Development Of A Multi-Axis Wire Embedding Device For A Large Area Thermoplastic Pellet-Fed Additive Manufacturing System

Christopher Jasiel Minjares

University of Texas at El Paso

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DEVELOPMENT OF A MULTI-AXIS WIRE EMBEDDING DEVICE FOR A LARGE AREA THERMOPLASTIC PELLET-FED ADDITIVE MANUFACTURING SYSTEM

CHRISTOPHER JASIEL MINJARES
Master’s Program in Mechanical Engineering

APPROVED:

David Espalin, Ph.D., Chair

Yirong Lin, Ph.D.

Amit Lopes, Ph.D.

Stephen L. Crites, Jr., Ph.D.
Dean of the Graduate School
Dedication

This Thesis is dedicated to my parents, Rodrigo Minjares and Margarita Reyes, and my brother Jonathan Minjares who supported me to continue with this journey.
DEVELOPMENT OF A MULTI-AXIS WIRE EMBEDDING DEVICE FOR LARGE AREA THERMOPLASTIC PELLET-FED ADDITIVE MANUFACTURING SYSTEM

by

CHRISTOPHER J MINJARES, B.S.M.E

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Mechanical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

August 2020
Acknowledgements

I would like to extend my gratitude for giving me this enhancing opportunity to Dr. Espalin, Associate Professor from the Mechanical Engineering department at UTEP and also Director of Research at the W.M Keck Center for 3D Innovation. During these years, he has been an enormous support not only on the research area but also developing my skills as an Engineer. In Addition, thanks to all the staff within the Keck Center for this enormous opportunity which I know I will never encounter any similar experience through my career.

My friends and colleagues from the Keck Center who also deserve recognition. Mr. Jose Motta and Xavier Jimenez for their enormous contribution to this project on the controls and the mechanical design for it. In addition, they made me become a better engineer since they always pushed me to think ahead. Mr. Jose Coronel whose professionalism I admire and who helped me be more conscious at work. Mr. Emerson Armendariz for creating such a good environment at the lab and Mr. Kazi Billah who helped me performing experiments which was a big contribution to my thesis. Also, Angel Vega and Adrian Belmontes for always giving relevant feedback during this project. Additionally, special thanks to Bobby Baer and Steve Taphorn from Cincinnati Incorporated, for their contribution installing and programing the Articulated Arm on the BAAM system.

Finally, my mom Margarita Reyes, and dad Rodrigo Minjares for always giving me the support and love to continue with this journey, and my brother Jonathan Minjares who taught me what being an engineer means.
Abstract

This research focused on the development and implementations of a six degrees of freedom (6DOF) articulated arm onto a Big Area Additive Manufacturing (BAAM) system to interact with complex 3D geometries. BAAM is a large-scale machine which falls under material extrusion additive manufacturing (AM) – a process that selectively dispenses molten plastic layer-by-layer. The development of the 6DOF articulated arm required a mechanical design which went through several iterations before getting to the final design. Also, implementation of the tool was performed with the help from Cincinnati Incorporated (CI) which is the company that developed the BAAM.

First, the mechanical design of the 6DOF arm was planned based on the wire embedding needs and the BAAM system. It was decided to use the prismatic gantry of the BAAM to leverage the three degrees of freedom. In addition, the BAAM system also possesses high material deposition rates and large printing volume when compared to medium size material extrusion AM systems which makes it attractive to add these capabilities to the system.

Secondly, the 6DOF arm has the capabilities to displace in different planes, but for this case of study a tool which will be delivering copper wire was designed for this specific arm, therefore adding process which may be the beginning of emerging technologies. Previous AM systems have implemented methods to produce conductive traces, typically of solid copper wire or conductive inks, to generate circuitry within the AM fabricated parts.

Lastly, it was required for the 6DOF arm to be able to function together with the BAAM system, therefore CI offered his help in order to make physical modifications on the gantry in order to install the 6DOF arm and also to modify the Human-machine Interface (HMI) which is the software used to deliver instructions to the BAAM. The modifications made on the HMI included
instructions for the added degrees of freedom which are called A, B and C which made the BAAM system function as one system.
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Chapter 1: Introduction

1.1 BACKGROUND

Additive Manufacturing (AM), commonly known as 3D printing, has become a promising solution for fabricating parts that require high geometrical complexity and reduced lead time for producing low volumes, especially when compared to traditional manufacturing such as machining, casting or injection molding which have high tooling costs. In general, AM parts with complex geometries including internal channels can help dissipation heat. This and the many benefits of AM have fostered interest from medical, automobile, and aerospace fields due to the design freedom and cost reduction of fabricated parts (Campbell, Bourell, & Gibson, 2012). Additionally, the integration of multi-functionality allows for the implementation of extra features that expand the capabilities of an AM fabricated part beyond a simply structural. For instance, incorporation of capacitive sensors (Shemelya, et al., 2015), microprocessor, accelerometer (Macdonald, et al., 2014) and copper wire interconnections (Coronel, et al., 2017) into a AM fabricated part. In recent years, large area thermoplastic-based AM has attracted much attention because of the possibility of fabricating large tools like composite layup molds, compression molds, and concrete molds. It should be noted that large area thermoplastic-based AM and fused deposition modeling (FDM) fall within the material extrusion AM category where heated thermoplastic is extruded and deposited through a nozzle in a layer by layer fashion (ASTM-F2792, 2012). Thermoplastic extrusion AM produce parts using industry grade thermoplastics such as polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polyether ether ketone (PEEK), thermoplastic polyurethane (TPU), etc.

