	6	48	track covers		consult Rory	8	4	32
				track misalignment	3	24	Reinforced Frame		consult Rory		2	16
				motor failure	2	16	Quality motors		consult Rory		1	8
				no power	1	8	backup battery		consult Rory		1	8
				timing belt breaks	1	8	stronger belts		consult Rory		1	8
				severe track corrosion	1	8	weatherproof material		consult Rory		1	8
Seeding	Doesn't pick up seed	seed wont get planted	8	misalignment	3	24	large tolerance		larger holes on seed bay	8	2	16
				insufficient air velocity	1	8	bigger pump		calculate pump size		1	8
				obstruction of flow	2	16	small tip large hose		reversible flow direction		1	8
				no power	4	32	backup battery		include backup battery		2	16
				wrong tip size	6	48	explicit instructions		include user manual		4	32
				bent tip	4	32	stronger tip		calculate material strength		3	24
Watering	excessive/ insufficient	drown/ starve plants	6	valve miscalibration	3	18	proper programming		consult programmers	6	1	6
	flow			pinched hose	3	18	anti-kink coil hose		see recommended action		1	6
				clogged exit nozzle	1	6	clearance from ground		design with clearance		1	6
	no flow	no watering	8	kink in hose	2	16	anti-kink coil hose		see recommended action	8	1	8
				valve stuck	1	8	sufficiently power valve		calculate power requirement		1	8
				disconnected hose	2	16	explicit instructions		include user manual		1	8
Interchangeable Tools	does not attach tool	negates farmbot	8	linear actuator stuck	4	32	low stiction acutator		calculate actuator stiction	8	2	16
		functions		actuator pin breaks	1	8	strong actuator pin		calculate actuator pin strength		1	8
				misalignment	2	16	taper/larger tolerance		design with taper/clearance		1	8
				holder breaks	2	16	stronger material		calculate material strength		1	8
	Drops/release tool at	drops tool on plant,	7	holder breaks	2	14	stronger material		calculate material strength	7	1	7
	inopportune moments	incomplete performance		pin releases improperly	4	28	proper circuitry		use circuit analysis		2	14
	Data/power not working	Tools do not function,	8	misalignment of contacts	3	24	larger tolerance		design with clearance	8	2	16
		Farmbot does not know		insufficient power	3	24	design to power spec		use circuit analysis		2	16
		what to do with tool		excessive power	2	16	design to power spec		use circuit analysis		1	8
				wrong format data	2	16	proper programming		consult programmers		1	8

Potential
Failure Mode and Effect Analysis
(Design FMEA)

___ System
_X_ Subsystem
___ Component

FMEA Number: 2

Design Responsibility:

Page 1 of 1

Model Year(s)/Vehicle(s): Farmbot 2.0 Water Delivery

Key Date: 11/20/2014

Prepared By: Scott Herrington

Core Team: Farmbot Farmboys

FMEA Date (Orig.) (3/12/2014

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Sev	Occur	Crit
Hose	No flow	No watering	8	Kink	2	16	anti kink hose	20-Nov	anti kink hose	8	1	8
	Leak/ Crack	Decreased Flow, wasted water	6	Sun Damage	4	24	use UV resistant hose	20-Nov	use UV resistant hose	6	2	12
Solenoid Valve	Doesn't open	No flow, no watering	8	insufficient power	2	16	proper poewr source and programming	20-Nov	proper poewr source and programming	8	1	8
	miscalibration	incorrect water/nutrient ratio	5	improper programming	4	24	proper programming	20-Nov	proper programming	5	2	10
Nutrient Pump	doesn't suck up nutrients	plants don't get nutrients	7	insufficient power	3	21	proper circuitry	20-Nov	proper circuitry	7	2	14
				hose doesn't reach reserviors	3	21	program movement with tolerance	20-Nov	program movement with tolerance		2	14
	miscalibration	incorrect nutrient ratio	6	improper programming	3	18	proper programming	20-Nov	proper programming	6	2	12
Sprinkler Tip	clogged tip	decreased or stopped flow	7	Dirt clog by improper tolerance with ground	3	21	proper programming & tolerance	20-Nov	proper programming & tolerance	7	1	7

