

WPI

AGR*Bodine*
The Arthur G. Russell Company

Worcester Polytechnic Institute

A Major Qualifying Project

Industrial 3D Printer

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Abstract

Fused Deposition Modeling (FDM) 3D printing is an increasingly more prevalent way of fast-paced manufacturing and design. FDM allows manufacturers a low cost, iterative manufacturing for rapid prototyping and design of parts. This process is limited in terms of the size of parts able to be made, the durability of the printer, and the variety, strength and other properties of the printing materials used. The main objective of this MQP was to design and build an FDM printer comprised of industrial-grade components that overcame the downfalls of FDM in an industrial setting. Despite multiple design setbacks, spatial constraints, and difficulties obtaining required materials, the end product was an FDM system composed of industrial grade parts, including a Denso four axis robot arm, with the ability to print a large size prototype and other end-use parts for our sponsor, AGR Bodine Co.

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Table of Contents

Abstract	ii
Table of Contents	iv
Table of Tables	vi
Table of Equations	vii
Table of Figures	viii
1. Introduction	- 1 -
2. Background	- 3 -
2.1 3D Printers	- 3 -
2.1.1 Extruders	- 3 -
2.1.2 Materials	- 5 -
2.1.3 Heated Beds and Chambers	- 6 -
2.1.4 Slicers	- 7 -
2.1.5 Control Systems	- 8 -
2.2 Vibratory Systems	- 8 -
2.2.1 Components of a System	- 8 -
2.2.2 Benefits	- 10 -
2.2.3 Downsides	- 11 -
3. Methodology	- 12 -
3.1 Design Considerations	- 12 -
3.1.1 Decision charts	- 12 -
3.1.2 Work Piece Vs. Print Head Movement	- 17 -
3.1.3 Structural Rigidity	- 18 -
3.1.4 Heated Chamber and Plate	- 18 -
3.1.5 Filament Choice	- 21 -
3.2 Design	- 21 -
4. Results	- 23 -
4.1 Setbacks	- 23 -
4.1.1 Location	- 23 -
4.1.2 Material Availability	- 23 -
4.1.3 Software Incompatibilities	- 24 -
4.2 Project Results	- 25 -
5. Conclusions	- 26 -

5.1 Discussion of Results	- 26 -
5.2 Future Work	- 26 -
Appendix 1: Industrial 3D Printer	- 28 -
Citations	- 29 -

Table of Tables

Table 1: Motion System Decision Matrix.....	- 13 -
Table 2: Extruder Decision Matrix	- 16 -

Table of Equations

Equation 1: Fourier's Law.....	- 19 -
Equation 2: Specific Heat Capacity Equation.....	- 19 -
Equation 3: Solving for Change in Temperature of Lexan.....	- 20 -
Equation 4: Watts to Joules.....	- 20 -
Equation 5: Change in Temperature of Air.....	- 21 -

Table of Figures

Figure 1: Vibratory Bowl.....	- 2 -
Figure 2: Bowden vs Direct Drive Extruders	- 4 -
Figure 3: Vibratory System.....	- 9 -
Figure 4: VibroBlock	- 10 -

1. Introduction

3D printing is the process of making a physical object from a digital model. This is usually done by laying down thin layers of material successively rather than removing material from a larger piece. It has been around since the late 1980's when it was known as Rapid Prototyping. The process was originally conceived as a fast and more cost-effective method for creating prototypes for product development. Today 3D printers are used in many industries as well as for personal use. However, there are very few printers that are can produce larger, heavier, and more robust industrial components.

The Arthur G Russell company uses vibratory systems made of bowls, as shown in Figure 1, and rails to orient and move parts on their machines. Currently, these bowls and rails are created using cast aluminum moldings of various sizes. These moldings then need to be milled and machined to ensure they are precise enough to orient and move the parts properly. These moldings are also heavy and therefore require larger and heavier frames in order for the vibratory systems to work properly. The implementation of a 3D printer to create these bowls and rails will reduce time and cost when making these machines. After the bowls and rails are printed, less machining would be involved in comparison with the traditional methods.



Figure 1: Vibratory Bowl

2. Background

2.1 3D Printers

3D printing is a form of additive manufacturing that builds a physical object layer-by-layer, based on a computer model. This technology dates back to the early 1980s when Charles Hull invented stereolithography (STL), which is the process of using ultraviolet light to harden liquid polymers. By the late 1990s he had created a stereolithographic apparatus machine, which made it possible to create parts, layer-by-layer, in a fraction of the time it would normally take [1]. As technology progressed, many versions of 3D printers and 3D printing technologies were developed. Some of these include selective laser sintering (SLS) and Fused Filament Fabrication (FFF). On top of the various printing technologies that have developed, printers have adapted to be able to print a wide variety of materials.