Of particular interest to those fabricating molds using large area thermoplastic-based AM is the inclusion of conductive materials into parts to function as interconnect or heating elements.
Interconnect are being considered for integrated sensors (e.g., strain, temperature) and heating elements for heating mold surfaces to accelerate curing of materials (e.g., cement, pre-preg). This study focused on the development of a six degree of freedom (6DOF) tool intended to embed wire within a thermoplastic part using a large-scale 3D printer. To facilitate the embedding process, the wire was heated by creating an arc while driving wire past the arc. The arc heating method used a non-consumable tungsten electrode which was subjected to electrical current to produce a plasma and heat the wire while providing a shielding gas to reduce oxidation (Espalin, 2017). Other forms of wire embedding have been investigated including the use of ultrasonic embedding which employs high frequency vibrations to introduce the copper wire into the printed part by deforming the substrate. Secondly, the heating wire embedding where a heating (e.g., cartridge heater) source is used to elevate the temperature of the wire above a temperature that induces thermoplastic softening. These embedding methods have been used to print parts with multiple functionalities. For instance, introducing a capacitive sensor to a thermoplastic printed part (Shemelya, et al., 2015) to differentiate between three metallic materials and distinguish salt water from distilled water. This last technology of introducing interconnections within the substrate enabled parts to have a functionality other than physical or mechanical.

For this study, the Big Area Additive Manufacturing (BAAM) machine developed by Oak Ridge National Laboratory (ORNL) in partnership with Cincinnati Incorporated (CI) was used. The 6DOF wire embedding tool was mechanically and programmatically integrated into the machine. Figure 1.1 shows a front view of the BAAM-100 machine and a person standing on the platform for scaling purposes. The BAAM had a build volume of 7.7305 m$^3$ (273 ft$^3$) and a deposition rate up to $1.639 \times 10^7$ mm$^3$/hour (1000 in$^3$/hour) (Love & Duty, 2015). For comparison, a desktop material extrusion printer that has a build volume of 0.5057 m$^3$ (18 ft$^3$) and deposition
rates up to 81935.3 mm$^3$/hour (5 in$^3$/hour). As an example, figure 1.2 shows a sample desk with dimensions of 7620 x 7600 x 6096 mm, which took one hour and forty-three minutes to build.

![Front view of the Big Area Additive Manufacturing (BAAM) System](image1.jpg)

**Figure 1.1:** Front view of the Big Area Additive Manufacturing (BAAM) System

Additionally, the cost per kg of filament material at the time of producing this manuscript ranged from 100 to 200 USD in the case of desktop printers. On the other hand, the BAAM thermoplastics pellets ranged from 2 to 10 USD per kilogram (Love & Duty, 2015).

![Sample Desk printed using the BAAM system](image2.jpg)

**Figure 1.2:** Sample Desk printed using the BAAM system
1.2 Motivation

Large-scale material extrusion systems have been around since 2015 which makes it a new emerging technology where opportunities exist to make this machine multi-functional. In this case, the addition of the 6DOF tool and a wire delivery end effector was the initial step in many possible technology paths that lead to large-scale hybrid systems. As mentioned before, the cost of the material and the fast deposition rates make the BAAM machine very attractable for mold making (Roschli, et al., 2018), and such interest is expected to increase when tooling includes embedded interconnect or heating elements that can shorten curing times. The tool and end effector developed in this manuscript presents work towards realizing large scale parts with embedded conductors.

1.3 Thesis Objectives

This thesis addresses four technical objectives:

- Develop and demonstrate the functionality of a robotic arm having three independent degrees of freedom needed to embed wire on three planes (XY, YZ, and XZ).
- Prescribe process parameters through a custom HMI in collaboration with Cincinnati Incorporated (CI)
- Integrate a wire embedding tool including an arc heating torch
- Demonstrate the capabilities of printing and using the robotic arm

1.4 Thesis Outline

The remainder of this document contains five chapters. Chapter 2 contains an overview of the seven AM process categories with particular focus on material extrusion. In addition, large
scale material extrusion technologies are described as well as hybrid material extrusion technologies, which serve as motivation for developing the tool described in this work. Chapter 3 covers the technology’s design requirements and the addition of three more degrees of freedom to the BAAM gantry. Additionally, the mechanical design of the tool as well as the end effector, components, mechanisms and materials used will be described. Chapter 4 describes the implementation of the tool in collaboration with Cincinnati Incorporated as well as the description of the developed Human machine interface (HMI). In addition, the implementation of the tool to the BAAM gantry brought design changes that will be described. Chapter 5 contains the results and discussion related to the tool implemented into the BAAM system. Chapter 6 contains a final conclusion of the project as well as future work recommendations.
Chapter 2: Literature Review.

To begin to understand the framework of this project, a background on Additive Manufacturing (AM) is discussed. Traditional processes, technologies, and categories, with emphasis on the material extrusion process, large-scale material extrusion, materials typically utilized, and existing applications. The literature review presented in this chapter will explain current work related to BAAM, the importance of hybrid additive manufacturing systems, as well as applications that include wire embedding processes within AM technologies.

2.1 ADDITIVE MANUFACTURING

Initially known as Rapid Prototyping (RP) during its initial research and development stages, additive manufacturing (AM) is a process which allows one to design a prototype, or a scaled model, from digital data, to prepare and fabricate the conceptual design of a specific product, and provides near immediate feedback after printing to enable adjustments before the release of a final product (Gibson, Rosen, & Stucker, 2010). As the technology continued to evolve, further improvements on the fabrication process allowed for functionality integration into final parts for certain applications. Having already fabricated fully functional parts early in AM history, rapid prototyping was no longer descriptive of this technology. Eventually, the layer-by-layer manufacturing technology was titled Additive Manufacturing by the ASTM F42 Committee in 2009 (Wholers & Caffrey, 2009).