Potential
Failure Mode and Effect Analysis
(Design FMEA)

System: Farmbot
Subsystem: Universal Tool Holder
Component: Universal Tool Holder System

Model Year(s)/Vehicle(s): Farmbot 2.0

Core Team: James, Scott, Bryan

Design Responsibility: James, Scott, Bryan

Key Date: 03/12/14

FMEA Number: 1.0

Prepared By: James Cruz

FMEA Date (Orig.) 3/12/14 (Rev.) 1

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Sev	Action Results: Occur	Action Results: Crit
Holds tool	Bottom of holder cracks/snaps	Tools all inoperable	8	Weak material	6	48	Use Strong plastic or metal	Whole team	Use Strong plastic or metal	8	3	24
				Bottom too thin	5	40	Properly design thickness	Whole team	Properly design thickness		2	16
				actuator pin breaks	1	8	Use adequate actuator	James	Use adequate actuator		1	8
				Spring force and tool weight too high	6	48	Keep in mind the wieght of tools when designing attachments. Reduce spring force if necessary	Whole team	Keep in mind the wieght of tools when designing attachments. Reduce spring force if necessary		3	24
Picks up tool	Actuator jams	Renders tools unusable	8	Stiction in actuator	7	56	Select strong enough actuator; design to pre-compress actuator	James	Select strong enough actuator; design to pre-compress actuator	8	5	40
				Actuator pin/nub has ineffective geometry	5	40	Select actuator with and appropriate nub	James	Select actuator with and appropriate nub		2	16
	Guidance nub misses guidance v-notch	Unable to pick up tools	8	Notch to small, tolerance too tight	4	32	Design notch to be big enough. Make some allowance for the nub slot	Whole team	Design notch to be big enough. Make some allowance for the nub slot	8	3	24
		Guidance nub breaks off of tool interface	7	Material too weak	4	28	Choose a material with adequate strength	Whole team	Choose a material with adequate strength	7	2	14
Releases tool	Actuator jams	Renders tools unusable	8	Stiction in actuator	7	56	Select strong enough actuator; design to pre-compress actuator	James	Select strong enough actuator; design to pre-compress actuator	8	5	40
	Tool interface gets stuck in tool holder	Renders all other tools unusable	7	Obstructions, debris caught between tool interface and mount	6	42	Keep tool mount and tools clear of debris, dirt, etc	Whole team	Develop ideas to minimize exposure of tool interfaces	8	5	40
							Have a "dummy" tool that the tool holder holds while other tools not in use	Whole team	Have a "dummy" tool that the tool holder holds while other tools not in use	8	3	24
		Renders all other tools unusable	7	Tool too light to drop free and/or spring too light to eject tool	5	35	Estimate and/or calculate the force necessary to eject tool	Whole team	Select a spring that can provide sufficient force	7	2	14

Potential
Failure Mode and Effect Analysis
(Design FMEA)

System: Farmbot
Subsystem: Universal Tool Holder
Component: Universal Tool Holder System