2.1.1 Extruders

The extruder on a FDM 3D printer is an integral component of its functionality. The extruder is responsible for moving the correct amount of material through a heating element for the printing of layers. Extruders contain a stepper motor that moves the material through a drive and idle gear that work together to push the filament towards the heated end. There are a few different types of extruders used in 3D printing that each have their own benefits.

The two main types of extruders used in 3D printing are Bowden and direct drive extruders, as shown in Figure 2. The main difference between these is the process in which the material is fed into the printing end of the carriage. In Bowden extruders, filament is fed through a Bowden tube into the printing end of the carriage [2]. This process results in a much lighter print head, faster printing, more accuracy, and increased resolution. The downside to the Bowden

extruder is increased friction resulting in difficulty creating flexible filaments which is caused from the long travel distance of the filament [2]. In direct drive extruders, the extruder is directly attached to the printing end. The short travel distance allows for increased responsiveness to extrusions and retractions, which results in more accurate print results. Other benefits of these extruders include lower required torque to extrude the filament and ease of printing flexible materials. The downside to the direct drive extruders is the increased mass of the driver head which increases the chances of error in printing [2].

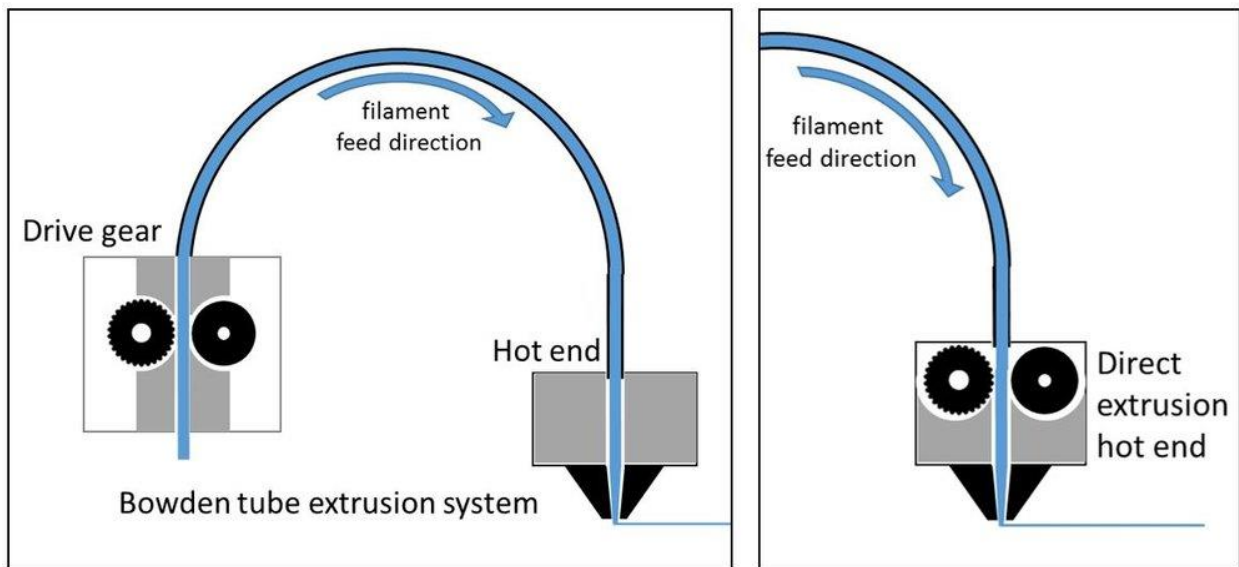


Figure 2: Bowden vs Direct Drive Extruders

Pellet extruders are one of the newer emerging types of extrusion. These extruders eliminate the manufacturing process and cost involved in turning plastic pellets into spools. One kilogram of filament can cost up to ten times as much as the same amount of material in pellet form making this form more desirable [3]. An additional advantage is the rapid speed at which pellet extruders can print. However, there are some disadvantages that come along with these extruders including their weight and retraction. Pellet extruders are much heavier than traditional extruders because of the need to convert the pellets into usable filament. They also do not have

the ability to retract and therefore have decreased control over the print. This technology is relatively new and therefore is not as robust as traditional filament extruders.

2.1.2 Materials

3D printers have the ability to print a wide variety of materials with different characteristics and requirements. The most common types of materials are Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), and Polyvinyl Alcohol (PVA). However, there are many more, uncommon materials used in 3D printing such as polycarbonate, nylon, carbon fiber, and metals.

ABS is one of the most popular materials to print because it is inexpensive, applicable to most printers, mechanically strong, and has a long lifespan. However, some downsides to ABS are that it is toxic, requires a heated bed, and is prone to warping. This material has a print standard of 230°C and requires an enclosure as it releases toxic fumes.

