PRINT FARM OPTIMIZATION FOR MEDIUM-BATCH ADDITIVE MASS-MANUFACTURING

By

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AN HONORS THESIS PRESENTED TO THE UNIVERSITY OF FLORIDA'S HERBERT WERTHEIM COLLEGE OF ENGINEERING WHILE PURSUING THE DEGREE OF BACHELOR OF SCIENCE IN AEROSPACE ENGINEERING WITH MAGNA CUM LAUDE LATIN HONORS

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Additive manufacturing, especially in the form of 3D printing, has long been regarded as an engineering process best suited to rapid-prototyping and small-batch production of specialized parts. In modern times, however, additive manufacturing has taken an increased role in production processes typically reserved for traditional manufacturing methods. Increased interest has been placed in the development of novel additive manufacturing methods that will increase the efficiency and viability of non-traditional manufacturing in medium- to large-batch mass-production of goods. Such development has so far focused on advancement and optimization of print farm design to maximize throughput and minimize human labor costs. Commercial solutions to the issue of print farm optimization do exist but are largely cost-prohibitive to smaller-scale, medium-batch operations. A demand thus exists for cost-effective, self-made methods of optimizing print farm efficiency for medium-batch mass-manufacturing.

Two crucial elements of print farm optimization were identified: coordination, referring to the integration of a large number of printers to a single software interface, and automation, referring to the removal of the human element from the printing process. An off-the-shelf 3D printer was purchased and modifications designed, manufactured, and installed in an attempt to address the issue of print farm automation, with a focus on the automatic ejection of completed parts. The issue of coordination, which is largely a matter of software engineering, was considered and briefly discussed, but was left as a matter of future research and investment in the project. The project resulted in a fully assembled but yet nonoperational modified 3D printer with a conveyor belt in place of a traditional print bed, along with organized CAD files for the components – either machined or 3D-printed – involved in reproducing the modified 3D printer.

I. INTRODUCTION

Additive manufacturing – that is, the process of building a part up layer-by-layer – is a relatively novel, yet very promising, tool in the engineering world [1]. Typically, additive manufacturing is considered to be synonymous with 3D printing – indeed, 3D printers are the most common and most versatile additive manufacturing machine. The long-term potential of 3D printing to revolutionize the manufacturing world is widely recognized, and as such much effort is being made to expand upon existing 3D printing technology and improve the field of additive manufacturing.

In its early years, 3D printing was used primarily for rapid prototyping: that is, the quick and cheap production of often non-functional prototypes during the design phase of a project [1]. The potential for 3D printing to find a place beyond the design phase of a project – to print shelf-ready products rather than prototypes – was always recognized, and in recent years companies have begun integrating 3D-printed parts into their final-end products.

Despite this, integration of additive manufacturing into mass-manufacturing, assembly-line style environments has proven difficult. The use of additive manufacturing methods in product production has, for the most part, been limited to small-batch parts created using highly advanced manufacturing methods. For instance, NASA and Relativity Space have collaborated in the use of laser powder bed fusion and directed energy deposition methods to manufacture small batches of parts for installation on rocket engines [2].

When an attempt is made to scale up additive manufacturing processes, a number of challenges arise. Generally speaking, production of large lots of parts takes longer when using additive manufacturing methods versus traditional methods [1]. Attempting to cut down on production time typically leads to an unacceptable drop in product quality and process reliability, making the use of additive manufacturing methods for mass-production of high-quality parts a serious challenge.

Despite the many difficulties involved in integrating additive manufacturing into production lines in the commercial world, interest still exists in improving the efficiency of mass production of 3D printing, even on the small scale. In particular, a need exists for a more efficient means of medium-batch additive manufacturing production.

Presently, additive manufacturing is highly effective for small-batch production – say, on the order of tens of parts – and ineffective for large-batch production – say, on the order of thousands of parts of more. The middle case, when demand necessitates production of a few hundred parts, creates a difficult dilemma. Such medium-batch production may not warrant the creation of specialized molds and casts for a traditional manufacturing arrangement, yet additive manufacturing techniques become increasingly time-prohibitive on such a scale.

A need then exists for 3d printing methods to be optimized for mass-manufacturing of medium-batch parts. Such optimization cannot arise from increased print speed: this approach compromises print quality, which is often intolerable for final-end production. Instead, optimization may derive itself from elimination of human involvement: that is, making additive manufacturing as automated as possible.

One such approach to the issue of medium-batch 3D-printing optimization is the print farm. The premise of a print farm is to compile a number of printers – on the order of tens to hundreds – in one place such that many parts may be printed simultaneously. Such an assembly offers the most basic arrangement for additive mass-manufacturing, from which a number of modifications may be made to improve efficiency.

In 2017, the Warsaw University of Technology (WUT) opened its own print farm, with great consideration taken to the various means of print farm optimization available at the time; examination of this system offers excellent insight into print farm optimization methods [3]. In developing the WUT print farm, two primary methods of efficiency optimization were considered: coordination and automation.

Print farm coordination involves development of a cohesive system of 3D printers, rather than a number of independent, unintegrated machines. Commercially available print management systems offer one method of achieving coordination in a print farm. Take, for instance, the Winbo Vertical 9 Units 3D Printer, shown in Fig. (1), considered by the WUT as a means of print farm coordination [3]. This off-the-shelf print farm assembly offers integrated and cohesive control of nine individual 3D printers.

Figure 1. Winbo Vertical 9 Units 3D Printer assembly, a commercially-available solution to printer farm coordination which offers seamless control of nine individual 3D printers [4].

Such an assembly is certainly a straightforward method of achieving print farm coordination, though there are several drawbacks that must be considered. The principal issue with commercially-available print farms such as that shown in Fig. (1) is the limitation these assemblies present to expansion. Such assemblies do not typically coordinate with one another natively: as such, great effort must be taken to integrate multiple print farm assemblies together. If a large print farm is desired, these assemblies do not provide an efficient solution to the issue of coordination. Another considerable drawback to these commercially-available assemblies is cost: the Winbo Vertical 9 Units 3D Printer had, as of 2017, a market price of $13,999 [4]. For many small-scale operations, such a price is incredibly prohibitive; from a purely economic standpoint, alternatives to coordination are often necessary.

One such alternative to an over-the-counter coordinated printer assembly is a software-based solution created by the owner of the print farm. A number of software exist which allow a print farm owner to integrate their 3D printers themselves. One such software is OctoPrint, which facilitates 3D printer control via a Raspberry Pi interface [5]. A sufficiently savvy print farm owner may employ OctoPrint to control a number of printers from a single computer; since OctoPrint is open source, there are virtually no limitations to what the software may enable in terms of print farm coordination. Indeed, the number of printers which may be integrated with OctoPrint, as well as the sophistication of the integration, is limited only by the programming abilities of the print farm owner and the quality and quantity of the hardware involved. The software is also free, making it a much more cost-effective approach to print farm coordination than commercially-available solutions.

Creating a coordinated print farm is the first step to creating a more efficient additive mass-manufacturing system. However, such coordinated systems still require a high level of human interaction to facilitate the printing process: finished prints must be removed from the print bed, new prints must be started by a terminal command, and filament must be replaced and swapped out as needed. This human element introduces a serious efficiency issue, even for relatively small-scale print farms. As print farm size increases so too does the human demand: for sufficiently large print farms, this human element becomes the limiting factor in operational efficiency. The human element of a print farm also limits operation hours: a farm cannot be operated 24/7 unless a person is there to monitor and aid in the process. As such, a truly efficient print farm requires some degree of automation, so as to limit the human time and energy required to operate the system.

As with the issue of coordination, several commercially-available solutions exist to automate a print farm system. Two such solutions were considered by the WUT in development of their university print farm [3]. The first solution involved use of a robotic arm, developed by Voodoo Manufacturing and shown in Fig. (2), to remove completed parts and clear print bed space for subsequent prints to begin.

The robotic arm developed by Voodoo Manufacturing, under the name Project Skywalker, aims to boost print farm efficiency enough to rival traditional mass-manufacturing systems [6]. The premise of the system is a robotic arm which removes the print bed of a printer, along with the completed part, places the bed and part on a conveyor belt, and then replaces the print bed so another print may commence. The project is still in development, as is an undeniably ambitious approach to solving the issue of automation in additive mass-manufacturing. Though not a viable solution in the present day, projects such as this are crucial to the continued advancement of the additive manufacturing field.

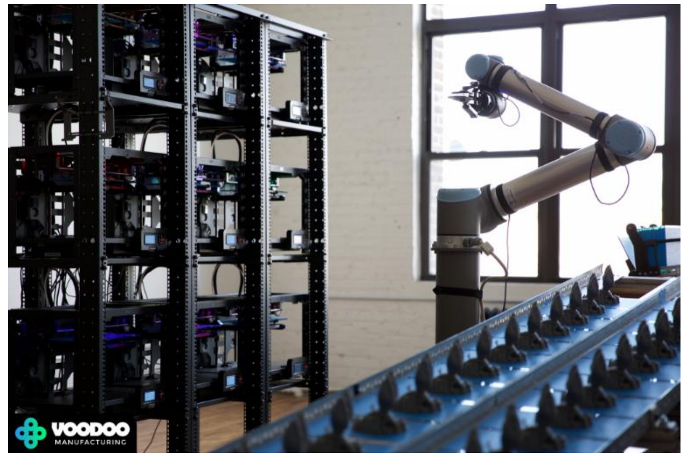

Figure 2. Voodoo Manufacturing's Project Skywalker concept, wherein a robotic arm is used to automate a 3D print farm [6].

The other automative solution explored by the WUT is currently available: a modular print farm assembly created by Stratasys, called the Continuous Build 3D Demonstrator [3]. This system, shown in Fig. (3), solved not only the issue of automation but also of print farm coordination: modules containing three individual printers come pre-integrated, and multiple modules may be co-integrated ad infinitum [7]. The automation side of the system functions via employment of "post-modular foil sheets that are then retracted and cut off" [3].

Figure 3. Stratasys Continuous Build 3D Demonstrator; pictured are three co-integrated modules, with each module containing three individual printers [8].

The system boasts a number of useful features to facilitate seamless automation, including fail safes to reorganize printer commands if certain modules run out of filament mid-process [7]. The Stratasys Continuous Build 3D Demonstrator is an undeniably excellent solution to the issue of automation in additive manufacturing; however, such a product is more suited to large-scale operations with a high budget and high throughput. Smaller operations may want to consider self-made automation solutions.