Design Responsibility: James, Scott, Bryan

FMEA Number: 1.0

Page 1 of 1

Model Year(s)/Vehicle(s): Farmbot 2.0

Key Date: 03/12/14

Prepared By: James Cruz

Core Team: James, Scott, Bryan

FMEA Date (Orig.) 3/12/14 **(Rev.) 1**

									Action Results			
Item / Function	**Potential Failure Mode**	**Potential Effect(s) of Failure**	**Sev**	**Potential Cause(s) / Mechanism(s) of Failure**	**Occur**	**Crit**	**Recommended Action(s)**	**Responsibility & Target Completion Date**	**Actions Taken**	**Sev**	**Occur**	**Crit**
	Spring falls out of tool holder	Reduce ability to effectively eject tools	6	Spring not sufficiently secured in tool holder	5	30	Design a means to hold the spring in place	Whole team	Design a means to hold the spring in place	6	3	18
Transfer data and power	Contacts misalign	Disables flow of powers to tools that need it	7	Tool interface doesn't align properly within tool holder	4	28	Design self-aligning system for tool interface and tool holder	Whole team	Incorporate self-aligning system for tool interface and tool holder	7	2	14
		Disables tools from transferring data	6	Tool interface doesn't align properly within tool holder	4	24	Design self-aligning system for tool interface and tool holder	Whole team	Incorporate self-aligning system for tool interface and tool holder	6	2	12
	Contacts burn out	Disables flow of powers to tools that need it	7	Tool interface doesn't align properly within tool holder	4	28	Research materials used for electrical contacts	James	Use proper material for contacts	7	2	14

Potential
Failure Mode and Effect Analysis
(Design FMEA)

___ System
_X_ Subsystem
___ Component

FMEA Number: 2

Design Responsibility:

Model Year(s)/Vehicle(s): Farmbot 2.0 Small Seeder

Key Date: 11/20/2014

Prepared By: Bryan Rodriguez

Core Team: Farmbot Farmboys

FMEA Date (Orig.) (3/12/2014

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Sev	Occur	Crit
Air Pump	wrong flow direction	user confusion, reverse functionality	6	miscalibration	3	18	explicit instructions, proper programming		include user manual	6	2	12
				-----------	------	-----			consult programmers		----	----
				connected improperly	5	30	explicit labeling		include labels in design		2	12
	too little flow	insuficient flow velocity to pick up seed	7	insufficient power	2	14	design to power spec		use circuit analysis	7	1	7
				obstruction	4	28	anti-clogging mesh		add mesh as recommended		2	14
				too small of a pump	2	14	larger pump		calculate pump size needed		1	7
	does not flow	loss of primary function	8	obstruction	4	32	anti-clogging mesh		add mesh as recommended	8	4	32
				pump failure	3	24	quality pump		consult advisor and Rory		2	16
				corrosion of internal parts	3	24	weatherproof material		research weatherproofing			
				no power	4	32	backup battery		include backup battery		1	8
				air leak	3	24	sealed pump		seal exits and parts of pump		1	8
Air Hose	rip/tear	prevent air flow	7	internal from object	2	14	smaller hose (nothing in)		see recommended action	7	1	7
				UV degradation	4	28	UV protected hose		see recommended action		1	7
				external attackers	6	42	enclosure		design enclosure for hose		2	14
	too little flow	loss of functionality	8	rip or tear	3	24	thicker hose walls		see recommended action	8	2	16
				obstruction	2	16	smaller hose		see recommended action		1	8
				pinched hose	3	24	anti-kink coil hose		see recommended action		1	8
Seeder Body	structurally unstable	breaks easily, cannot force seed into ground	8	low material strength	4	32	stronger material		calculate material strength	8	2	16
				high compressibility	5	40	stronger material		calculate buckling		2	16
				external attacker	2	16	enclosure		see recommended action		1	8
	does not transfer flow	loss of functionality	8	leaking at flow entrance	3	24	sealed flow entrance		see recommended action	8	1	8
				crack in body	4	32	stronger material		calculate material strength		2	16
				connected improperly	5	40	explicit instructions		include user manual		2	16
Seeder Tip	does not attach	unable to pick up seed	8	improper installation	5	40	explicit instructions		include user manual	8	2	16
				broken tip	3	24	stronger tip material		calculate material strength		1	8
	Drops/releases seed at wrong moment	incomplete performance	8	tip pops out	2	16	stiffer/less maleable mat.		analyze material properties	7	1	7
				tip breaks	4	32	stronger tip material		calculate material strength		2	14
				not enough air	3	24	seal connectors, proper pump		see recommended action		2	14
				wrong tip size	5	40	explicit instructions		include user manual		2	14