PLA is also a popular printing material because it is easy to print, does not require a heated bed, is environmentally friendly, and prints quickly. It is often used for medical purposes as it is biodegradable [4], but it is also often used by hobbyist using 3D printers because of its usability. Some difficulties with PLA is that it is not very sturdy and prone to deform as well as it is difficult to machine after printing. This material is one of the most commonly used materials in 3D printing.

PVA has the main advantage of being water-soluble. It is commonly used in printers that have multiple extruders in order to create support structures of prints that have overhangs. PVA can then be removed through water, leaving the other materials safely intact [4]. The major disadvantages are that PVA needs to be stored in a sealed container with a desiccant, it is difficult to acquire, and is also very costly [4].

Uncommon materials have their own advantages and disadvantages. They are used less often than the materials above because of the difficulty printing each material or the cost to obtain the material in filament form. Polycarbonate is very flexible and durable and has a high tensile strength. It has a wide variety of applications as it is transparent and easy to print [4]. Polycarbonate requires a heated bed to print and varies in price based on the durability. Nylon is a strong flexible material with UV and chemical resistance [4]. It is less commonly used in printing because it needs to be kept dry, can shrink during prints, can expire, and may require alterations to the printer to be used.

2.1.3 Heated Beds and Chambers

Heated beds are a key part of most 3D printers as they help to improve print quality. Printing onto a heated bed helps to prevent warping during the print process by keeping the part warm during printing which allows for more predictable and uniform shrinking of the plastic. Most materials used in 3D printing require a heated bed to be printed properly as these materials will cool too quickly and cause the parts to warp during the print process. There are a few materials that can be printed without using a heated bed such as PLA, however, parts made with this material can always benefit from a heated bed.

Heated beds can be covered with various different materials with various characteristics to ensure the part sticks to the bed properly. Since different materials have different properties the bed covering can vary by material. For example, a material like PLA can be printed onto a bed covered with painter's tape while a material like Nylon needs a garolite or similar covering to ensure the material will stick to the bed. Ensuring the base layer of the part sticks to the bed is crucial to preventing warp and other inconsistencies with the print. Covering the bed in the correct material can help ensure the best print result.

Heated beds can also be supplemented with heated chambers. Commercial heated chambers, however, are not very common, and as such will require designing and testing for construction and operation of the chamber. Most hobby implementations of heated chambers involve using cardboard and PVC pipes for the structure, and some sort of heating element along with a fan making a kind of convection oven. While this may work for amateur printers doing simple parts with loose tolerances, a commercial printer will require something with more robust design.

2.1.4 Slicers

A slicer software is required in order to be able to print a part on a 3D printer. Slicers take a 3D model and slice it into multiple layers. It then interprets these layers and creates machine code for the printer to use to create an object layer by layer. Most slicer software also allows the user to control extrusion speed, head speed, temperature, wall thickness, fill patterns, and other details for each print. In addition to controlling how the object will be printed, most slicers come with basic modeling options like resizing, mirroring, and merging solid objects.

Multiple slicers, such as CURA, Skeinforge, and Slic3r, are available for personal and commercial use. Each slicer has minor differences from the others, such as UI and supported printer types, but all complete the same task. Some slicers are proprietary as they are tailored to work with a specific brand of printer, such as MakerBot Print which must be used with MakerBot printers and is not compatible with any other brand of 3D printers. Other slicers, such as CURA, can be used for free or bought to be used on any 3D printer. In this case, since the functionality of slicers are the same, the decision of which slicer to use is up to the user and their personal preferences. For slicers that are not proprietary, the user can pick which slicer they would prefer to use based off of UI style, cost, and modeling options.

2.1.5 Control Systems

3D printers are controlled through slicers and the G-code that is generated by slicer software. The G-code is then sent to a controller for the printer which contains multiple PID loops for the movement of the print head, and the temperature of the hot end. These two loops work together to create the desired result. The controller uses thermal sensors called thermocouples to measure the current temperature of the print and build chamber. The thermocouples are used in the temperature PID loop to adjust and regulate the temperature of the heating elements. The controller also can include an automatic bed leveling feature that uses probes to easily level the bed for a more effective print.

2.2 Vibratory Systems

Vibratory Systems are a type of sorting system used in production and assembly lines in place of traditional sorting systems. They are made up of several different components and are used for various reasons. Vibratory systems have the ability to move and orient parts on an assembly system just as efficiently or more efficiently than a traditional sorting system.

2.2.1 Components of a System

A vibratory system is composed of bowls, rails, VibroBlocks, and the counterweight for the system. Each of these components serve different purposes, and are created in different ways. In Figure 3, VibroBlocks are attached to a rail to vibrate the system which moves and orients parts to the bowl on the right side. This bowl is also vibrated by VibroBlocks to move parts further through the system.