Ultimately, the WUT print lab did not find need for an automation system as sophisticated as Stratasys' system [3]. Indeed, being in a university setting with a focus on design and prototyping rather than on manufacturing, no automation system was required at all. The issue of coordination, though more relevant to the WUT print lab, also fell to the wayside in favor of individually-controlled printers. Unfortunately, such compromises are all too common in the world of small-scale additive manufacturing operations: commercially available solutions for print farm optimization are highly cost-prohibitive, and self-made solutions require a degree of technical expertise many print farm owners do not possess. Nevertheless, self-made options are a worthwhile area to explore, from an engineering perspective, for their potential to be developed into more cost-effective commercially-available options.

Self-made solutions to the issue of print farm coordination are somewhat limited in diversity and creativity: these solutions are, by nature, software-based, and choice of software is somewhat trivial. OctoPrint was discussed earlier as one option, but choice of software is ultimately the at the discretion of the print farm owner. Self-made solutions to the issue of print farm automation, however, are much more varied.

Print farm automation presents a very interesting engineering problem which may be tackled from a number of different approaches. The core issue to be solved is a means for a completed part to be removed from the print bed; once this is accomplished, the matter of commencing a subsequent print is simply an issue of additional coordination on the software end of the system. Additional levels of automation may be accomplished beyond this most basic task: a method of automatically replacing empty filament reels, a method of collecting and sorting completed parts, etc. These additional tasks, though useful, are secondary to the issue of part ejection; as such, attention must first be turned to solving the issue of automated part ejection from the print bed.

Solutions to the issue of part ejection largely fall into two categories: ejection of the part and print bed or ejection of the part only. The two commercially-available automation solutions already discussed – Voodoo Manufacturing's Project Skywalker and Stratasys' Continuous Build 3D Demonstrator – both rely on ejection of both the print bed and print surface. Such an approach has one key limitation: a dispensable print surface introduces an additional material, asides from filament, which may run empty and limit operational duration. This limitation introduces an additional, rather considerable layer of complexity to any viable engineering solutions to the automation problem; as such, focus for this project was placed on designs which made use of only a single print bed.

In considering potential solutions to the issue of automated part ejection, it is worthwhile to explore both commercially-available options as well as homemade solutions which people have shared online. There is a vast community surrounding the field of 3D printing, and much interest exists in the realm of DIY modification and enhancement of off-the-shelf printers. These DIY solutions, though often less sophisticated than commercially-available options, are usually much more cost-effective, and in many cases much cleverer, than their profit-seeking counterparts.

One of the simplest methods of part ejection found in the DIY landscape is use of the printer head assembly to dislodge and push aside a completed part [9]. This approach involves adding a series of commands to the end of a gcode file which would first pause the printing procedure while the completed part cooled before moving the printer head in a fashion that would push the part off the print bed and into a collection bin near the printer. A few additional lines of code then prompt the printer head to return to its default position and begin another print. The benefits of this approach are clear: little to no hardware is required and the software modifications are minimal and unintrusive to the printer's own programming. From a technical perspective, modifying a print's gcode to facilitate this process is relatively simple, and a plethora of resources exist online to offer guidance on the programming.

This approach does, however, introduce some major downsides. Primarily, this approach finds itself ill-suited to small, flat parts. The mechanical procedure requires generation of a moment about the top of the part which will induce a reaction moment on base, which is adhered to the print bed. Part ejection relies on a reaction moment large enough to overcome the adhesive force between the print bed and the part. If the part is very flat, the moment arm of the force of the printer head pushing on the part will be too small to induce a sufficiently large reaction moment, and part ejection will be impossible. Even if it is technically possible to generate a large enough moment, short parts with small moment arms will require a greater force to be exerted by the printer head; this introduces additional strain on the motors of the printer and may even damage the printer head. As such, care must be taken in selection of what kinds of parts are printed in such a system. Finally, the reliance of this approach on allowing the part to cool to near-room temperature introduces a serious loss of efficiency: it would be much more efficient to design a printer which may eject parts as soon as the printing process is completed, without having a significant delay between prints.

Another popular approach, both in the commercial and DIY realms, is use of a conveyor belt to eject completed parts from the printer. One commercial example of this approach is the Blackbelt 3D, a high-end off-the-shelf printer capable of automatic part ejection facilitated by an extended conveyor belt [10]. The conveyor belt approach to printer automation involves use of a specially-designed conveyor belt in place of a traditional print bed; when the part is completed, software prompts the conveyor belt to turn for some set amount of time, moving the part out from under the printing head. As the part passes over the edge of the conveyor belt, a wedge of some kind aids in dislodging the part from the conveyor belt and guiding the part to a collection bin of some kind. If the conveyor belt is sufficiently long, the part may rest on the belt, outside of the printing area, to cool down before ejection without delaying the printing of subsequent parts. Such an arrangement is ideal, as fully-cooled parts prove significantly easier to eject without damage, and are less likely to adhere to one another when dropped into the collection bin. The Blackbelt 3D, which makes use of an extended belt to allow for part cooling, is shown in Fig. (4).

Figure 4. The Blackbelt 3D, a printer equipped with a specialized conveyor belt in place of a traditional print bed, allowing completed parts to be moved outside the print area, cooled to room temperature, and ejected into a bin [10].

Such a design may also be created as a modification to any standard 3D printer. A number of conveyor belts suited to 3D printing are available online, such as the Formula32 Conveyor Belt produced by Powerbelt 3D [11]. These belts are relatively cost-effective – the Formula32 retailed for $57.00 prior to its discontinuation – and are often pre-dimensioned for a specific printer. Indeed, a number of guides exist online to provide step-by-step instructions, or at least general guidelines, for the process of adding a conveyor belt to a particular 3D printer.

The conveyor belt approach is, of course, not without its downsides. Commercially-available conveyor belt printers, such as the Blackbelt 3D, are quite cost-prohibitive and as such are typically designed for use by medium- to large-scale companies, not by small business owners or academic researchers. As such, these off-the-shelf options are once again ill-suited to the issue of medium-batch additive mass-manufacturing. This once more punctuates the need for a more economical, self-made solution to the issue of medium-scale mass production in 3D printing. As one small business owner stated: “3D printers that are fully automatic out of the box just aren’t economically viable for the owner of a really small business like myself, or almost any other small business owner for that matter” [9].

Modifying 3D printers to enable conveyor belt part ejection is not a trivial task, however. Unlike the part-pushing approach discussed earlier, which has no hardware requirements and limited software requirements, adding a conveyor belt to a printer requires considerable expertise in the areas of printer hardware and software. While guides and tutorials do exist online, use of such sources severely confines the creative choices and freedom of design available to the print farm owner. These tutorials provide instructions for making a specific kind of automatic printer from a specific off-the-shelf printer model: even minor deviation from these specifications requires considerable technical knowledge on the part of the print farm owner.

Nevertheless, the conveyor belt approach offers arguably the best solution to the issue of print farm automation that is achievable without reverting to expensive off-the-shelf options. Conveyor belt automation, coupled with printer coordination through software such as OctoPrint, provides a robust solution to the issue to print farm optimization. These approaches offer an immense degree of flexibility and freedom on the part of the print farm owner: a DIY conveyor belt automation system may be added to almost any printer model or type, and the open-source nature of OctoPrint allows for a wide range of integration features and farm capabilities. Such an arrangement does, however, require considerable engineering expertise, both in the fields of mechanical design and software development. This project endeavors to tackle the first half of this project: to design, manufacture, and assemble the hardware modifications required for development of an automated conveyor-belt ejection 3D printer from a standard off-the-shelf base printer.

II. Motivation

Print farms are by no means an uncommon addition to a university’s assortment of engineering facilities. In most cases, university print farms are used for rapid prototyping and manufacturing of small-batch, often single-batch, products; indeed, this was the function of the Warsaw University of Technology’s print farm which was discussed previously. However, certain instances arise in academia wherein additive mass-manufacturing becomes necessary: 3D printed products necessary for academic research, coursework, or both may be demanded at a quantity that exceeds the capabilities of a typical print farm. In such an instance, optimization methods, such as coordination and automation, may be necessary to meet the demand made by the project at hand.

Such a scenario introduced itself in the University of Florida’s GatorKits Lab in the Fall 2023 academic semester. GatorKits Lab is a faculty-led research lab in the University of Florida’s Department of Mechanical and Aerospace Engineering which specializes in remote engineering education, especially through the development of engineering lab kits which may be utilized in an asynchronous learning environment [12]. One such project under the lab’s purview was development of a lab kit for use in the University of Florida’s EGS1006 Introduction to Engineering course [13]. The lab kit developed for this project was comprised of twenty-four printed parts, with a mix of PTEG and PLA materials. If a single printer was employed, the parts for a single kit required 12.3 hours of printing time. However, use of university print labs and clever organization of the printing process allowed for a printing procedure with an average print time of 1.625 hours per kit.

Though employment of multiple printers, and the inclusion of multiple parts on each print bed, drastically reduced the overall duration and complexity of the print process for this project, much was left to be desired in terms of printing efficiency. A total of 73 lab kits were distributed to students enrolled in the 2024 Summer B term of the EGS1006 course [13]. At 1.625 hours per kit, production of these 73 kits required approximately 119 hours of printing. Because the university's print farms have no degree of optimization – that is, they are simply collections of individual printers – printing of parts for these lab kits required almost constant human supervision. A lack of printer coordination meant remote monitoring or control of the printing process was impossible, and all prints had to be commenced and managed from the printers themselves. A lack of printer automation meant that remote part ejection or filament replacement were impossible, and human interaction was constantly required to remove completed parts and replace empty rolls of filament. As a result, the 119 hours of printing required to create the parts for the 2024 Summer B term was a considerable tax of human time and energy; such a tax would ideally be avoided through clever print farm design.

This lack of optimization becomes a serious issue when considering project scaling. For the Fall 2024 term, roughly 540 lab kits were requested by the university for production and distribution [13]. With no changes made to the manufacturing process, production of so many kits would require as much as 878 hours of printing, with a human present for the vast majority of that time. Clearly, such scaling is incredibly problematic and potentially infeasible. This is the crux of the issue with additive manufacturing: for medium-batch production, additive manufacturing is too time-prohibitive, yet traditional manufacturing methods are too cost-prohibitive. With this dilemma in mind, there was a need for GatorKits Lab to develop its own print farm which focused not on rapid prototyping but rather on additive mass-manufacturing via print farm coordination and automation.