ME428 DVP&R Format

Report Date	3/13/2014	Sponsor: Rory Aronson	Component/Assembly: Farmbot 5.0	REPORTING ENGINEERS: James Cruz, Scott Herrington, Bryan Rodriguez

TEST PLAN										TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Watering nozzle sprays water	Visual inspection of flow	By visual inspection, water is released	Cal Poly Senior Project Team	DV	2	Prototype 2.0	5/26/2014	11/20/2014	Water sprayed	2	0	Successfully sprayed water 1st time too much pressure; forced off barb from solenoid Added hose clamps for 2nd time: successful
2	Flowrate of water sprayed can be controlled	Flowrate test	Water is ejected at specified (variable, user selected) flow rate	Cal Poly Senior Project Team	DV	1	Prototype 2.0	5/26/2014	11/20/2014	Too much flow	0	1	Too much pressure from water line due step downs Could not control flowrate with solenoid
3	Nutrient Pump sucks/releases nutrients into water stream	Visual inspection of flow	Specified amount of nutrient (or test fluid) sucked up and mixed into water flow	Cal Poly Senior Project Team	DV	1	Prototype 2.0	5/26/2014	11/20/2014	Nutrients suck and release	1	0	Successfully mixed nutrients into water line
4	Nutrient Pump calibration	Measure the flowrate of the nutrient pump at a given motor speed to calibrate the pump	Nutrients are sucked and released at a constant flowrate	Cal Poly Senior Project Team	DV	1	Prototype 2.0	5/26/2014	11/20/2014	0.1675 L/min	1	0	Set stepper motor to constant speed for set time frame Measured by varying time frame to get flow
5	Seeder picks up and carries small seeds	Pass/fail test	Visual inspection to observe that seeds do not drop	Cal Poly Senior Project Team	DV	10	Prototype 2.0	5/26/2014	11/20/2014	Seed picked up	10	0	Used sweet pea seed as small seed Successful Occassionally had a bit of difficulty in picking up seed
6	Seeder plants/releases small seeds	Pass/fail test	Visual inspection to determine if seeds are planted at sufficient depth (variable, depends on seeds	Cal Poly Senior Project Team	DV	10	Prototype 2.0	5/26/2014	11/20/2014	Seed released	10	0	Cutting power released seed
7	Seeder picks up large seeds	Pass/fail test	Visual inspection to observe that seeds do not drop	Cal Poly Senior Project Team	DV	10	Prototype 2.0	5/26/2014	11/20/2014	Seed picked up	10	0	Used squash seed as large seed Successful
8	Seeder releases large seeds	Pass/fail test	Visual inspection to determine if seeds are planted at sufficient depth (variable, depends on seeds	Cal Poly Senior Project Team	DV	10	Prototype 2.0	5/26/2014	11/20/2014	Seed released	10	0	Cutting power released seed
9	Tool mount can pick up tool	Pass/fail test	Visual inspection; alignment pin enters slot; actuator engages tool interface	Cal Poly Senior Project Team	DV	50	Prototype 2.0	5/26/2014	11/20/2014	Tool picked up	45	5	Hand-manually tested Passed all tests for magnet-on-magnet interfaces
10	Tool mount holds tool	Timed duration test	Visual Inspection: room in holder for one tool interface	Cal Poly Senior Project Team	DV	1	Prototype 2.0	5/26/2014	11/20/2014	Tool held indefinitely	1	0	This was expected because we were using magnets
11	Tool mount releases tool with ease	Pass/fail test	Tool ejects free from tool holder	Cal Poly Senior Project Team	DV	1	Prototype 2.0	5/26/2014	11/20/2014	Tool released	1	0	Direct magnet-on-magnet was hard to release Fixed issue by adding rubber washer in between
12	Tool mount power and data connections function	Continuity test	Audible inspection; voltmeter beeps to show continuity between connections	Cal Poly Senior Project Team	DV	2	Prototype 2.0	5/26/2014	11/20/2014	Voltmeter beeped (showed continuity)	1	0	Tested all possible connections/interfaces for continuity