AM is a process of fabricating a 3-Dimensional solid object by adding material in a layer upon layer fashion. The AM process starts from a 3-D computer aided design (CAD) model that is divided into layers of specified thicknesses. A stereolithography (STL) file is what is built by the CAD software after its design and contains all digital data encompassing the combined layers that is interpreted and utilized by AM systems (Gibson, et al., 2010). Then, the STL file is
transferred to that particular AM system’s software and outlines the necessary pathways of each layer to fabricate a complete object. The main advantage of building with AM processes as compared to traditional fabrication methods like that of milling and injection molding is the ability to attain object geometries of high complexity, and can fabricate these features directly from a CAD model without any tooling constraints. Some existing applications of AM produced parts, functional and non-functional, include high efficiency temperature sensors, mounting brackets for airplanes, pulleys in mechanical assemblies, biomedical implants, and parts embedded with various electronics (Gibson, et al., 2010) (Wicker, et al., 2014).

The most common materials in AM processes are metals, polymers, and ceramics. Metals and polymers are the most widely used. The AM processes that fabricate with metals are principally selective laser melting (SLM) and Electron beam melting (EBM). The SLM process utilizes a high-power laser to sinter or melt metals in powder form. Sintering refers to the heating of a powdered material to coalesce into a solid or porous mass without inducing its liquid state in order to provide support to a part’s material properties, ultimately to minimize internal stresses on the forming layers within powder bed fusion systems. SLM functions in an inert gas environment of nitrogen or argon as they provide ideal conditions for this process to take place in (Gibson et al, 2010). The EBM process falls under the same principle as SLM in producing dense metallic parts with a crucial difference being the use of an electron beam for sintering and melting of the metal powder instead of a high-powered laser, and consequentially, produces parts of slightly different material properties.

The AM processes that utilize polymers are selective laser sintering (LS), stereolithography (SL), and material extrusion, also known as fused deposition modeling (FDM) (Wholers & Caffrey, 2013). Like SLM for metals, the LS process utilizes a high-power laser to sinter and melt
the polymer in powder form. The LS process functions with an ultraviolet light to cure a photopolymer. The FDM process, which will become the focus of this literature review section, operates with a polymer filament and a nozzle that preheats the material allowing it be deposited layer-by-layer for part fabrication (Gibson et al, 2010). In AM processes, each technology has different characteristics regarding part accuracy, part precision, material properties, post-processing time, building time, part size, and fabrication cost (Wholers & Caffrey, 2013).

2.2 MATERIAL EXTRUSION/FUSED DEPOSITION MODELING (FDM)

Material extrusion is an AM process designated for polymers and is also referred to as FDM. This manufacturing process consists of injecting a thermoplastic filament into a heated liquefier which then delivers the material in a semi-molten state through a nozzle of small diameter. The extrusion head moves within a build platform print area (XY directions) to deposit the semi-molten material to fabricate the corresponding layer. The build platform typically moves up or down (Z direction) according to a predefined thickness of the layer. This process is repeated until the part is completed. Also, the build process is done in a temperature-controlled envelope that supports controlling material shrinkage and prevents development of internal stresses (Wang, Xi, & Jin, 2007).

The most common materials used in FDM systems are acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC), PC-ABS blends, ABS-M30, and polyetherimide (ULTEM 9085). In AM machines an important aspect to consider is the envelope size that indicates the maximum in length, width, and height of part that a system can build. The envelop size vary from system to system however; a very common envelope in FDM is 406.4 x 406.4 x 406.6 mm (16 x 16 x 16 in). BAAM (big area additive manufacturing) is a large-scale material extrusion process developed at the Oak Ridge National Laboratory (ORNL) in collaboration with Cincinnati Incorporated (CI).
Previously observed envelope sizes handled by BAAM systems are 3556 x 1651 x by 914.4 mm (140 x 65 x 36 in), 3556 x 1651 x 1828.8 mm (140 x 65 x 72 in), 3556 x 1651 x 2489.2 mm (140 x 65 x 98 in), and 6096 x 2286 x 1828.8 mm (240 x 90 x 72 in) depending on the model. Materials that have been built successfully are ABS, PPS, PC, PLA, TPU, and PEI. In addition, it has been found that adding carbon fiber, glass fiber, organic fibers, and other additives improves the strength and stability of the parts manufactured. (Cincinnati Inc, 2020). It has been found that fiber reinforced polymers substantially increase the strength of a part by a factor of 4-7 times in number (Ajinjeru, et al., 2016)

![Figure 2.1: Schematic of a heating barrel, with pellets entering at the top, then the location of the four heating zones and finally the material being deposited. (Courtesy of Chesser, et al., 2019)](image)

Instead of using a liquefier to heat a thermoplastic filament typically seen on desktop material extrusion systems, BAAM uses a single screw extruder to melt pelletized feedstock that is contained in a heated barrel (Ajinjeru, et al., 2016). The heated barrel contains four heating zones meant to control the temperature of the pellets and they travel through it. First, the heated barrel melts the pallet feedstock, where the screw then drives the melted polymer through a nozzle causing the extrusion. This process is shown in Figure 2.1 (Roschli, et al., 2019). In BAAM
systems, there are four common diameter sizes: 0.254, 0.508, 0.762 and 1.016 mm (0.1, 0.2, 0.3 and 0.4 in). Although, FDM nozzles can have a range between 0.127 and 0.330 mm (Figure 2.2). BAAM system uses a substantially larger gantry systems to move the extruder in X, Y, and Z directions to fabricate a part. The gantry system is able to achieve peak velocities of 5080 mm/s (200 in/s) with accelerations of 1635.76 mm/s² (64.4 in/s²), and position accuracies of 0.0508 mm (0.002 in) (Post, et al., 2016).