Figure 3: Vibratory System

Vibratory feeder bowls are used to feed components for industrial production lines. The bowls are shaken by vibratory blocks which cause the components to vibrate around the bowl into a specific desired orientation and to a specific location. These bowls are created from blanks that are used to mold cast aluminum that is then machined into the required bowl.

VibroBlocks provide the motion required for the system to operate as seen in Figure 4. These blocks are made from “a compact, self-contained magnetic motor, generating straight-line vibratory motion when a pulse of electric current [is] passed through its coil” [5]. These blocks are the base of any vibratory system. They are controlled by controllers that change the duration of the electrical pulses to the motor which changes the amplitude of the vibration [5].



Figure 4:VibroBlock

The frame supports the vibratory system. The vibratory frames hold the bowls, blocks, and counterweight. The frames are constructed by bolting pieces of aluminum together and attaching all the required components to them. The construction is as symmetrical as possible to reduce unwanted vibration forces on the system.

2.2.2 Benefits

There are multiple benefits to a vibratory system as opposed to a traditional sorting system. The vibratory systems are more energy efficient than sorting systems because they are vibrated at a resonant frequency which requires a small amount of energy to keep moving. There are fewer moving parts in a vibratory system in comparison to a traditional sorting system, which is easier to maintain since there are fewer points of potential failure. In addition, vibratory systems have finer control over the movement of the components which results in the ability to handle much smaller and more fragile pieces.

2.2.3 Downsides

Vibratory systems come with multiple disadvantages. These disadvantages relate to the creation and maintenance of the system itself and lead to a much more time and capital consuming process.

Vibratory systems are very precise and the components are very challenging to machine. The largest challenge is the precise machining of the bowls. Machining the feeder bowls is a trial and error process that begins with an aluminum mold that needs additional machining after the first step. This process is very time consuming and results in material waste.

The frames on vibratory systems are created by bolting pieces of aluminum together. The aluminum pieces cannot be directly adjacent to each other due to the placement of the fasteners. This results in an asymmetrical construction in which each aluminum piece is not in alignment with its neighbor. The asymmetry leads to uneven distribution of the vibratory forces on the system and can cause the system to have unexpected results and a larger complexity of calculations for the system.

The counterweight of the system scales at a rate of 10 to 15 times that of the weight of system. As such, there is an upper limit on weight because of the rapid increase of counterweight. The larger counterweights are harder and costly to produce.

3. Methodology

3.1 Design Considerations

The 3D printer we designed had to adhere to multiple considerations to be successful. The potential key components of the printer were decided upon by using decision charts. The method of printing also needed to be researched. Calculations were done on the heated chamber. These calculations ensured that the chamber would safely contain the heated volume under OSHA guidelines. The printer also needed to be able to print using high-strength materials as the end result would be under multiple stress factors. The filament choice was limited by the multiple factors.

3.1.1 Decision charts

When designing the industrial 3D printer, two decision matrices shown in Table 1 and Table 2 were used to choose a motion system and an extruder. For both matrices, the scale for each category was from one to four, with four being the best, and one being the worst. The scale is strictly based on comparison between the objects in the matrix for a number of influential features. The total of all the categories was used to choose the motion system and extruder best suited for the project.

For the motion system, the Haas Mini Mill 2 CNC, Laguna Flat Bed CNC, Macron Dynamics MCS-R6Y, and the Epson RP-HMSz Robot were evaluated. Shown in Table 1, the four gantries were ranked by overall size to build volume, overall weight to build volume, customization, and existing control systems. Size to build volume measured the overall size of the motion system in comparison to the actual build volume. Weight to build volume functioned

similarly. Customization ranked the ability to change the motion system to meet the needs of the project. Existing control systems was a binary that looked at if there was already software for the motion system.

Table 1: Motion System Decision Matrix

	Haas Mini Mill 2 CNC	Laguna Flat Bed CNC	Macron Dynamics MCS-R6Y	Epson RP-HMSz Robot
Overall Size vs Build Volume	1	2	4	3
Overall Weight to Build Volume Size	1	2	4	3
Customization	1	2	4	3
Existing Control Systems	1	1	0	1
Total	4	7	12	10

Aside from existing control systems, all of the considerations are weighted equally. The existing control systems is binary since it is hard to judge if one system is better than another system. Controls being included with the robot saves a lot of design time and saves cost of additional components. The other categories are all equally weighted because each one is required in the ideal motion system. The size and weight affect how big the build volume is, and the customization is how readily adaptable we estimate the robot would be to our application.

As seen in Table 1, both the CNC machines are ranked the lowest. There are multiple reasons that caused these rankings. When the design started for the project, there was an idea of using a pre-built CNC machine, and modifying it to work as a large-scale 3D printer. There were advantages and disadvantages with this approach. First, all the components of the CNC machine were already designed and tested in industrial spaces. Second, the CNC machine would provide a strong solid basis for the printer to be created in.