To this end, a customer needs statement (CNS) was drafted by the graduate researcher commissioning the project, Alexander Lacerna, and approved by the GatorKits Lab faculty advisor, Dr. Matthew Traum. The statement itemized eleven requirements of the project to ensure that the needs of the research laboratory were met; those requirements are:

(1) The design must make use of the FLSUN Super Racer as the base off-the-shelf printer that is modified.
(2) The design must have future-looking capability to be adapted to the FLSUN V400.
(3) The upgrade package cost must be kept below $200.
(4) Metal parts on the off-the-shelf printer, excluding fasteners, cannot be replaced or removed from the existing hardware.
(5) Adding hardware to the base printer frame must make use of pre-existing mounting support.
(6) The printing surface must be capable of heating to and sustaining 90ºC during printing.
(7) The available build volume should be a minimum of 230 x 110 x 230 millimeters (x,y,z).
(8) The printer must be capable of printing both PTEG and PLA materials.
(9) The design should be compatible with at least two conveyor belts from different manufacturers to prevent delays due to supply chain issues.
(10) The conveyor belt should be relatively easy to remove for maintenance purposes.
(11) If an additional external controller board is used, it must only use one standard US power outlet.

These ten requirements offered a baseline from which the design process was initiated. One of the greatest variables in the design process – the base printer which would be modified – was already prescribed by the CNS as the FLSUN Super Racer, or SR. The SR, shown in Fig. (5), is a delta-style 3D printer capably of printing PLA and PTEG material and retailing for $300 as of 2024 [14]. A delta printer offers a number of advantages over a traditional printer, hence its selection for this project; however, no aspect of a delta printer makes it particularly better suited to conveyor belt automation than any other style of printer.

Figure 5. The FLSUN Super Racer delta-style 3D printer; this is the base printer upon which modifications will be made to facilitate automatic ejection of parts via the conveyor belt approach to 3D printing automation [15].

Requirement (2) needs only minor consideration: the FLSUN V400 is geometrically identical to the SR model, with most changes being internal hardware upgrades (i.e. superior motors, print nozzle, etc.) and software upgrades. Preparing the design for integration with the V400 is primarily an issue of software adjustment, which falls outside the purview of this project. Likewise, requirements (6) and (8) are largely trivial, as all off-the-shelf conveyor belts designed for 3D printing will, by nature, be rated for temperatures of at least 90ºC and be compatible with both PTEG and PLA filament. Requirement (9) is also relatively simple to satisfy: there is no shortage of conveyor belts available on the market that could be used for this project. Requirement (11) pertains more to the software end of the project, as a Raspberry Pi requires its own outlet connection to operate. However, since the Raspberry Pi occupies the only allowed power connection for the project, this requirement dictates that any stepper motors used for control of the conveyor belt must make use of the printer's own power as opposed to an external power source.

Certain requirements, however, do necessitate careful consideration during the design process. Requirement (3) provides a strict, and not necessarily generous, limitation on the modification costs associated with the project. This limitation is especially restrictive when one considers the cost of a Raspberry Pi unit, which is required for OctoPrint integration on the software end of the project and which typically retails for upwards of $50 [16]. Requirements (4) and (5) both provide fairly restrictive design and manufacturing constraints on the project, in that they require minimal deconstruction or replacement of base printer parts. Essentially, these requirements dictate that project modifications must build upon the existing printer without compromising the integrity of the printer's structural design. Requirement (7) likewise provides geometric constraints, especially in the required width of the conveyor belt and the depth within the printer that the belt must be mounted. Finally, requirement (10) offers a reasonable constraint that the design must allow for the conveyor belt to be removed for maintenance: that is, the design must be able to be disassembled, and thus cannot involve permanent connections such as welded joints or glued parts.

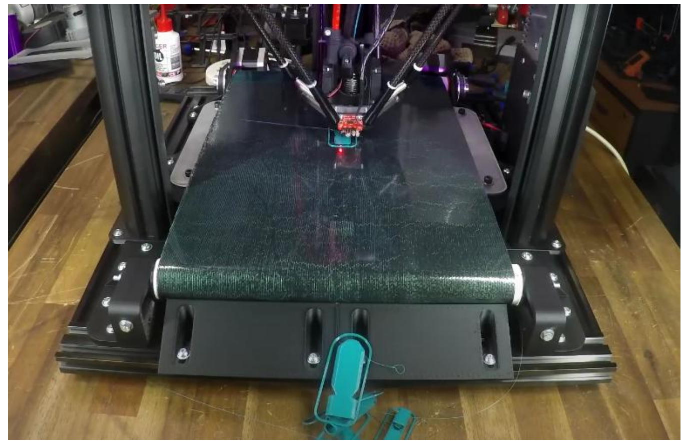

Figure 6. Automated 3D printer developed by TeachingTech from the FLSUN Super Racer base printer model; shown is a testing run included in a video produced by TeachingTech showcasing the design [17]

Figure 7. Base of the FLSUN SR printer purchased for the project.

III. Design Process

Before design work truly began, inspiration was sought in existing iterations of conveyor-belt automated printers, both in the commercial realm and in the DIY community. A particular project was found which also made use of the FLSUN SR printer; this project was published by a community creator by the organizational name of TeachingTech to the popular 3D printing community site Printables [14]. The design, shown in Fig. (6), provided the baseline from which the GatorKits Lab project developed.

While the TeachingTech design offered excellent inspiration for this project, the requirements outlined in the CNS prompted several significant deviations from the design shown in Fig. (6). Most significantly, the TeachingTech design replaced the base of the SR printer, shown in Fig. (7), with a novel base made of aluminum 4020 extrusions [14]. Such a replacement would violate requirements (4) and (5) of the CNS provided for the project, and so a significant deviation from the TeachingTech design was needed in this area. Additionally, to satisfy the budget constraints outlined in requirement (3) of the CNS, cost-saving measures would be needed which would deviate from the TeachingTech design. Nevertheless, the design shown in Fig. (6) provided a jumping off point for the design process.

The first design consideration made was the length of the overall assembly. This length was primarily a function of the conveyor belt chosen for the project: belts were sold in specific circumferential dimensions, and from these dimensions the approximate length of the design could be ascertained. Because of this limitation, it was desirable to first select a belt and then design the printer frame according to the dimensions of that belt. Of course, in order to allow belt interchangeability per requirement (9) of the CNS, some tolerance in the design was necessary to accommodate slight deviations in the belt dimensions; this, however, would be addressed later in the design. The belt chosen was the CHPOWER Updated 3D Printer Conveyor Belt IR3-P1, which was purchased from Amazon for $40.99 (see Appendix A: Bill of Materials) [18]. This part was modelled in SolidWorks; its dimensions, found through a combination of manufacturer reporting and direct measurement, are shown in Fig. (8).

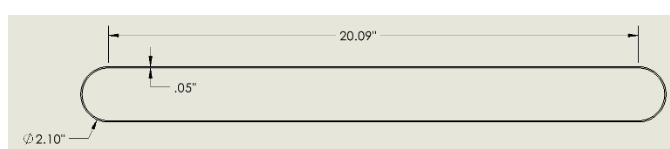

Figure 8. SolidWorks drawing of conveyor belt model (CHPOWER Updated 3D Printer Conveyor Belt IR3-P1) with dimensions in inches.

From this drawing, it was determined that the overall conveyor belt length would be…

$$l_{belt} = 20.09" + 2 \cdot \frac{1}{2} \cdot 2.10"$$

$$l_{belt} = 22.19"$$

A revised version of one of the preliminary concept drawings for the overall printer design is shown in Fig. (9). The concept depicted would have the conveyor belt pressed closely to the rear vertical support of the printer, with the frame also pressing against this support. Some kind of wedge – the details of which had not been considered at this junction – was imagined at the front end of the assembly, to aid in dislodging completed parts from the conveyor belt. As such, it was recognized that the frame would have to extend at least a few inches beyond the end of the belt, to allow room for such a wedge to be included. Since the length of the belt was found to be 22.19”, a logical choice for the length of the frame – which at this stage in the design was imagined a solid piece of aluminum plating– was 24”. Such a length would allow ~1.5” for a wedge to be mounted, which was thought to be sufficient. The wedge itself was unlikely to be so short, but if the wedge hung over the end of the frame, there was no issue.

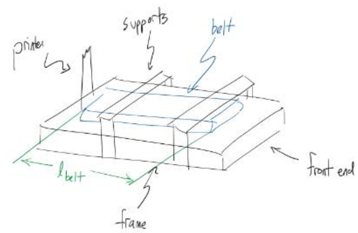

Figure 9. Concept drawing depicting the preliminary layout imagined for the printer. Labelled are key components, including the frame upon which modifications are to be built, supports for the conveyor belt, and the belt itself. See Appendix B: Concept Drawings, Fig. (A) for the original version of this sketch.

The width of the frame was much easier to determine: this dimension was limited by the distance between the frontmost vertical supports of the printer, measured to be 11.5”. Another revised preliminary concept sketch, depicting the dimensions of the frame, is shown in Fig. (10). Based on these dimensions it was decided that the most appropriate stock material to create the frame from was a 12” x 24” piece of stock aluminum plating.

The thickness of this plating, however, was of some debate. The front end of the assembly would be hanging over the edge of the printer frame and thus in a cantilever loading position. However, the loading on this cantilevered section would be negligible: printed parts have very little weight, mechanical components such as the wedge, conveyor belt rollers, etc. were to be 3D printed themselves. The only non-plastic components that would be loaded on the cantilevered section of the frame were the belt itself, which is a polymer of negligible weight, small fasteners such as nuts and bolts, and any components such as ball bearings or driving rods that would be required to construct the roller. By far the heaviest load on the cantilevered frame would be the weight of the frame itself, which would not be sufficient to cause failure (aluminum can, of course, support its own weight except when cantilevered significantly). As such, it was determined, without the need for calculation, that the aluminum frame need not be excessively thick

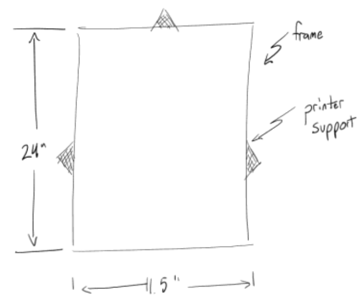

Figure 10. Concept drawing depicting first-iteration dimensions of the aluminum frame of the assembly. See Appendix B: Concept Drawings, Fig. (A) for the original version of this sketch.