![Figure 2.2: Side view of a nozzle previously used by the BAAM system, 1.016 mm in diameter (Left), Bottom of view of the same nozzle (Right)](image)

A current application interest for BAAM system consists of the customization of electric cars (Lonnie, 2014). This work was developed by Oak ridge National Labs (ORNL) where they printed sections of an electric car and were able to make design modifications throughout its conception to make possible the printing of a design which also to included electrical components. Other notable applications have been oriented to making molds for Autoclave (Kunc, et al., 2016), Vacuum Assisted Resin Transfer Molding (Hassen, et al., 2016), in addition to pre-casted molds for concrete (Roschli, et al., 2018).

For the concrete pre-casted molds, a comparison between traditional manufacturing and large-scale additive manufacturing is provided in Table 1. Fabricating the molds using BAAM costs $9000 USD and can be used 190 times. On the other hand, traditional manufacturing costs
$1800 USD but can only be used 10 times. This means that using BAAM for printing those molds can be beneficial from a financial standpoint.

Table 1: Cost and use comparison of pre-casted concrete molds, between traditional fabrication methods involving the use of wood against BAAM using ABS 20%CF as a printing material. Courtesy of (Roschli, et al., 2018)

<table>
<thead>
<tr>
<th></th>
<th>Traditional</th>
<th>BAAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/Mold</td>
<td>$1800</td>
<td>$9000</td>
</tr>
<tr>
<td>Pours per Mold</td>
<td>10</td>
<td>190</td>
</tr>
<tr>
<td>Cost per Pour</td>
<td>$180</td>
<td>$47.37</td>
</tr>
</tbody>
</table>

2.3 Printing Procedure and Designing Considerations for BAAM

The configuration of the BAAM system consists of the machine itself, a desiccant dryer, and a chiller. First, the material in pellet form is introduced to the dryer in order to remove all possible moisture that may have developed from the surrounding ambient environment, which if not removed, can create swelling of the material within the system, produce small pockets of steam (air bubbles), and degrade the material upon rapid heat subjection. The material should be dried for three hours at 82.2° C (180 F°) prior to print. Secondly, the software to control the BAAM system is called the Human-Machine Interface (HMI), and it is here where the heating zones of the extruder are activated and where every zone retains a specific temperature depending on the material and its anticipated behavior within the extruder. The heating zones will take 30-40 minutes to reach a given temperature. The printing bed also has heating zones which are meant to avoid large temperature differences between the printing substrate and the building bed, ultimately to avoid the buildup of residual stress. Therefore, the heaters for the bead should always be activated. The temperature used for bed is usually 100°C but can be changed accordingly for experimentation. Once the heating zones of the bed are activated, it anywhere between 10 and 20 minutes to reach the given temperature. Similar to that of desktop material extrusion systems, CAD model information of an object to be printed is retrieved. The process begins with a CAD model which is exported as an STL file that will then be divided into a layer by layer toolpath via slicing
software. In this case, the software is called ORNL Slicer which was developed by ORNL specifically for the BAAM machine. Once the code with the instructions are generated, they are imported to the HMI where a demo bounding box movement encompasses the expected location of the print’s execution space. Then, material deemed ready by the drier will be pulled to a hopper which acts as the reservoir for a pelletized material and then supplies the material to the extruder. Upon executing the print, the system will calibrate the Z-axis with the bed, as well as the tip of the extruder. After the calibration, the system will purge material for a given amount of time previously given on the slicing software. The purging process normally takes about 15 seconds. Purging of the material is conducted in order to get rid of unwanted residuals of material previously used for printing and to ensure constant flow of the new material. Once it finishes purging material, it will start manufacturing the part layer by layer and translates the build platform downwards upon every layer’s completion. Lastly, the removal of the printed part from the bed is performed. Depending on the resulting parts quality inspection, post-processing of the part is required. For instance, machining for better tolerancing or trimming of the edges to get rid of excess of material. Figure 2.3 contains a process flow plan of the expected stages in operating the BAAM.

**Figure 2.3:** Overall flow steps for printing in the BAAM system
Designing criteria for parts to be manufactured using the BAAM system involves using different guidelines that are traditionally expected of an FDM printer, desktop or industrial grade. Bridging, cavities, surface finish, and bead width constraints are some examples of features that should be in consideration when designing for parts that will be printed using the BAAM system (Roschli, et al., 2019). It is important to note that BAAM systems also experience failures seen at the traditional FDM level. For instance, delamination is observed when there is long wait time between layers (Compton, et al., 2017). This can be expected if the layer adjacent to the layer being deposited lies near the material’s glass transition temperature, and will consequently create poor bonding between the layers which results in delamination.

2.4 LARGE-SCALE ADDITIVE MANUFACTURING SYSTEMS

Large-scale additive manufacturing is not only dedicated to thermoplastics; for instance, there is also the use of articulated arms with mounted extruder heads capable of depositing concrete (Figure 2.3, A) (Gosselin, et al., 2016). The Large-Scale Additive Manufacturing (LSAM) machine developed by Thermwood. is also thermoplastic-oriented. This system also has post-process machining capabilities to manufactured parts with better surface roughness and tolerancing. The Largest machine that LSAM provides is called the LSAM1040 (Figure 2.4, B), which has a printing volume of 679.6 m$^3$ (24000 ft$^3$) (Thermwood, 2018). Furthermore, Electron Beam Additive Manufacturing (EBAM) developed by Sciaky Inc. is a large-scale machine which is dedicated to produce metal parts. This system falls under the Direct Energy Deposition (DED) AM technology which uses an Electron beam gun as a thermal energy source and wire as a feedstock material. EBAM 300 (Figure 2.4, C) is the largest machine that Sciaky provides which has a printing volume of 8.61 m$^3$ (304 ft$^3$) (Sciaky Inc, 2020). Lastly, The Reactive Additive Manufacturing (RAM) system produced by Magnum Venus Products in collaboration with ORNL
can be seen in Figure 2.4, D. The RAM is an extrusion-based system dedicated to printing thermosets with a printing volume of 12.74 m$^3$ (450 ft$^3$) (Hershey, Lindahl, Romberg, Compton, & Kunc, 2020).