Appendix H: Assembly Guide And Operator's Manual

Assembling the Magnets into the Tool Mount

1. Using plastic epoxy glue, affix one magnet into the air line of the tool mount. Warning: Be careful not to obstruct the passageway with glue. You may use some kind of long rod (such as a stretched paper clip or wire hanger) to prevent glue from seeping into the passageway.
2. Using plastic epoxy glue, affix magnets into the water and nutrient lines of the tool mount. These magnets should be placed in the opposite magnetic orientation than the first magnet.
3. Cover the bottom of the tool holder with tape to hold the magnets in place while the plastic epoxy glue dries. Let sit for at least 30 minutes.

Assembling the Magnets into the Tools

1. The nozzle of the seeder tip lines up with the front barb of the tool mount. Align the magnets in the seeder tip so that they attract to the corresponding magnets in the tool mount.
2. Use plastic epoxy glue to affix the magnets within the seeder tool tip.
3. Use superglue to attach rubber washers on top of the magnets. The top of the rubber washers should be nearly flush with the top surface of the tool.
4. Place M5 screws through the holes in the tool.
5. Connect a short wire between the two screws. Fix one end of each wire to each screw by clamping it to the tool with an M5 hex nut.
6. The fluid lines of the water and nutrient tool tip line up with the rear barbs of the tool mount. In a similar manner, attach the magnets and gaskets within the water and nutrient tool tip in the same magnetic orientation as the seeder tool tip.

Assembling the Power and Data Contacts within the Tool Mount

1. Take one of the contact screws. Place one of the contact springs around the threaded portion.
2. Hold the tool mount upright. Slip the screw through one of the screw holes on the bottom so that the head is oriented downwards.
3. Hold the screw in place so that the head of the screw is flush with the bottom of the tool holder, and the end of the screw protrudes from the top of the tool holder. Thread an M5 nut on to hold the screw in place on the tool holder.
4. Slip on a ring terminal on top of the hex nut.
5. Add another hex nut on top of the ring terminal to hold the ring terminal in place. Tighten both hex nuts toward each other to secure the ring terminal in place.
6. Repeat steps 1-5 to add the other three contact screws to the tool mount.

Attaching The Universal Tool Mount to the Farmbot Tool Arm

1. Orient the tool mount so that the barbs for the air, water, and nutrient lines face up. Align the mounting screw holes in line with the slot of the extrusion. The bottom of the tool mount should be flush with the bottom of the extrusion.
2. Place two M5 tee-nuts into the slot of the extrusion and align them with the mounting screw holes of the Tool Mount
3. Insert an 10mm M5 screw through each hole and secure. Tighten the screw enough to prevent the screw from falling out. Warning: Do not overtighten the screws, as this may fracture the mounting bracket of the tool mount. Use M5 washers or tee-nuts as spacers between the mounting bracket and the screws to create a secure fit.

Attaching the Nutrient Syringe to the Farmbot Tool Arm

1. Attach the syringe cap to the top of the syringe plunger. Place the cap on the top of the plunger and screw four 5mm M3 screws into the holes to secure the cap.
2. Place the tool arm down on a horizontal surface with the tool holder on the top face.
3. Place the syringe spacers within the top-facing slot of the tool arm. The spacer with the mounting flange should be placed farther from the tool mount. The spacers should be 1-2 inches apart.
4. Place the syringe on top of the syringe spacers. Arrange them until they are spaced appropriately with the tool holder.
5. Place an M5 tee-nut within the slot with the syringe spacer with mounting bracket and line it up with the mounting hole.
6. Insert and tighten an 8mm M5 screw to secure the bracket to the tool arm.
7. Wrap a zip tie around the syringe and tool arm, securing the syringe to the tool arm as tightly as possible to prevent slipping.
8. Facing the front of the tool mount, attach a ⅜” vinyl tube by screwing it onto the tip of the syringe. Attach the other end to the tool mount by carefully slipping it over the back left barb.
   Warning: Unless proper care is taken, the barbs on the tool holder can be broken easily.