Increasing the thickness of the frame would also increase the cost of material significantly. A 12” x 24” 6061 aluminum plate of 0.25” thickness from McMaster-Carr retails for \$251.75; a plate of the same dimensions but of 0.5” thickness retails for \$310.59 [19]. As such, a frame thickness of 0.25” was decided upon. It should be noted that while McMaster-Carr was used throughout this report to find reference parts – in large part due to their library of SolidWorks models for their products – the pricing of McMaster-Carr does not reflect the pricing of the actual parts used. In the majority of cases, more cost-effective part sourcing options were found to stay within the project budget. See Appendix A: Bill of Materials for a full list of part pricing and sourcing.

Of course, the issue of manufacturing was also a consideration throughout the design process. It was decided from an early point that the most efficient and accurate method of manufacturing the frame – that is, of cutting out the necessary through holes and slots from the frame – would be using a waterjet. The University of Florida Mechanical and Aerospace Engineering Department owns a waterjet that is sufficiently powerful to cut through 0.25” aluminum, or much thicker, and is available to students with the proper training. However, for accurate cuts to be made by a waterjet, the part must be fully outlined from its stock material: that is, all four sides of the frame would need to be cut from within the stock material, with none of the original edges of the stock material actually being used. This presented a problem, as it would be impossible to have a frame of length 24” be cut from a piece of stock also of length 24”.

The remedy for this issue would come from the design for the idler roller mount assembly, which would also double as the wedge assembly to dislodge the completed part. This assembly was so-named for its position on the idler side of the conveyor belt (at the front of the printer, as opposed to the drive side at the rear of the printer) as well as its role of mounting the conveyor belt roller rod to the frame. To understand the roller mount assemblies it is crucial to first understand the roller assemblies themselves. A concept drawing for the roller assemblies is shown in Fig. (11).

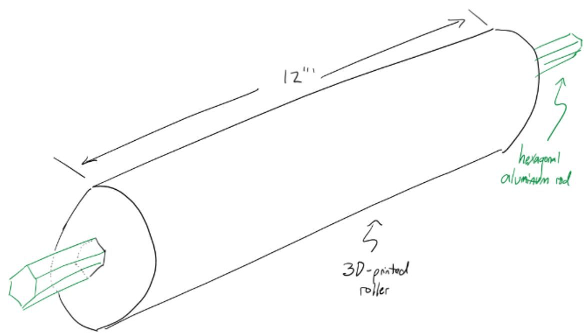

Figure 11. Concept drawing for the roller assembly (drawing applied to both the drive and idler rollers). The drawing depicts the central hexagonal aluminum rod which runs through a 3D-printed cylindrical roller which the conveyor belt presses against.

The key design feature of the roller assembly is central the hexagonal rod which runs through the 3D-printed roller and protrudes from either end of the assembly. A hexagonal rod was chosen to allow the rod to have grip against the cylindrical shell: a cylindrical rod would run the risk of simply rotating within the shell without actually rotating the shell alongside the rod. Heat-sunk inserts, which would be threaded into the plastic shell and press against the aluminum rod, were considered; ultimately, however, a hexagonal rod was determined to be a more elegant, simple, and cost-effective solution.

Since the aluminum rod would need to connect to ball bearings (to facilitate smooth motion when connected to the roller mount), it would be necessary in the manufacturing phase to shave material off the ends of the hexagonal rods to circularize the end profile of the rods. This modification would be accomplished using a manual lathe. The width of the roller rod was initially planned as 12”, as shown in Fig. (11); however, as the design phase progressed, the dimension had to be shortened, as width was limited by the width of the frame and the dimensions of the mounting hardware. Additionally, the length of the hexagonal rods would be determined by the mounting hardware and, in the case of the drive roller rod, the configuration of the stepper motor which would be used to drive the conveyor belt. Such dimensioning will be revisited once the design of the roller mounts has been discussed.

The design of the roller mounts went through several phases and concepts. In the case of the idler-side roller mount, the design was largely driven by the need to have the end of the conveyor belt as well as the dislodging wedge overhang from the frame (a constraint dictated by the use of a waterjet to manufacture the frame, as discussed previously). The final version of the idler roller mount is shown in Fig. (12) as a SolidWorks model.

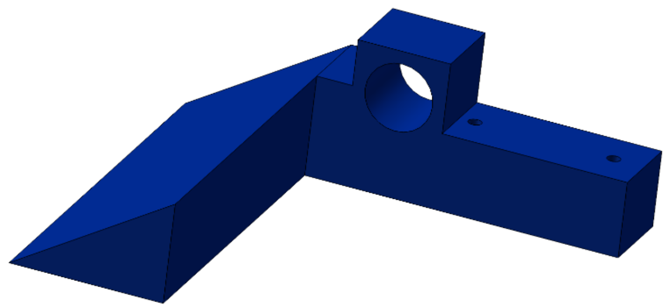

Figure 12. SolidWorks model of the finalized right-half idler roller mount part. The model for the left-half idler roller mount is a mirror image of this part.

The mount is an L-shaped piece with side acting as the dislodging wedge and the other acting as an attachment point to both the frame and the roller. The large hole is intended to house a ball bearing, with the hole diameter being exactly 0.875”. This dimension was chosen to create a tight interference fit between the mount and the ball bearing, such that the bearing is secure in the mount without the use of an adhesive. Two through-holes allow for a fastener connection to the frame, as shown in Fig. (13). This connection type: a bolt running upwards through the frame and hardware, before being secured on top by a nut, was the chosen method of attaching all roller mounting components to the frame.

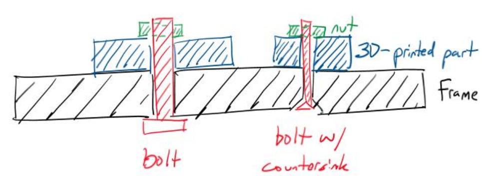

Figure 13. Concept sketch depicting generalized method for attaching 3D-printed parts (blue) to the frame (black) by passing a bolt (red) through the frame and part and securing the bolt with a nut (green) at the top. The bolt may or may not be countersunk depending on whether the frame rests on the printer base or hangs over the base’s edge at the point of attachment.

The idler roller mount part shown in Fig. (12) is so designed for several reasons. The first advantage of this design is that the part attaches to the frame near its rear: that is, the through holes used for attachment to the frame are placed asymmetrically on the side of the part opposite the ball bearing and dislodging wedge. As previously discussed, a key requirement of this part was that it overhang from the frame such that the frame may be shortened below 24”, making it feasible to manufacture using a waterjet. By placing the frame attachment through holes near the rear of the part, the roller and dislodging wedge are indeed able to overhang from the frame.

Another advantage of this design comes from its utility in tensioning the conveyor belt. For the printer to function properly, the conveyor belt must be taut; however, to install and remove the conveyor belt, tension must be let out. Thus, some component of the design must be able to slide in and out to add or release tension in the belt; this component, naturally, is the idler roller mount. Rather than having the attachment bolts for this part run through holes in the frame, they will run through slots – this geometry will allow the idler roller mounts to move forward or backward relative to the frame. However, to account for any issues of tolerance or inaccuracy during the manufacturing process, it is best for the idler roller mount to be split into left- and right-half parts. These parts can then be tensioned independently to prevent unnecessary bending and strain of the 3D-printed parts.

Hence the idler roller mount depicted in Fig. (13) is carefully designed indeed. This design both allows for more feasible manufacturing of the frame and aid is bringing the design to compliance with the CNS requirement of a conveyor belt that may be readily removed for maintenance. This design will also provide the base geometry for the drive roller mounts.

Briefly, the design returns to considerations of the frame. Because of clever engineering of the idler roller mounts, the length of the frame was able to be reduced from 24" to 22". Additionally, slots would need to be included to allow for tensioning and de-tensioning of the conveyor belt, as described previously. At this point in the design process, measurements were taken to determine locations for through holes used to attach the frame to the base of the stock printer. The stock printer initially had, attached to its base, a heating pad with a glass printing surface on top of it. Upon removal of these components, six M4 threaded holes were made available; these holes were an obvious choice for the attachment point of the frame to the printer base. The locations of these holes were measured and the SolidWorks model of the aluminum frame part was updated with through holes at these locations. Fig. (14) shows a sketch of the frame design at this point in the design process.

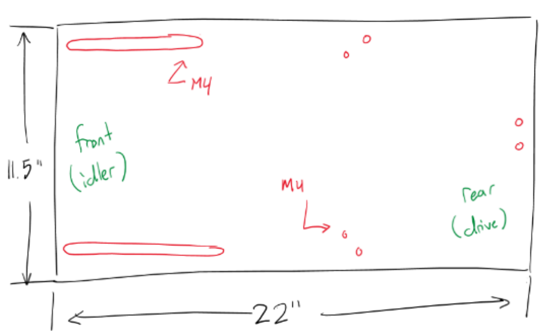

Figure 14. Sketch of the frame design at this intermediary point in the design process.

Of course, the frame design could not be completed without finalizing the rest of the design elements, since all parts are attached to the frame. The next aspect of the assembly which was considered was the drive roller mounting design. It was determined, based on similar designs found online – most especially the TeachingTech design – that only one NEMA 17 stepper motor would be required to generate the torque needed to turn the conveyor belt [14]. As such, the drive motor mounts, unlike their idler counterparts, would be two completely different designs. One mount would simply contain a ball bearing and facilitate connection of the roller to the frame; the other mount would accomplish this and would additionally facilitate connection of the drive roller rod to the stepper motor.

The motorless-side mount was designed based on the idler roller mount, using much of the same geometry: the dislodging wedge component of the idler roller mount was removed, and the through holes used for mounting were rearranged, since this mount did not need to – or in fact, physically could not – overhang from the frame. The resulting part is shown in Fig. (15) as a completed SolidWorks model.

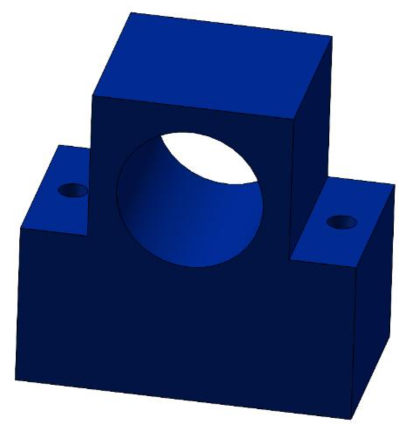

Figure 15. SolidWorks model of the finalized motorless-side drive roller mount.