![Figure 2.4](image)

**Figure 2.4:** Large-Scale Systems: A) ABB 6620 6-axis robotic arm in a custom system for printing concrete (Courtesy of Gosselin, et al., 2016). B) LSAM 1040 developed by Thermwood (Courtesy of Thermwood, 2018). C) EBAM 300 System Courtesy of (Sciaky Inc, 2020). D) Reactive Additive Manufacturing (RAM) system (Courtesy of Hershey, et. al. 2020)

### 2.5 Hybrid Additive Manufacturing Systems

The combination of additive manufacturing and subtractive manufacturing processes are growing in popularity since this approach reduces the limitations in use of either process individually by combining their advantages. This combination of manufacturing processes
increases the quality of the parts manufacture by AM technologies by improving surface finish, precision, and accuracy on critical part features (Manoghran, et al., 2015). This approach is known as hybrid additive manufacturing, and has come to witness existing systems that utilized a combination of both technologies to manufacture a final part. AM technologies such as FDM, EBM, and SLM, with the aid of subtractive technologies including CNC machining tools, laser cutting, and electric discharge machining, have become prominent platform combinations for hybrid additive manufacturing systems. Usually, hybrid AM systems are conducted sequentially; a part can be initially fabricated using an AM machine before being transferred to a subtractive machine to complete the overall manufacturing process.

Development of machines that integrate both technologies are currently being researched and developed as they have the potential to reduce manufacturing costs and processing times while increasing the quality of the final part. Mazak developed a hybrid multi-tasking system titled INTEGREX I-400 where the entire process is completed within a single machine. INTEGREX I-400 includes a laser metal deposition system integrated within a CNC machine of 5 axes. The principal applications for this system are near-net shape manufacturing, repair processing and coating (Yamazaki, 2016).

A case study was conducted to develop a hybrid system using a designed spindle, an FDM extruder, and a five-axis machine tool. The system was to transition between FDM extrusion and machining platforms. The system achieved fabricating parts without using support materials and attained more accurate dimensions and better surface finish by using optimizing machining capabilities (Lee, et al 2014). The LSAM is a large-scale additive manufacturing system developed by Thermowood that has both printing and trimming capabilities within the same machine. LSAM utilizes the near net shape procedure where the part is fabricated at high speeds and is then trimmed
to a desired size and shape (Thermwood, 2018). The BAAM machine could potentially become a hybrid system with the capabilities of trimming and/or for producing wire embedded parts. However, the first step is to build a robotic arm that could move within six degrees of freedom while remaining attached to the BAAM’s gantry and controllable from an improved HMI system.

2.6 Previous Applications Involving Material Extrusion and Electronics

Previous work showing the use of FDM technologies combined with the implementation of electronics may provide benefit from a manufacturing stand point. Manufacturing parts with embedded electronics within one system removes the need to use separate equipment and preserves the integrity of components by acting as one solid device with embedded and protected electronics (Shemelya, et al., 2015). Integrating electrical components and producing interconnections within the same manufacturing process can also improve volumetric use of allotted space, ultimately reducing overall required part volumes and print times. Integration of copper to act as the conductive pathways between electronics, capacitive touch sensors, and surface mounted components within a printed structure has been seen in a hybrid additive manufacturing system at the University of Texas of El Paso, which excersises a ‘pause-and-go’ approach to transfer parts being printed within an FDM industrial grade printer from Stratasys to a 3-axis CNC station with customized tooling for secondary processes before being returned to the FDM printer for print continuation (Coronel J. L., 2015).

Previous work has shown applications involving a BAAM system combined with a Wire Co-extrusion tool. This tool adds a custom head which has the capability to feed a wire concurrently with extruded thermoplastic which combines at a junction point to create one single bead with a wire present within (Arkins, et al., 2019). This application is oriented to develop self-heating molds which incorporate wire by passing current through it (also known as Joule heating).
as it is being deposited, therefore heating the wire and its surroundings which accelerate the curing time of some molds where heat is required.

The embedding of wire in a material extrusion process might be accomplished by following two steps: a wire must be heated while it is being fed into the part, and secondly, pressure must be exerted on the wire via a mechanical system in order to be embedded into the thermoplastic. The heat and the pressure allow the wire to be enclosed inside the thermoplastic during the fabrication process. The first phase of designing a wire embedding system inside a large-scale AM process such as the Cincinnati BAAM machine begins with the development of the heating system for the wire. Research was conducted to develop a heating methodology for a wire embedding tool that could be installed into a BAAM machine (Espalin, 2017).

The design requirements to develop the heating system were to target a copper wire diameter of at least 1 mm, a wire feed rate of about 5000mm/min, and a minimum embedding temperature of 250°C. Two wire heating methods were analyzed: a resistance heating method and an arc heating method. Experimental data determined that the arc heating method induced a higher temperature increase with less current than the resistance heating method. This is due to the fact that resistance heating systems work efficiently with materials that have high resistivity. Since the targeted material of the wire is copper and is low in resistivity, the arc heating method is more efficient for this application. The arc heating approach was adapted from the tungsten inert gas (TIG) welding systems (Espalin, 2017).