Attaching the Stepper Motor to the Tool Arm

1. Screw the motor into the motor bracket using M3 screws. The bottom, with the large hole for the lead screw, should face toward the tool mount.
2. Push the syringe plunger completely into the syringe body.
3. Turn the lead screw of the stepper motor until it is in its lowest position with the top end flush to the top surface.
4. Mount the motor to the tool arm using two M5 tee-nuts in the same manner as the tool mount. Do not tighten the screws yet. Line up the lead screw of the stepper motor with the top hole in the syringe cap.
5. Slide the motor towards the syringe until the lead screw fits inside the hole on the top of the syringe cap.
6. Turn the lead screw so that the flat face lines up with the set screw hole in syringe cap.
7. Carefully screw in the set screw to secure the lead screw within the syringe cap.
   Warning: Do not overtighten the set screw against the lead screw. Doing so will misalign the leadscrew and possibly stall the stepper motor, as well as strip the hole in the syringe cap.
8. Tighten the screws holding the stepper motor bracket to the tool arm. Add washers or spacers as necessary.
9. Connect the stepper motor to an Arduino control board.

Attaching the Vacuum Pump

1. Hold the vacuum pump with the flat side against the extrusion on the same side that the motor bracket is screwed to. The barbs should be oriented towards the tool mount.
2. Secure the vacuum pump by tying it to the tool arm with a zip tie. Tighten it as much as possible.

3. Facing the front of the tool mount, connect a ⅜" vinyl tube from the suction end of the vacuum pump to the frontmost barb in the tool mount.
4. Connect wires for electricity from a 12V power supply to the contacts on the vacuum pump

Attaching the Water Supply Line and Solenoid Valve

1. Connect garden hose to spigot.
2. Connect the other end of the garden hose to the solenoid valve.
3. Connect the ¾"-to-⅝" adapter to the other end of the solenoid valve.
4. Connect a ⅝" tube to the barb on the adapter, followed by a ⅝"-to-½" reducer coupling.
5. Connect a ½" tube followed by a ½"-to-⅜" reducer coupling.
6. Connect a ⅜" tube from the reducer coupling to the rear right barb on the tool mount.
7. Zip tie a portion of the water tube to the tool arm where convenient to prevent the tube from breaking off the barb.
8. Connect wires for electricity from a 12V power source to the contacts on the solenoid valve.

How to Operate the Farmbot Tool Testing Apparatus

Attaching/Detaching Tools to the Tool Mount

1. Hold the desired tool upright with the nozzle pointing downwards.
2. Holding the fully assembled testing apparatus upright, gently bring it directly over the tool with the magnets correctly aligned with each other.
3. Holding the tool in place, slowly bring the tool mount into contact with the tool. Warning: Do not allow the tool to snap into the tool mount. This may cause the magnets to detach from the tool mount or pinch your hand or finger.
4. Release the tool. It should now be firmly connected to the tool mount.

Operating the Syringe Pump and Stepper Motor

1. Ensure that the lead screw is firmly connected to the syringe cap and is adequately aligned. Check that the Arduino is properly programmed and connected to a power source.
2. Connect the stepper motor to the Arduino. The stepper motor should move the lead crew up and down, thereby operating the syringe.

Operating the Solenoid Valve

1. Check that all water lines are properly and securely connected.
2. Attach the water and nutrient tool tip to the tool mount.
3. Turn on the water spigot that the garden hose is attached to.
4. Warning: Point the nozzle in a safe direction away from furniture or devices that may be damaged by water.
5. Connect the power lines to the contacts on the solenoid. Warning: the water may eject from the nozzle at high velocity and/or pressure depending on the pressure of the water coming into the solenoid valve. It is recommended that the water should be released outside only.