The basis for a CNC machine is subtractive machining. Subtractive machining is the process of creating an end product by the removal of material. 3D printing is based on additive machining which is the process of creating an end product by adding material. Therefore, CNC machines are designed with much larger and more robust components to handle the high cutting forces of subtractive manufacturing.

In contrast with their large size, their work spaces tend to be much smaller. This means that in order to have a large workspace, a substantially larger volume is needed for the machine to enclose the workspace. The machine would have to be modified to increase the limited workspace which may become costlier than starting from scratch.

The Epson and Macron gantries then became the two top contenders in the matrix. The biggest contributing factor that led to the decision of choosing the Macron gantry was the ability to customize it which reduced the size and weight to build volume over the Epson robot. The customization of the Macron also allowed it to meet the required project specifications direct from the manufacturer.

From a technical standpoint, the choice of motion systems was decided. However, there were several logistical challenges to be considered before acquiring the motion system. First and foremost were the considerations of our sponsor, who wanted to leverage established

connections they have with previous vendors. Understandably so, this will save them money as well as time to order components. Consequently, the Epson robot was chosen over the Macron, because it was the next best gantry coupled with the fact that AGR has a long standing relationship ordering Epson products.

The next major logistic hurdle was the ordering of the specified Epson gantry. An Epson representative informed us that due to a recent shift in company sales policy, they were no longer selling the model of robot specified. The part was discontinued, and their website and cad models available on their website had not yet been updated to reflect this change. The only comparable replacement robot they could offer was much too small and too expensive for our application. Their professional recommendation was that a SCARA (selective compliance assembly robot arm) was the more economically feasible option for our project, being about one half to one third of the cost of a gantry robot.

Due to these supplier issues and the fact that the entire mechanical design needed to be overhauled, a SCARA robot motion system was chosen for use instead. Conveniently, the project sponsor had a Denso HM-40A03G SCARA robot in stock which had been ordered for an older cancelled job. The Denso had a 1000mm reach, a 10kg max payload, a 0.025mm accuracy, and a max travel speed of over 11,000 mm/s [6]. Because the Denso exceeded the initial technical requirements, and was the most logistically available, the Denso was chosen as the motion system.

Table 2: Extruder Decision Matrix

	Flexion Dual High temp	Randecastle RCP- 0250	DyzEND-X + DyzeXtruder GT (2x)	E3D Volcano (2x)
Temperature Range	3	1	4	4
Retraction	1	0	1	1
Weight	2	1	3	4
Price	3	1	2	4
Resolution	2	1	3	4
Total	11	4	13	17

The criteria are equally weighted except for retraction. Retraction is not weighted equally since it only affects the end result not necessarily the overall operation during extrusion. The other categories are weighted equally as they are all key parts of an extruder.

For the extruders, each of the extruders were judged by temperature range, retraction, weight, price, and resolution. Temperature range was based on the temperature range of operation for each extruder. The temperature range affects the filaments that can be printed. Retraction is a binary factor that is based on the ability of the extruder to retract material when printing. Retraction reduces the pressure from the melt zone during non print movements. The

reduction of pressure increases print quality. Weight is the factor of how light each extruder is which affects the speed of the print head. Resolution is divided into horizontal and vertical resolution. The horizontal resolution is the minimal movement that the extruder can make within a print layer. Vertical resolution is the minimum thickness print layer.

The Randcastle extruder was the worst in all the categories. It had the smaller temperature range, inability to retract, heaviest weight, highest cost, and lowest resolution. The weight, inability to retract, and cost were a result of the industrialized Bowden design. The industrial design means the components are more expensive and heavier than their counterparts.

The Flexion extruder was the next in total points. It did have retraction, but had an inferior temperature range as compared to both the DyzeXtruder, and the E3D Volcano. The Flexion is also the second heaviest and second lowest resolution. It did cost less than the DyzeXtruder.

The DyzeXtruder tied with the Volcano for temperature range. The DyzeXtruder had retraction and a lower weight than the Flexion, but cost more than the Flexion. The resolution afforded by the DyzeXtruder was the second highest, only beaten by the Volcano.

The Volcano had the highest total as it was the best in all of the categories. It had the lowest price and weight, while having the highest resolution and temperature range. Volcano was then chosen as the extruder for the project.

3.1.2 Work Piece Vs. Print Head Movement

3D printers can operate with either the workpiece or the print head moving while the other is stationary. For this project, the work piece is stationary as having it move would lead to additional moving parts which leads to a larger complexity overall. Moving the workpiece means that the heated bed has to also move. A moving heated bed would require multiple motors and an

increase in the size of the printer to accommodate the motors. In comparison, moving the print head is much simpler as it will be attached with end of arm tooling to the Denso arm. Additionally, the arm has more precise positioning than what could be done by moving the heated bed.