The TIG process utilizes a non-consumable electrode to induce the emission of electrons that heats the targeted material and a shielding gas to produce ionized plasma while minimizing contamination of the electrode and the weld pool. The material utilized as the welding electrode is a tungsten-based material due to its improved mechanical properties such as high melting
temperature, low vapor pressure, low thermal expansion, high thermal conductivity, and low work function. Argon was utilized as a shielding gas due to its high density, high thermal conductivity, low ionization energy, and noble nature. The elected power supply configuration was a DC power supply with a direct current electrode negative setting (DCEN). The DCEN setting consists on placing the negative terminal to a tungsten electrode and the positive terminal to the workpiece. This allowed for almost 70% of the heat generated by the arc to be used on a workpiece, and thus, the most efficient option. For the development of the arc heating method, the commercial Syncroware 2010 TIG welding unit (Miller, Appleton, Wisconsin) was utilized in a DCEN setting employed with a MR712SF micro-torch (CK Worldwide, Auburn Washington) and a pointed, ceriated tungsten electrode 2.38 mm (3/32”) in diameter (Espalin, 2017).

The experiments were performed with a 14 AWG wire (Ø = 1.628 mm) using a 120V power supply and 10A to operate the welding unit and argon gas at a flow rate of 12L/min. The first experimental set up was conducted for a stationary wire in order to determine the best electrode position for the most reliable arc start behavior. Stationary set up is illustrated in Figure 2.5 A, with the best electrode position found. The same set up was also utilized with a wire driven at a rate of 4,792 mm/min and additional experiments were performed with the welding unit operating at 10, 15, 20, and 25 A. Figure 2.5, B, illustrates the set up for the driven wire. Temperatures of the wire were recorded using an infrared camera and the resistivity, temperature profiles, and mechanical properties of the wire were characterized. The average temperature obtained from the experiments range from 200°C to 300°C (Espalin, 2017).
Degrees of freedom is widely used in the field of mechanics to describe the possible directions in which a body can move, and typically refers to that body’s physical constraints. According to Shabana, “we may define the degrees of freedom as the minimum number of independents required to describe the system configuration” (Shabana, 2020). Usually, problems involving degrees of freedom involve a traditional cartesian coordinate which involves the use of X, Y and Z axes. Moving a particle along the X, Y and Z axes can only approach a point in space by doing linear movements. Therefore, in order to approach and extend the capabilities, there are rotational axes known as Roll, Pitch, and Yaw, and for the purposes of this tool’s development, will be known as A, B, and C, respectively. This approach is extensively used in industry. For instance, CNC machining with 5 axis capabilities are machines with traditional X, Y, and Z coordinate system movements albeit with the addition of A and B axes, which allows the machine to interact with a part in angles not possible without the addition of A and B axes. HAAS is a company dedicated to developing machining systems that involve the use of 5-axes. For instance, UMC-750 is a machine provided by HAAS which is a 5-axis milling machine with the additional
A and B degrees of freedom implemented on the working table. In addition, the UMC-750 has the capabilities of 3+2 and 5-axis machining. 3+2 meaning the use of 3 axes at the same time with the other two axes locked, and 5-axis meaning that all 5-axis can work simultaneously in order to achieve complex geometries, for instance, curvatures (HaasCNC, 2020). Figure 2.6 shows an image of the UMC-750 machine (Left) and the working table showing the A and B degrees of freedom (Left).

Figure 2.6: UMC-750 machine (Left). Working table of the UMC-750 showing the additional degrees of freedom A and B (Right) (Courtesy of HaasCNC, 2020)
Chapter 3: Tool Design

3.1 Design Requirements

To develop a 6-axis articulated tool on the Big Area Additive Manufacturing (BAAM) system, an articulated arm was needed to complement the X, Y and Z motion of the gantry, with three rotational axes, A, B and C. This implied that the articulated arm had to be designed with rotational axis A, pivoting axis B, and rotational axis C (Figure 3.5). In addition to the three axes, design requirements that were considered included the length of the 6DOF arm due to the possibility of collisions between the tool and both the substrate, and the BAAM extruder. Having established a design for the 6DOF arm, the end effector attached could vary depending on the application. Figure 3.1 presents an overview of the steps followed by the 6DOF arm + wire delivery tool, serving as the end effector, for embedding copper wire onto a thermoplastic substrate, perpendicular to the Z-axis using the BAAM system. The process is as follows:

- The machine pauses the print at a layer where embedding will occur, defined by the user.
- The tool is positioned automatically at the desired location for wire delivery.
- The 6DOF arm is deployed to a position below the extruder to avoid any collisions while working in 3D planes (Figure 3.1A).
- The 6DOF arm equipped with the wire delivery tool approaches the plastic surface, parallel to the substrate, until contact (Figure 3.1B).
- The wire driving motor and the heat source are both activated to feed the copper wire, heat it, and execute the embedding (Figure 3.1C).
- Copper wire maintains contact with the substrate as the wire delivery tool travels across the substrate (Figure 3.1D).
• When the tool reaches its travel destination, the heat source and motor will deactivate (Figure 3.1E).

• The copper wire is cut after finishing the process (Figure 3.1F).

• The 6DOF arm shifts to a completely stable position (Figure 3.1G).

• The 6DOF arm will translate up to avoid any collision between the wire embedder and the substrate (Figure 3.1H).

• Continuation of the printing process, if necessary (Figure 3.1I).