The motor-side mount was designed from the base geometry of the motorless-side mount shown in Fig. (15). An addition was made to this base geometry of a small platform upon which the stepper motor would rest, along with a small wall which the stepper motor could attach to using M3 screws. The only requirements of this part was that the stepper motor be placed far enough from the ball bearing that a radial coupler could be included, to attach the stepper motor to the drive roller rod, and that the platform be dimensioned properly so as to leave enough room for the stepper motor.

Coupling of the stepper motor to the drive motor rod was accomplished using an 8 mm to 5 mm parallel cut clamping precision flexible shaft coupling sold by McMaster-Carr [20]. As before, this is only a reference part used for the convenience of the SolidWorks model of the part made available by McMaster-Carr. The dimensions of this coupler are driven by the standard 5 mm diameter of a NEMA 17 stepper motor drive shaft and use of hexagonal rod with an 8 mm thickness;

justification for the latter dimension will be included in the discussion of the roller rods designs. The length of the shaft coupler used was 19.8 mm; this was a driving factor in the spacing of the stepper motor mount from the ball bearing slot in the motor-side drive roller mount. The shaft coupler and motor-side drive roller mount are shown as SolidWorks models in Fig. (16) and (17), respectively.

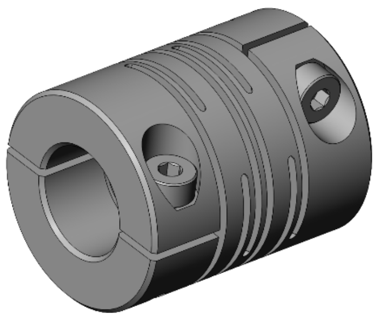

Figure 16. 8 mm to 5 mm parallel cut clamping precision flexible shaft coupling, McMaster-Carr Part No. 8011N233, used to connect the NEMA 17 stepper motor used to drive the conveyor belt to the drive roller rod in the conveyor belt assembly. Part is rendered in SolidWorks, model courtesy of the McMaster-Carr website [20].

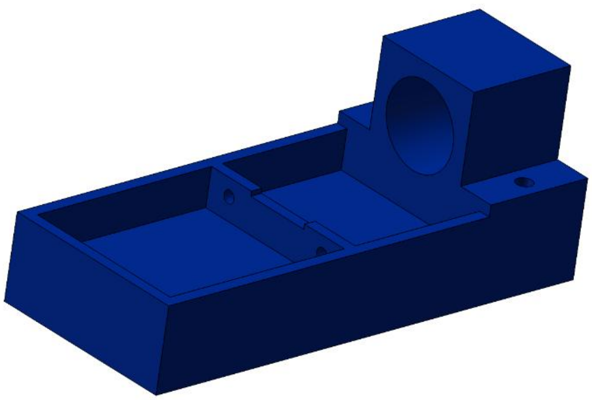

Figure 17. SolidWorks model of the motor-side drive roller mount. A small bay was created to house the NEMA 17 stepper motor used to drive the conveyor belt, with a small wall containing M3-sized through holes for securing the stepper motor to the mount. The stepper motor is mounted at a distance from the ball bearing housing sufficiently sized for installation of the shaft coupler shown in Fig. (16).

Each of the drive roller mounts – motor-side and motorless-side – required two through holes to be added to the frame so they may be mounted in the method shown previously in Fig. (13). Conveniently, these parts were attached to the frame at areas where the frame overhangs from the printer base; as a result, countersinking of the fasteners was not required.

It is worth discussing at this junction the manner in which the stepper motor was powered. As discussed previously, CNS requirements demand that the stepper motor be powered through the printer itself rather than from its own external power source. Initially, it was thought that this would be a very challenging aspect of the design – indeed, most electronics are not design for additional, unexpected loading, and there was concern that the stepper motor, when turned on, may cause power distribution issues on the printer-side of the assembly. However, when working with the printer internals it was discovered that the SR printer comes stock with an additional stepper motor port: the motherboard of the printer has four available stepper motor ports, yet the printer only employs three motors for printer head movement. As such, the matter of connecting the stepper motor to the printer was trivial: the motor was plugged into the extraneous port with a sufficiently long cable and then installed to the motor-side drive motor mount.

The next aspect of the design which was considered was the roller rods. The general design of the roller rods had, at this point, already been established: that is, hexagonal aluminum rods. However, the exact dimensions of these rods had yet to be determined. The thickness of the rods was determined somewhat arbitrarily: in the GatorKits Lab workspace there happened to be a number of 8 mm internal diameter ball bearings. In the spirit of not using adhesives during assembly, an interference fit between the ball bearings and the roller rods was desired. Thus, to make use of these ball bearings, and conserve budget, 8 mm roller rods were selected. These rods could then be faced down in a manual lathe to circularize their ends to a diameter of ~7.9 mm, allowing them to fit snuggly in the 8 mm internal diameter of the ball bearings. The length of the idler roller rod was not terribly significant: the only requirement was that the rods at least spanned the 11.5" distance between the ball bearings, and that the rods were circularized at the ball bearing and hexagonal at the roller interface. The length of the drive roller rod was somewhat more exact so that the rod would meet the coupler, though there was still a significant amount of tolerance in this design. Nevertheless, reasonable tolerances were included in the manufacturing drawings used to produce these parts. The dimensions of the idler and drive roller rods, as they were manufactured, are shown in Fig. (18) and (19), respectively.

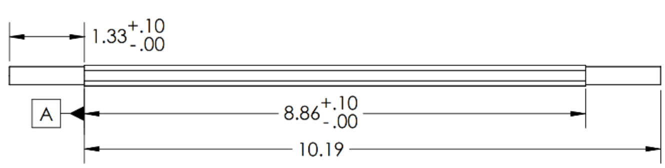

Figure 18. Idler roller rod manufacturing drawing, rendered in SolidWorks, with dimensions in inches.

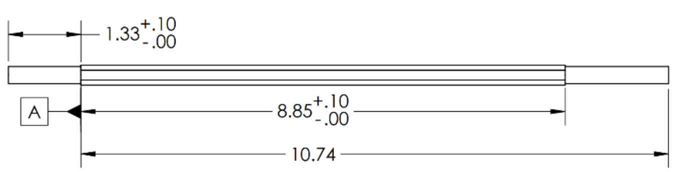

Figure 19. Drive roller rod manufacturing drawing, rendered in SolidWorks, with dimensions in inches.

With the conveyor assembly nearly fully designed (the width of the rollers and conveyor belt were still somewhat unclear at this point) attention was turned to the hot plate assembly. The goal was to reuse the printer's original hot plate by somehow mounting it underneath the conveyor belt and re-wiring the plate to its original connections. A number of potential designs were considered for the cross-sectional arrangement of the hot plate assembly; the final concept which was executed is shown in Fig. (20).

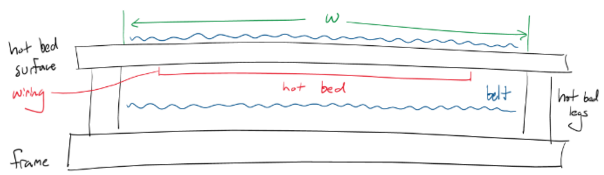

Figure 20. Revised concept sketch depicting the cross-sectional arrangement of the hot plate (hot bed) assembly and its geometry relative to the conveyor belt. See Appendix B: Concept Drawings, Fig. (C) for the original version of this sketch.

The premise of this design is an aluminum surface, called the hot bed surface, which stands on four legs, called hot bed legs, with the upper half of the conveyor belt resting on top of the hot bed surface and the lower half passing underneath it. The hot plate would then be attached below the hot bed surface and wired along the side to its original connections within the printer base. One notable consequence of this design is the restriction it imposes on the conveyor belt width, labelled as *w* in Fig. (20). In preliminary designs, the conveyor belt was imagined to span the entire width of the frame (i.e. 11.5"), limited only by the distance between the frontmost vertical supports of the printer itself. However, the hot plate assembly design shown in Fig. (20) imposes a new, more restrictive limit on the width of the conveyor belt: the belt must be able to pass between the hot bed legs. The hot bed legs were to have a 1" diameter so as to allow M4 threading in their interior, meaning the distance between the legs was, at most, 9.5". However, a reasonable distance was necessary between both the legs and the edge of the frame and between the legs and the conveyor belt. As such, it was decided that the width of the conveyor belt would be 8.86", or 225 mm – this width still far exceeded the CNS-specified minimal printing area in this dimension of 110 mm, and allowed a comfortable level of distance between the moving conveyor belt and the stationary support elements. Based on this dimension, the width of the rollers were also able to be set as 8.86"; this left the conveyor belt assembly fully designed and dimensioned.

The design of fasteners for the hot plate assembly was notably more complex than for the conveyor belt assembly. Fig. (21) shows the arrangement of fasteners for the hot bed legs. The premise of this arrangement is that M4 bolts would be threaded into the legs from both directions: the lower bolt would secure the legs to the frame while the upper bolt would secure the hot bed surface to the legs. Because of the position of the hot bed surface relative to the frame (the hot bed surface was designed to be centered relative to the printer, such that the "zero" or default position of the printer head was at the direct center of the printing area) two of the legs were positioned where the frame rest on top of the printer base while two of the legs were positioned where the frame hung over the edge of the printer base. As such, two of the lower bolts were countersunk while the other two were not. The upper bolts, on the other hand, did not need to be countersunk because they were not coincident with the path of the conveyor belt.

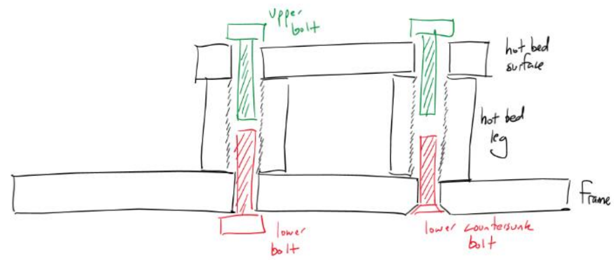

Figure 21. Concept sketch depicting the arrangement of fasteners connecting the hot bed surface to the frame through the hot bed legs.