3.1.3 Structural Rigidity

Structural rigidity was a key design consideration as the printer was going to be in an industrial setting at all times. The frame of the printer needed to be strong enough to handle all the stresses that result from this environment. The structure of the printer was created using the same components as other machinery from AGR Bodine. The components were Maytec extrusion. Maytec extrusion is designed to handle the industrial work environment as well as being easily configured to meet project needs.

3.1.4 Heated Chamber and Plate

The printer was designed to have a heated chamber and plate. With the heated chamber, came the concern of safety. While the temperature of the chamber was to be raised to oven-like temperatures, the structural materials had to be safe to touch during operations. The heated chamber was not implemented into the final design. The calculations for the heated chamber were done for implementation in future iterations.

Calculations had to be done on Lexan panels to ensure that they did not melt, and would be OSHA compliant. Calculations used Fourier's Law (shown in equation 1) to calculate the conductive heat transfer across the surface.

$$q(W) = \left(\frac{k \left(\frac{W}{m^{\circ}C} \right)}{s(m)} \right) \times A(m^2) \times \Delta T$$

Equation 1: Fourier's Law

In Fourier's law, q is the heat transfer in Watts, k is the thermal conductivity of the material, s is the material thickness in meters, A is the heat transfer area in square meters, and ΔT is the temperature gradient in Celsius.

The thermal conductivity of Lexan is .2 W/m°C [7]. The material thickness is 0.00635 meters. The heat transfer area varies between each piece, with the smallest piece being 0.371612 square meters. The ΔT is the key element that is used to find the heat on the outside of the Lexan. In order to find q, another equation is needed which is the specific heat capacity.

$$E(J) = m(kg) \times c \left(\frac{J}{kg^{\circ}C} \right) \times \Delta T$$

Equation 2: Specific Heat Capacity Equation

In Equation 2, E is the transferred energy in joules, m is the mass of the substance in kg, c is the specific heat in J / kg°C, and ΔT is the change in temperature. The difference between the heated volume and room temperature is 177°C. The mass of air is the density of air which is 1.225 kg/m³ multiplied by the volume of the heated chamber (.742 m³) results in a mass of 0.4998 kg. The result of this equation is 89.53 KJ. This result can be put back in Equation 1 to find the change of temperature across the Lexan,

$$89.53(KJ) = \left(\frac{.2 \left(\frac{W}{m^{\circ}C} \right)}{.00635(m)} \right) \times .3716(m^2) \times \Delta T$$

Equation 3: Solving for Change in Temperature of Lexan

Solving Equation 3 results in ΔT being 4.17. The 4.17°C means that the temperature difference between the inside and the outside is only 7.65°C. The surface temperature of the Lexan would be 192.35°C. This change in temperature would result in an unsafe operation temperature in accordance with OSHA standards which require at maximum of 60°C surface temperature.

These equations would mean that a heated volume where the air is heated to 200°C would not be possible however, the printed object itself would be heated using IR heat lamps. The lamps are 35W halogen heat lamps. These heat lamps do not heat the air as much as they heat a surface resulting in a lower temperature of the air.

The maximum safe ΔT that can be transferred across the Lexan if the Lexan is initially 23°C is 37°C. The halogen lights are 35W in which 3.5% of the energy is converted to light. This leads to 33.775 watts of heat. Assuming the maximum print time is ten hours, the watts can be converted into joules using Equation 4 which results in 202650 J.

$$E(J) = P(W) \times t(s)$$

Equation 4: Watts to Joules

The change in temperature of the air can be found using Equation 2. Solving for ΔT results in Equation 5. This equation results in a ΔT of 8.95×10^{-4} °C of the air. The end temperature of the air is still room temperature. The Lexan would be safe to touch as a result.

$$\Delta T = \frac{E(J)}{m(kg) \times c(J / kg^{\circ}C)}$$

Equation 5: Change in Temperature of Air

Since the temperature of the heated chamber would be room temperature, the Maytec extrusion would be safe to touch as the aluminum is not being heated. With both the Maytec and Lexan being safe, the heated chamber would be OSHA compliant and could be constructed without heating concerns.

3.1.5 Filament Choice

The typical item that AGR Bodine produces is medically related. The medical nature of the items means that all the components that touch the items also need to be FDA compliant. The only real concern this presents for the project is the material that is being printed. The printed materials need to follow FDA guidelines – which limits the available filaments.

Additionally, the materials that are being used to create the bowls need to be structurally sound. Each bowl undergoes the forces of vibration from the VibroBlocks. This limits the filaments that can be printed by the printer as some filaments would not hold up under the stress from the vibration.