Figure 3.1: Embedding process using the 6DOF arm + wire delivery tool on a BAAM system
3.2 Degrees of Freedom added to the tool

A traditional desktop printer usually has the capability to move in three different axes which are normally X, Y and Z. One of the requirements for this project was to be able to control the wire embedder in 3D planes inside the BAAM, which meant that three more degrees of freedom were required to accomplish this. Figure 3.2 shows visualization of the traditional three axis, X, Y and Z, with the additional three rotational degrees of freedom for each axis normally known as A, B and C. These rotational degrees of freedom are also commonly known as roll, pitch and yaw. Enabling control of these additional degrees of freedom allows the tool to embed wire beyond 2D planes. This is the purpose of developing an articulated arm with 6DOF.

![Figure 3.2: Visualization of the A, B and C axes added to the tool](image)

An important design consideration was the movement of the articulated arm within the printing volume. Figure 3.3 shows the build space dimensions for the BAAM machine. It had a travel distance of 3556 mm along the X-axis, 1651 mm along the Y-axis and 1828.8 along the Z-axis. The gantry of the system sits on two rails that are parallel to the X-axis and are located on either side of the printing bed. Motion in the Y direction relied on two rails parallel to the Y-axis. Figure 3.3 was taken from the slicer software for BAAM which prepares the desired model and
transfers the information to G-Code. Additionally, the printing volume with its dimension for the X, Y and Z axes can be seen.

The previous information was relevant since the position of the tool inside of the BAAM system would affect the possible build volume when considering the relationship between the movements of the gantry and the physical space of the articulated arm. Figure 3.4 shows a real image of the interior of the BAAM system. The gantry that carried the extruder was considered for mounting the 6 DOF articulated arm. Due to the interior walls of the BAAM system it was thought that having the articulated arm mounted on either side of the extruder would compromise the tool and also significantly decrease the printing volume along the X axis since the articulated arm could collide with the walls and the extruder itself while the arm was in motion.

Figure 3.3: Dimensions of the build volume respect to X, Y and Z axes of the BAAM system
The final design of the 6DOF articulated arm was mounted in front of the extruder to maintain the printing volume of the BAAM system in the Y-direction, sacrificing some distance in the X-direction as it is twice as long as the Y-direction. In addition, an actuator moves the robotic arm up and down along the Z-axis offsetting the 6DOF articulated arm from the extruder to allow free rotation of the articulated arm. Also, the arm includes four motors that enables rotation about the Z-axis (A-axis), rotation about the Y-axis (B-axis), rotation about the X-axis (C-axis), and a motor to drive wire on the wire delivery tool. In addition, a slip ring was implemented to allow free rotation along the A-axis without the entanglement of the power and air lines of the embedding tool. The original connectors for the Parker motors were used with additional slack to allow the tool to rotate about the C-axis.

Figure 3.4: Interior of the BAAM system
For the reader’s convenience, the 6 DOF articulated arm was divided into four sections. The first section will cover all of the mechanisms and components used for the articulated arm that allow movement about the A-axis. The second section covers the B-axis. The third section covers the C-axis as well as the end effector that serves as the wire delivery tool. Figure 3.5 shows the major components previously described and the sections previously mentioned for better visualization of the system.

Figure 3.5: Final CAD version of the 6DOF arm showing the location for the A, B and C axes, the location of the end effector (wire delivery tool), the actuator for the Z-axis and the different sections for the tool which will be used for further analysis.

The following sections of the paper describe the mechanical design and associated dimensions which are expressed using the SI System. For convenience, some of the parts will be called out by their common name which will make reference to US customary units since parts of the design were designed specifically for the customary system. In addition, unless otherwise specified, all the screws used for this design are black-oxide alloy steel which have a tensile
strength of 170,000 psi. Also, final drawings for each individual part machined in order to build the articulated tool can be found in appendix A and B, which include heat treatment, tolerancing and material. Material used for most of the components is Aluminum 6061 unless a different material is described.

3.2.1. Section I (A-axis)

The A-axis rotary motor was offset with a pulley system for the purpose of routing wires from the slip ring. The wires and air lines needed to pass through the slip ring to achieve free rotation of the arm. The A-axis motor and the slip ring were secured to a base plate (Appendix A13). This base plate had four tapped holes for 10-32 screws which secured the motor. In addition, there were three tapped holes for 5/16”-18 screws that fixed two aluminum blocks (Appendix A18 and A19) which had L-brackets that attach to the slip ring that used the same type of screws. This prevented the slip ring from moving. The aluminum blocks were located 90º apart from each other. In the center of these two blocks, the plate had a hole with a diameter of 101.60 mm for the slip ring to fit through. The actuator which moved the tool vertically along the Z-axis was mounted and guided by an aluminum block with 3/8”-16 tapped holes on the top face to fix the base of the actuator. Additionally, the block also served as a guide as two sleeve bearing carriages were attached to the back that rode on guide rails made of anodized aluminum which constrained movement to only be vertical. The carriages and the guide rails were meant to withstand temperatures up to 149 C° which was important since the articulated arm would be operating in a heated environment. The ball bearings from the carriages were meant to reduce friction on the guide rails and perform under dry and high vibration environments. Figure 3.6 shows an isometric view of section I with the components previously described.
The pulley system used to transfer motion from the A-axis motor to a 2” shaft was divided into two sections, mechanism A and mechanism B. The pulley system needed an adjustable block to apply tension on the timing belt. In Figure 3.7 mechanism A and mechanism B are shown as well as the adjustable block.