There was then the matter of fastening the hot bed itself to the hot bed surface. The stock hot bed came with the printer attached to its own very thin circular metal sheet. This metal sheet had six screws arranged concentrically around its edge; with some force these screws could be removed and the resultant holes expanded to create six concentric M4 through holes. These through holes were measured and five (all six could not fit on the area of the hot bed surface, which was limited by the fixed vertical printer supports) countersunk holes were created in the hot bed surface to allow bolts to be passed through both the hot bed surface and hot plate, and a nut to be secured on the underside to clamp the two parts together. This arrangement is depicted in Fig. (22).

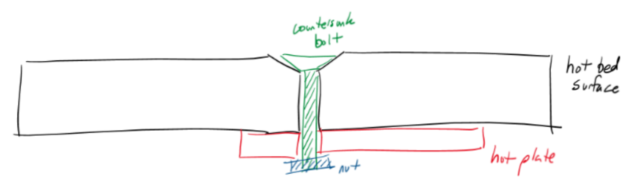

Figure 22. Concept sketch depicting the fastener arrangement used to attach the hot plate (red) to the hot bed surface (black) using a countersunk bolt (green) and a nut (blue).

Thus the hot bed surface design included nine holes for fasteners: four through holes for attachment to the hot bed legs and five countersunk through holes for attachment of the hot plate. For budget-constraint and waste reduction purposes, it was decided that the hot bed surface would be cut from the frame itself during the waterjet manufacturing process for the frame. This meant that the hot bed surface would be of 0.25" thickness – the same as the frame. Some concern arose as to the time it would require for such a thick piece of aluminum to reach the required temperature of 90ºC. A heat transfer analysis of this problem was forgone due to the lack of available information about the heating properties of the hot plate; instead, an experimental approach would be taken upon completion of the prototype assembly (see Outcomes). The finalized hot bed surface design is shown as a SolidWorks model in Fig. (23). The model of the hot plate created for the assembly is also shown in Fig. (24) to allow for a more complete visualization of the design.

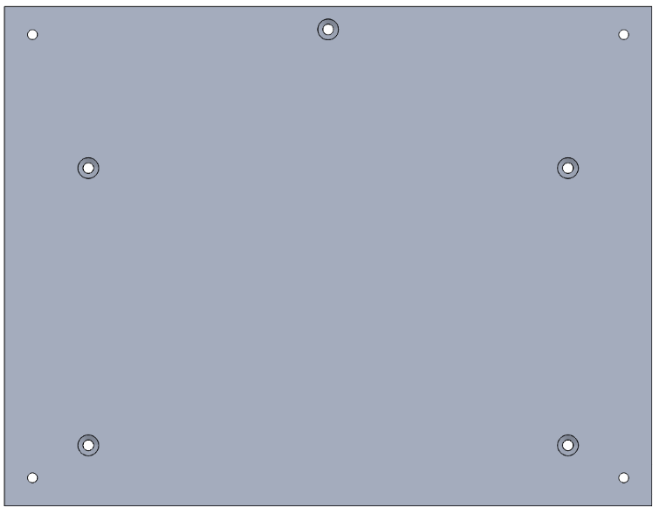

Figure 23. Hot bed surface model, generated in SolidWorks, depicting the arrangement of M4 through holes used for attachment of the surface to the hot bed legs and attachment of the hot plate to the surface.

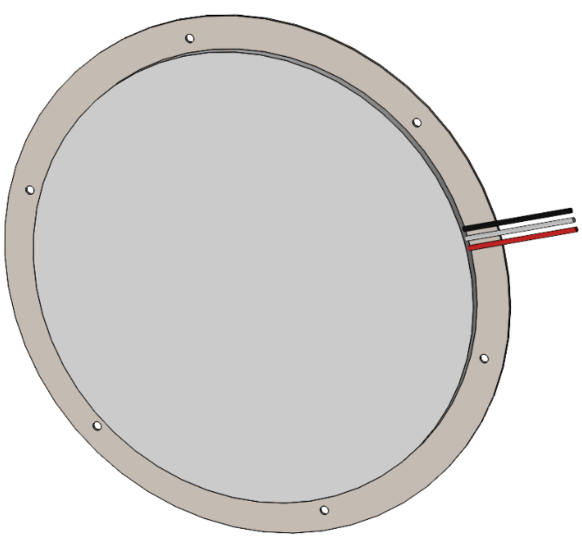

Figure 24. Hot plate recycled from the off-the-shelf FLSUN SR printer used as the basis for the project. The smaller disc is the hot bed itself. The larger disc is a thin aluminum sheet which the hot plate is attached to by an adhesive.

The height of the hot bed legs was carefully selected to ensure that the conveyor belt just rested atop, but did not get pressed upwards by, the hot bed surface, based on the position of the conveyor belt determined from the roller mounts, which had already been designed. To accomplish this balance of design, a height of 2.05” was chosen. The hot bed legs were manufactured on a manual lathe from 0.5” aluminum stock. Per the manufacturing documentation, shown in Fig. (25), an outer diameter of 0.48” was specified to allow for finishing of the outer surface of the legs; in practice, however, this step was considered unnecessary and was foregone.

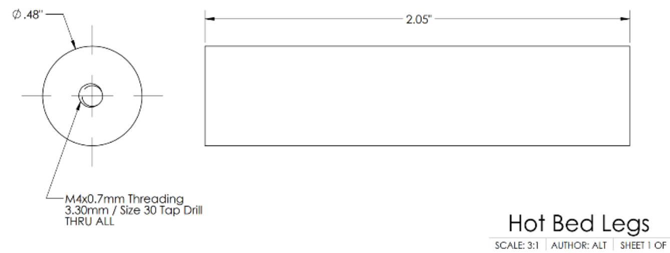

Figure 25. Hot bed legs manufacturing drawing, rendered in SolidWorks.

At this point in the design, both the conveyor belt and hot plate assemblies were fully dimensioned and all fasteners had been accounted for. All that was left to do was finalize the model of the frame and begin manufacturing. The finalized frame model is shown, fully dimensioned, in Fig. (26).

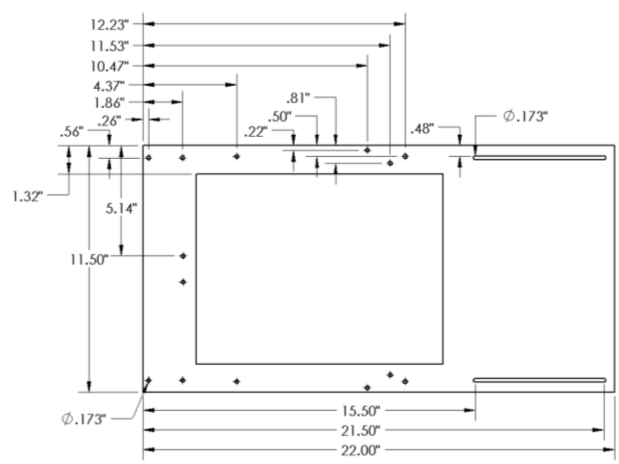

Figure 26. Fully dimensioned frame model, rendered in SolidWorks. Any unspecified dimensions may be found via symmetry. All holes and slots are sized as M4 clearance-fit holes per the University of Florida Tap and Drill Chart [21]. The frame was manufactured via waterjet from this SolidWorks model.

Before discussing the fully-assembled design, a number of remarks on the design process are in order. The process heretofore described is a general outline of the procedure followed. In reality, this design process spanned over a year and followed a much less linear path than what has been described. Many different iterations of parts were modelled in SolidWorks only to be added to the full assembly and be shown to be dimensioned erroneously or have some other significant design flaw. Likewise, some parts were designed and modelled only for it to be discovered that the part could not be manufactured with the tools available to undergraduate engineering students at the University of Florida.

Specifically, the task of dimensioning parts in a manner than allowed all parts to mesh with one another was not a trivial task. SolidWorks proved to be an invaluable tool in this regard: dimensions would be thought up through quick pen-and-paper calculations and then immediately visualized in a SolidWorks assembly. The dimensions listed for the parts used in this project were, in almost all cases, arrived at after a considerable amount of calculation, modelling, recalculation, and further modelling. It is impossible to describe every iteration of every part and the reasoning behind changes from one iteration to the next. Instead, only the preliminary and final design iterations of most parts were discussed. Nevertheless, it is important to note that, for each part, many design iterations were not mentioned or described in detail.

One particular part that proved very difficult to design properly was the frame. The limitations of the waterjet manufacturing method have been discussed previously: what was not mentioned, however, was that these limitations were not known until a significant portion of the design process had been completed. Thus, the realization that the frame could not be 24” long sparked a massive re-design phase that set the project back roughly one month. Another major challenge in designing the frame was adherence to the engineering principle that holes be placed at a distance at least 1.5 times their diameter from the edge of a plate. This restriction greatly limited design freedom when modelling the frame, and indeed this rule had to be broken for two particular holes which simply could not be moved further inward without extreme changes to the fundamental design of the assembly.

Nevertheless, through much trial and tribulation, a finalized design was reached. The SolidWorks model of this final assembly is shown in Fig. (27) to (31). The completed model consists of 64 total parts and 20 unique parts: 5 of which were 3D-printed, 3 of which were machined, and 13 of which were found off-the-shelf (see Appendix A: Bill of Materials for more details).

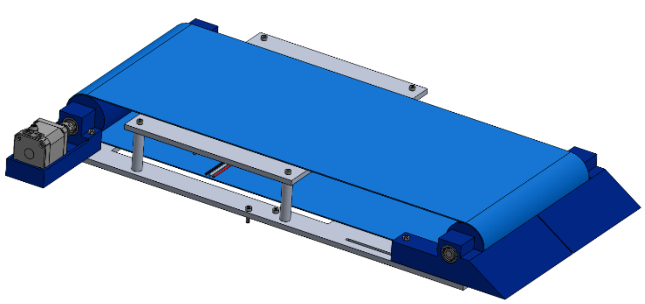

Figure 27. SolidWorks rendering of the fully-assembled printer modification assembly.

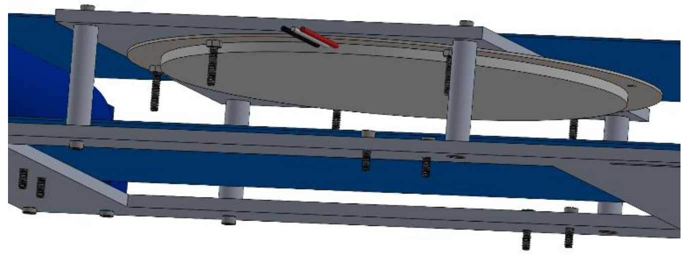

Figure 28. SolidWorks rendering of the fully-assembled printer modification assembly, zoomed in on the underside of the hot plate assembly.