3.2 Design

The build volume was the first part of the project to be designed. The volume was based on the size of the average vibratory bowl as it was the desired product. The desired volume was determined to be 1000mm by 750mm by 300mm.

Much of the design was informed by the goal of using industrial grade parts. The majority of the components for the printer are industrial grade parts. Maytec aluminum extrusion was chosen for multiple reasons. Maytec is very strong and customizable. Additionally, it is the standard material in AGR Bodine. In order to have a heated volume, the printer needed to have material that would enclose the printer. Lexan was chosen as this material. Lexan is clear which allows for users to monitor progress of a print. It can also safely contain the heat of the heated volume. In order to control all the IO devices of the printer, Beckhoff Ethercat terminals were used. The terminals are also an industrial standard for control, and can be controlled through a PLC.

The thermal components in the design include the thermocouples, extruders, and the water chiller. The thermocouples record the temperatures of the heating elements of the extruders for the heating PID. The water chiller helps keep the extruders from overheating.

An important design decision was the choice of microcontroller and software. Software was chosen first as it was a core part of design. Marlinfw was chosen as it is an open source firmware that supports multiple microcontrollers, and could be modified for any motion system. From this decision, an Arduino Mega was chosen as the team has worked with it extensively before and it is supported by Marlinfw. In order to communicate with the Beckhoff I/O terminals, an Ethercat shield was used with the Mega. The Ethercat shield came with the library, EasyCAT, which would allow the necessary Ethercat communication.

4. Results

4.1 Setbacks

Multiple setbacks occurred after the design phase of the project. These setbacks include project space concerns, product availability, ordering of materials, and software incompatibilities.

4.1.1 Location

A large setback was the project space chosen for the project. Originally, the project was to be built in 85 Prescott St. Worcester, MA which meant the printer needed a fume extractor in order to function as the building was not an industrial area. Concerns about weight limits inside 85 Prescott as well as noise inside of an office environment spurred a push to change locations. A space in Washburn Shops was made by clearing off a work cell and retrofitting the design of the printer base to be mounted to it. The changes to the steel plate which everything would be mounted on were designed in such a way that their effects would be minimal, as well as only drilling a few through holes on the work cell itself for mounting.

4.1.2 Material Availability

After the decision was made to order the Macron Dynamics gantry, it was found out that the company does not manufacture that product anymore. As such, the gantry had to be quickly switched so that the project could still move on. The gantry was switched to a Denso arm as it was available at AGR, and it would work with the current systems with adjustments. The switch led to a major redesign of existing CAD, electrical drawings, and programming aspects. The

largest change that resulted from the switch was the creation of a new metal base plate that took multiple weeks to be designed, cut, and shipped.

The heated bed was unfortunately not included in the final design. The exclusion was a result of a long process of ordering the correct heated bed not resulting in an order. The company simply stopped responding to emails, and the lack of time left after this process meant that a replacement option for the heated bed could not be found.

4.1.3 Software Incompatibilities

In order to control the heated elements and the stepper motors, the Arduino Mega needed to communicate through Ethercat to the Beckhoff terminals. An Ethercat shield was ordered for this purpose. However, the shield and its corresponding library were only designed for the Mega to serve as a slave and not as the master as required. The library that allows an Arduino to be an Ethercat master only works with an Arduino Due. The problem with the Due is that Marlinfw does not support it. This inability of support resulted in an additional component of the software design with the Marlinfw on the Mega in serial communication with the Due which sent data through Ethercat to the Beckhoff terminals. The Ethercat master library did not work correctly, and there was not enough time to troubleshoot the library. The functionality that the Due provided was replaced with Beckhoff Twincat 3 software.

The time constraints caused the Mega to also be replaced by Twincat 3. The Mega simply could not use RS232 to communicate with the Denso arm. The communication problems stem from the RS232 communication structure.

4.2 Project Results

Though there were multiple setbacks, the project did have fruitful results. All the components worked independently of each other but could not work together. Mechanically, all the project components were assembled into a set workspace. Additionally, the workspace of the printer provides a base for future expansions. The metal base plate has the functionality for future use in AGR Bodine.

Electrically, the printer has the correct safety functions as well as a fully wired industrial controls cabinet. The printer is designed for an industrial environment. The fume extractor is set up on top of the Maytec extrusion and ready for use. The water chiller has also been set up and tested for the cooling of the extruders.

Twincat 3 was able to control the stepper motors, and the extruders. The steppers were able to be controlled by the software and external buttons. Twincat used the thermocouples to measure the temperature of the extruders and keep the heating elements at the correct temperature through the use of PWM. The printer was able to move along a preprogrammed path and extrude the PLA filament onto the print bed.