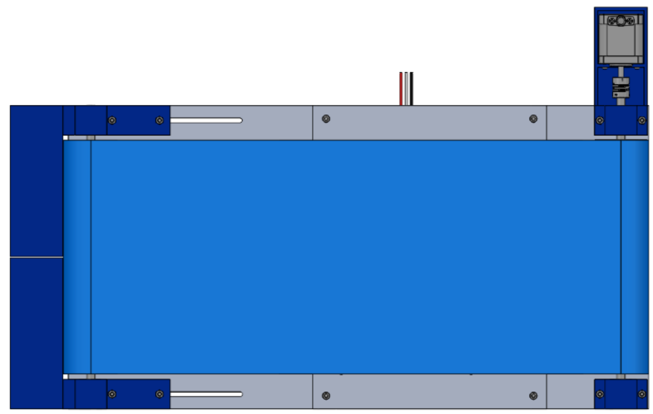

Figure 29. Top-down view of the fully-assembled printer modification assembly.

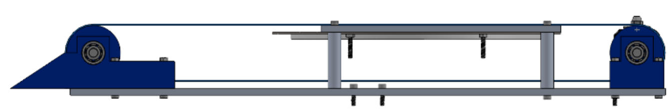

Figure 30. Side-on view of the fully-assembled printer modification assembly.

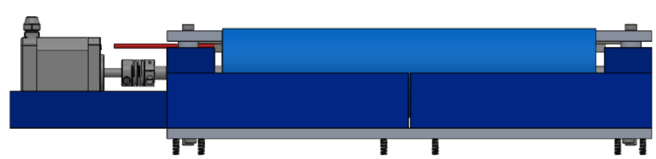

Figure 31. Front-on view of the fully-assembled printer modification assembly.

IV. OUTCOMES

The process of manufacturing the parts for the assembly was relatively straightforward. The only considerable deviation from the finalized SolidWorks designs were in parts that had interference fits. For instance, the first-batch prints of the roller mounts had holes that were slightly too large for the ball bearings to fit snuggly; as such, the SolidWorks models were updated to make the holes slightly smaller and the parts were re-printed. A similar exercise was done with the rollers: the first-batch roller prints had hexagonal shafts that were too small for the roller rods to fit in them. Unlike these 3D printed parts, which could be re-manufactured numerous times for little cost, the roller rods themselves needed to be nearly perfect after the first-batch: there was no budget to purchase new rods should the first batch fail. As such, great caution was taken not to remove too much material, lest the diameter of the circularized segment of the rods become too small to have an interference fit with the internal diameter of the ball bearings. One such rod did have this issue, and had to be discarded, though there was still enough stock material to manufacture the two required rods to specification.

The fully-assembled and installed printer modification assembly is shown in Fig. (32) and (33). To verify compliance with the CNS requirement that the conveyor belt be easily removed for maintenance, the conveyor belt was removed from the printer after the assembly was first installed. The removal process was relatively straightforward, with the greatest difficult being a few awkward angles on certain bolts; the entire process was completed in less than ten minutes.

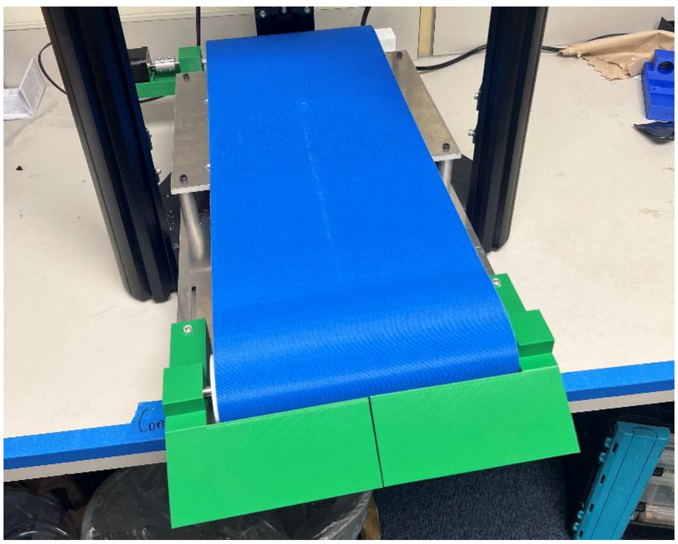

Figure 32. Completed printer modification assembled and installed on the FLSUN SR printer in the GatorKits Lab workspace.

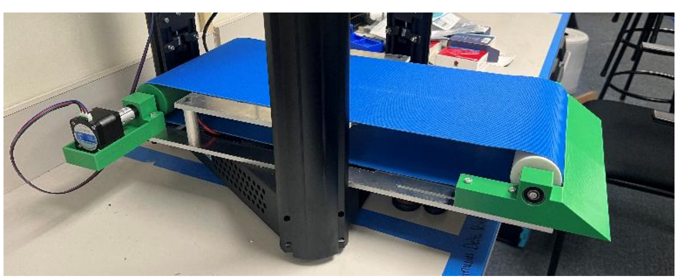

Figure 33. Completed printer modification assembled and installed on the FLSUN SR printer in the GatorKits Lab workspace.

Because the coordination side of the project was not undertaken at this time, only limited testing could be done on the finalized product. One important aspect of the printer that could be tested, however, was its ability to be brought up to 90ºC in a reasonable time period. To test this, the prongs of a thermocouple were taped to the conveyor belt surface and the printer was commanded to bring the hot plate temperature to 90ºC. Once the printer registered that the hot plate had reached the commanded temperature, the thermocouple began being read every 5 minutes. While it is not realistic that the conveyor belt would reach equilibrium with the hot plate immediately, the hope was that the conveyor belt would reach nearly 90ºC within 15-20 minutes of the hot plate. The results of this experiment are shown graphically in Fig. (34).

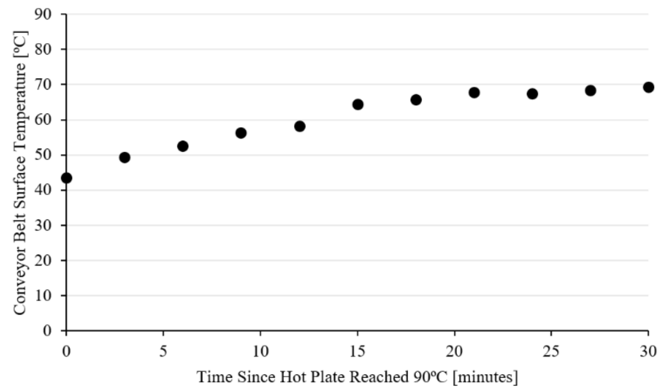

Figure 34. Results of thermal testing of the completed printer assembly. Conveyor belt temperature was measured by a thermocouple from the time the hot plate reach a temperature of 90ºC. The experiment was left to run for 30 minutes with the goal of the conveyor belt reaching 90ºC as well.

Examination of the experimental results shows that the thermal testing was largely a failure. For the first 15 minutes of the test the conveyor belt temperature seemed to steadily rise at a rate of ~1.5ºC per minute. After the 15-minute mark, however, this pace declined significantly to only ~0.3ºC per minute. Even if the original pace of ~1.5ºC per minute was maintained, the conveyor belt would take approximately 30 minutes to rise from its initial measured temperature of 43.5ºC; this performance wouldn't be entirely unacceptable, but would be far from ideal. And the real test results show that at the 30-minute mark the conveyor belt temperature is significantly below the target temperature.

No detailed heat transfer analysis is required to recognize the design issue that is limiting the conveyor belt's ability to reach the desired temperature. In selecting such a thick aluminum plate for the hot bed surface the design has introduced significant heat dissipation effects: as the temperature of the hot bed surface rises, it begins dissipating heat at an increasingly significant rate. The hot plate does not transfer enough heat to the hot bed surface to fully overcome this heat dissipation, and so heating of the bed surface stalls. Two design changes could be made to fix this issue: a more robust hot plate could be installed or a thinner hot bed surface could be installed. The first option could introduce power issues with the printer and is likely less cost-effective than using a thinner hot bed surface. However, such a choice would significantly increase the quantity of the project's wasted stock; after all, the hot bed surface was chosen to be cut from the same stock as the frame in order to reduce waste and total cost.

Asides from this heat transfer issue, the hardware portion of the project was a success. The hot plate was successfully re-wired to its original connections and the stepper motor was successfully attached to the printer motherboard. Unfortunately, without installing and programming a Raspberry Pi, testing of the stepper motor was highly limited. The conveyor belt was, however, confirmed to have freedom of movement, meaning that there are no significant interferences and that the ball bearings have sufficiently little friction so as not to impede the conveyor belt's motion.

As a final review of the success of the project, it is worth revisiting the CNS requirements and assessing which requirements were met and which were not:

(1) PASS: The design utilizes the FLSUN Super Racer.
(2) PASS: The design could be readily adapted to the FLSUN V400 printer.
(3) FAIL: The upgrade package costs $208.40
(4) PASS: The design does not discard metal parts from the original printer.
(5) PASS: The design makes use of mounting features from the original printer.
(6) FAIL: The print surface could not reach 90ºC within a reasonable amount of time.
(7) PASS: The build volume exceeds the requirement of 230 x 110 x 230 millimeters.
(8) PASS: The design is capable of printing both PTEG and PLA filament.
(9) PASS: The conveyor belt may be swapped with any number of commercially-available options, so long as basic dimension requirements are satisfied.
(10) PASS: The conveyor belt can be removed for maintenance in under 10 minutes with minimal effort.
(11) PASS: The only external outlet connection that will be required is a power source for the Raspberry Pi. The stepper motor used to drive the conveyor belt uses the printer's own power exclusively.

V. FUTURE WORK

The most pressing area of future work on this project is in rectifying the conveyor belt heating issue. This problem may be solved head-on using only intuitive knowledge of heat transfer and the thermal properties of materials such as aluminum and polymers. However, a more academic and likely more wholistic approach to the issue would be to do a proper heat transfer analysis of the system. This is, however, not trivial task: the exact material composition, and thus thermal properties, of the conveyor belt are unknown, and the energy transmission capabilities of the hot plate are unpublished and thus also unknown. A considerable degree of experimentation would be required to ascertain the thermodynamic properties and values required to solve for the system's heat transfer analytically. Nevertheless, this could be a worthwhile pursuit if an ideal thickness for the hot bed surface is desired.

The much larger area of continued work is, however, the matter of software integration and eventual cross-printer coordination. Automation is, of course, only half the battle of print farm optimization. For the benefits of automation to truly be reaped, the multiple printers must be assembled and integrated into a single interface as a coordinated print farm.

Before such work is done, though, there is the much more direct task of bringing the existing printer online. A small amount of work – only the most preliminary of software engineering tasks – was done at the end of this project in an attempt to ascertain the degree of difficulty of the software integration aspect of the printer's development. A Raspberry Pi was connected to the printer and work was begun to integrate OctoPi, the Raspberry Pi OctoPrint interface, to the printer. Additionally, an attempt was made to print a test part on the conveyor belt surface (despite the surface temperature being realistically too low for a successful print). It was here, however, that the first major obstacle in the software integration task was encountered. In making the modifications associated with this project, the effective print surface was raised several inches: that is, the upper surface of the conveyor belt was several inches above where the out-of-the-box print surface once was. This, as it turned out, proved rather problematic to the printer's functionality.

When the printer is commanded to commence a print job, it first orients itself by probing gently at various points on the print surface, in a sort of calibration procedure. It was assumed from the start of this project that this calibration procedure would allow the printer to re-orient itself to the new location of its print surface – that is, that the printer would re-calibrate its z-zero location and continue to print as normal. However, likely as a result of the extreme degree of change in the print surface z-position, the printer was unable to recognize the new print location was its new z-zero position; indeed, the printer seemed unable to recognize the existence of the new print surface at all. During the calibration procedure, the printer head could contact the conveyor belt surface, stop and retract itself as if preparing to proceed with the calibration procedure, then suddenly accelerate at the conveyor belt and try to force itself downwards. This reaction was observed numerous times, and each time the printer had to be manually turned off to prevent damage to the printer head or conveyor belt.

Examination of the settings of the FLSUN SR and its instruction manual indicated that there is no built-in method to re-zero or re-calibrate the printer head to accommodate a change in the z-position of the print surface. Research online, however, revealed that a third-party software, Klipper, has a number of programs which may potentially allow for roundabout re-zeroing of the z-zero location [22]. One such program is the "delta calibration" procedure, which conveniently may be run through OctoPi. Though no detailed research was conducted on this or other similar programs, it should be noted that Klipper solutions to the issue of z-zeroing may offer a good jumping off point for the next phase of this project.

VI. CONCLUSION

Though often overlooking and dismissed as inefficient and infeasible, additive mass-manufacturing may indeed offer a reliable and possibly necessary alternative to traditional mass-manufacturing techniques. In an economic landscape where small businesses and start-ups are increasingly common, it is increasingly important for engineering to prioritize equitable and cost-effective manufacturing solutions.

Medium-scale print farm optimization is one such way in which mass production may be de-commercialized and made more available to the general public as well as the often budget-constrained world of academia. Such optimization is achieved through a means of printer coordination and automation, and does not necessarily have to derive itself from commercially-available products. This project presents just one of many possible approaches to creating more optimized additive manufacturing processes. With sufficient time and continued research in the field, new technologies will certainly emerge which will change the landscape of additive mass-manufacturing for the better.

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VIII. Appendix A: Bill Of Materials

When possible, bill of material pricing is based on the per-unit cost of the item when purchased in the largest quantity reasonably available. For instance, pricing for the 0.5" rod used for manufacturing the hot bed legs is based on the fractional cost of a 24" x 0.5" aluminum rod which might be used to manufacture a number of hot bed legs for a number of printers. Additionally, effort was taken to find relatively inexpensive yet simultaneously reliable sources for stock parts online.

Part	Quantity	Sum Cost	Source
12" x 24" x 0.25" Aluminum Sheet	1	$67.05	[22]
0.5" Diam. Aluminum Rod	~8"	$0.68	[23]
18-8 Stainless Steel Low-Profile Socket Head Screws	8	$2.92	[24]
Aluminum Hex Nut	13	$3.37	[25]
NEMA 17 Stepper Motor	1	$19.99	[26]
316 Stainless Steel Button Head Hex Drive Screws	2	$0.15	[27]
Alloy Steel Socket Head Screws	12	$1.61	[28]
Black-Oxide Alloy Steel Hex Drive Flat Head Screws	7	$1.26	[29]
CHPOWER Updated 3D Printer Conveyor Belt IR3-P1	1	$40.99	[18]
8 mm x 22 mm Ball Bearing	4	$1.40	[30]
Multipurpose 6061 Aluminum Hex Bar, 0.375" Width	~24"	$2.63	[31]
8 mm to 5 mm Shaft Coupling	1	$8.54	[32]
PLA Filament	479 g	$7.81	[33]
Raspberry Pi 5 2 GB	1	$50.00	[16]
		$208.40	

IX. Appendix B: Concept Drawings

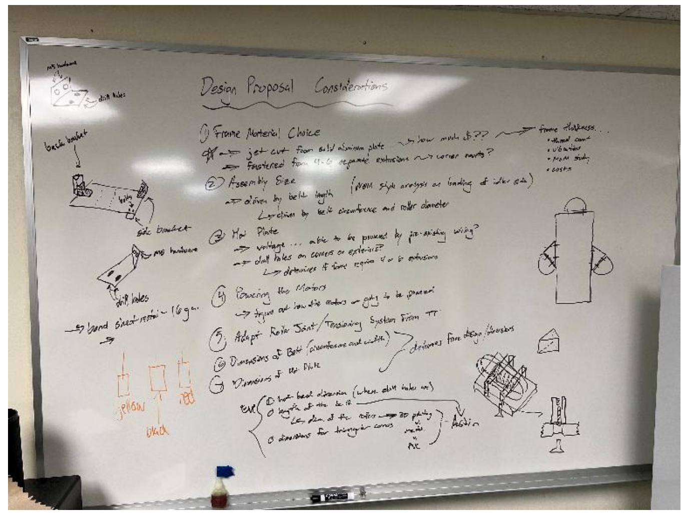

Figure A. Whiteboard from the preliminary design phase containing a list of initial design considerations as well as several sketches outlining basic design ideas. The sketch near the bottom right, next to the word "Austin," was the basis for Fig. (9). The larger sketch on the right of the whiteboard was the basis for Fig. (10).

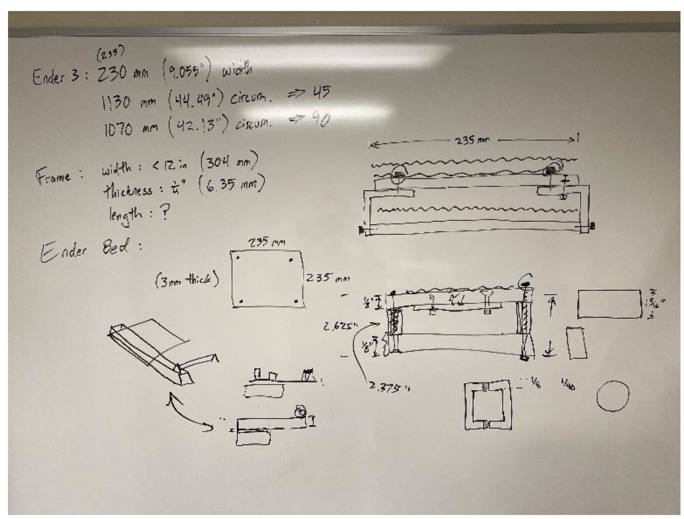

Figure B. Whiteboard from the preliminary design phase containing manufacturer-specified dimensions for several conveyor belts in consideration for purchase (upper left) as well as design ideas for the cross-sectional arrangement of the assembly.

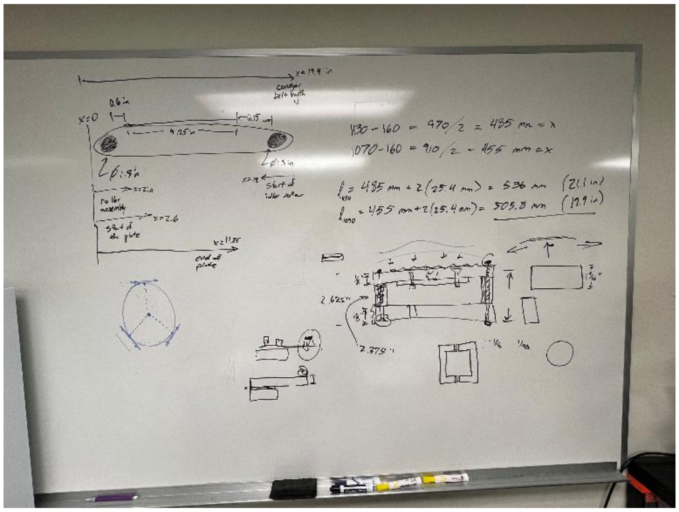

Figure C. Whiteboard from the early design phase depicting math surrounding the length of the conveyor belt assembly (upper half) and a more finalized version of the cross-sectional arrangement of the assembly (lower half).

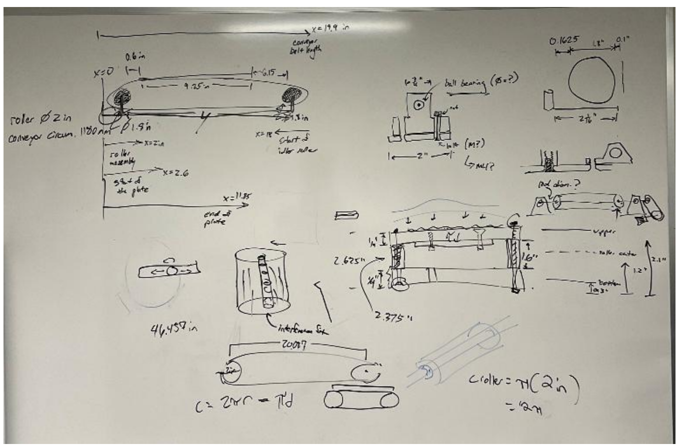

Figure D. Whiteboard from the middle design phase depicting more detailed drawings of the roller mount, roller rod, and hot bed support rod designs. Some rough dimensioning is included. Several sketches shown in Fig. (C) remain on the whiteboard.