5. Conclusions

5.1 Discussion of Results

The majority of the setbacks were a result of the non-industrial components of the project not functioning with the industrial components. The functionality provided by the non-industrial components was replaced by Twincat, and a PC. Twincat was difficult to work with, but the documentation and support for it were superior to the Ethercat Master and the Marlinfw. The setbacks associated with these two components could have been avoided with more research prior to designing around them.

Twincat was able to recreate all the functionality of a traditional 3D printer in the project. A problem was that there was not enough time to get the functionality working together and fully tested. Another problem was that there was no functionality for Twincat to read a STL file and generate the appropriate G-Code to send to the robot.

5.2 Future Work

The biggest area for improvement in this project is thermal improvements. The heated chamber only needs the IR heat lamps, and the curtains to seal the build chamber. Additional filament types could be printed by adding a heated bed. The bed could also have auto-leveling features that would further improve print quality.

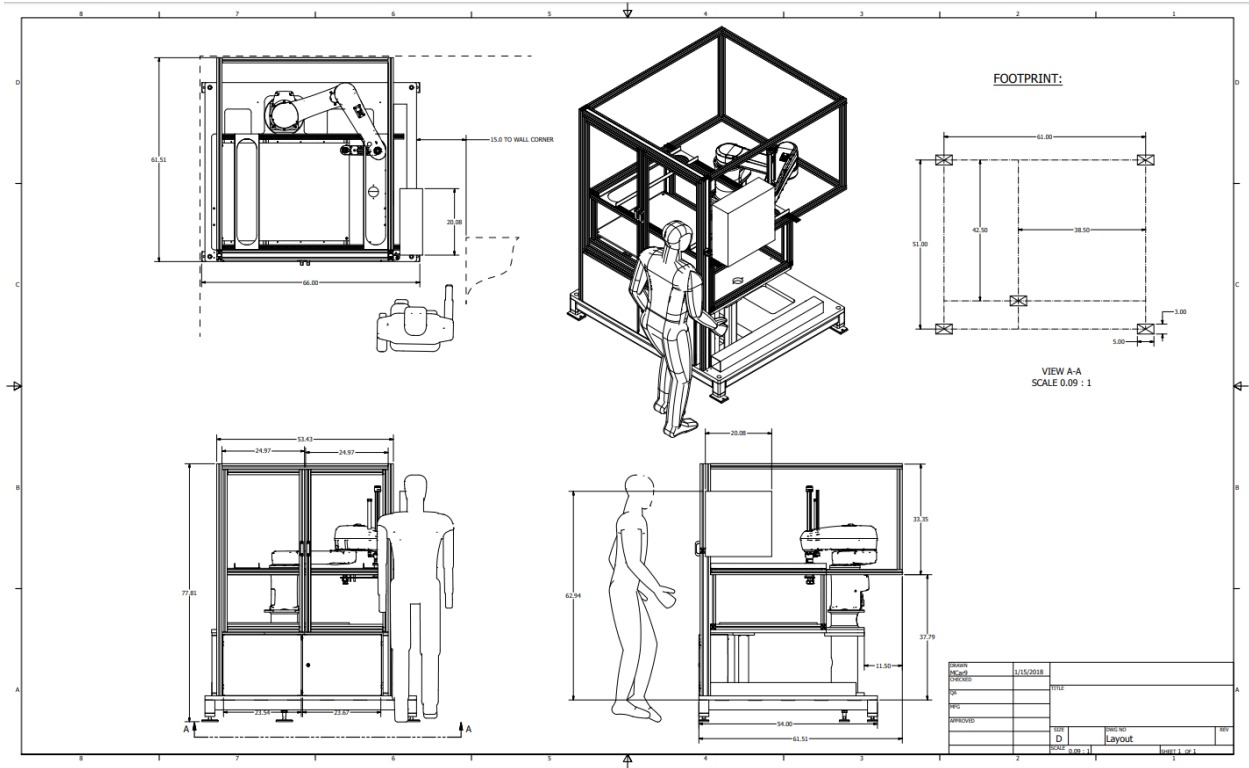
The programming aspect of the project can be improved in three different ways. The first way would be get the Due working with Ethercat and the Mega. The second way would be to replace the Arduinos with another electrical motherboard and replacing Marlinfw with a custom slicer. The last way would be to continue using Twincat 3 and seeing how to make it function as

a 3D printer firmware. This includes adding a UI, support for STL files, and communication through RS232.

There is also room for additional hardware components. There is also space for an industrial touchscreen PC that would be used to generate and upload STL files to the Mega or to Twincat.

There is also additional work in testing the print results of the printer. The printed vibratory bowls could be tested in a vibratory system. The printed bowls have to be compared to a traditional vibratory bowl. The different fill patterns can also be compared to one another to see the best outcomes when used in a vibratory system.

Appendix 1: Industrial 3D Printer



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