Figure 3.6: Isometric view of the CAD for section I

Figure 3.7: CAD of the side view for better visualization of the pulley system divided in mechanism A and mechanism B.
In order to incorporate the pulley system for the A-axis motor, components had to be selected to be able to design for the pulley. Starting from the shaft of the motor that transfers motion to a 5/8” stainless steel shaft with a length of 127 mm which gave ample room for the rest of the components required. To connect the shaft of the motor to the 5/8” shaft a spider coupler or jaw coupler was used. The coupling consisted of three pieces. The first is the top hub which had an inner diameter for a 16 mm shaft, a keyway, and a collar adjustment. Second, a spider-shaped cushion between the two hubs reduced shock and handled minor shaft misalignment. Lastly, the bottom hub which had the same features as the top whose only difference was the inner diameter which was for a 5/8” shaft.

To transfer motion from the 5/8” shaft to the 2” shaft a timing belt pulley (Appendix A15) with an appropriate timing belt was used. The timing belt pulley had to be redesigned in order to accommodate the 5/8” shaft with a collar that was fastened onto the shaft and pulley. The modified pulley had free-fit holes for 10-32 screws to attach to a standard 5/8” collar, fixing the two together. The pulley was 3D printed using a Fortus 400mc FDM printer with Polycarbonate (PC) as the printing material. The pulley had a trapezoidal profile for a trapezoidal timing belt with a pitch of 0.5” and maximum width of 25.4 mm. After attaching the pulley and the collar to the 5/8” shaft an additional 5/8” collar was used to prevent the shaft from moving up and down. This collar sat on a taper bearing that was located at the end of the shaft for smoother rotation.

The timing belt needed to be adjustable since the tension on it was to remain constant, therefore, an adjustable mechanism was designed to address this problem which can be seen in Figure 3.8. An adjustable aluminum block (Appendix A20) sat on the base plate (Appendix A11). The plate had a rectangular cavity where the aluminum block had the ability to move towards the timing belt in order to apply tension on it. Also, within the inner bounds of the rectangular cavity
there were three tapped holes that were 25.4 mm apart from each other for 5/16”-18 screws. The holes were used to fix the adjustable block to the desired tension. On the top portion of the block there was a slot with the proper dimensions for the screws previously mentioned. Atop the block there was a tapped hole for 1/4”-20 threaded rod which was 76.2 mm in length. The purpose of the threaded rod was to fix four ball bearings to the height of the belt. The ball bearings reduced the friction since the bearings were in contact with the timing belt. Figure 3.9 shows a CAD of mechanism A with the components previously described for mechanism B.

**Figure 3.8:** CAD of the isometric view of the adjustable block within the rectangular cavity.

**Figure 3.9:** CAD of Mechanism A completely assembled
The timing belt previously mentioned that transferred the motion from the 5/8” shaft to the 2” shaft had a diameter of 533.4 mm (21”). On mechanism B there was a custom timing belt pulley (Appendix A18) for a 2” diameter shaft. This was a modified pulley which was also 3D printed on a Fortus 400mc FDM printer using PC. On top of the pulley there was a flanged collar fixed to the 2” shaft and connected to a custom circular plate (Appendix A17) with 5/16”-16 screws. This circular plate was connected to the slip ring using M5 bolts and served as an adapter. Below the pulley there was a 2” inner diameter shaft collar that was connected to the pulley using 3/8”-16 bolts. Right below the shaft collar there was a taper bearing for the 2” shaft. In figure 3.10, the full assembly for mechanism B can be seen.

Figure 3.10: CAD of mechanism B completely assembled

The pulley system, as mentioned before, rested on a base plate (Appendix A10) that had the mating features for every component mentioned so far. On the base plate for the pulley system there were three plates (Appendix A12, A16 and A17) which served to enclose the pulley system to prevent any disruption of the rotating mechanisms. They also served as structural elements for
the motor and the slip ring. These three plates were attached from both the bottom and top using 5/16”-18 screws.

The pulley system base plate was fixed to the actuator guide, previously mentioned, and shaft guide block (Appendix A9) which was also connected to the actuator guide, thus when the actuator was activated, the tool would move vertically as one piece. The base plate and the shaft guide were attached to the guide mount using 1/2”-20 and 3/8”-16 screws, respectively. Also, the base plate and the actuator guide have structural brackets that counteracted bending forces at the mating points. These structural brackets were secured to both plates using 5/16”-18 screws. In addition, the shaft guide had cavities on the top and bottom surfaces for 2” shaft ball bearings to reduce friction on the shaft and allow for smooth rotation. Figure 3.11 shows a side view of the entire pulley system CAD. Section 2 will continue describing the rest of the assembly from the 2” shaft below the shaft guide block.

![Figure 3.11: Side view of Section I highlighting the components below the pulley system](image)

3.2.2. Section II (B-axis)

Section I interfaced with the rest of articulated arm through a flanged collar attached to the end of the 2” shaft from the A-axis rotation mechanism. A circular connection plate (Appendix
A8) needed to be designed to fit between the flange and the rest of the tool since the flanged collar had preexisting mating holes. The circular connection plate was made to have an outer diameter of 146.05 mm to accommodate the screws needed to fix onto the flange and an inner diameter of 53.34 mm that matched the 2” shaft diameter from the A-axis. The plate holes were tapped for 5/16”-18 screws since the flanged collar had free-fit holes for these screws. Additionally, the circular connection plate had free-fit holes for 3/8”-16 screws with counterbores for a standard socket head profile which connected the circular connection plate to the extension arms (Appendix A7). The counterbores kept the screws flush with the surface of the plate to avoid collision with the flanged collar.

As mentioned, the circular plate was connected to two extension arms that were designed as part of the enclosure for the B-axis motor. Each arm had dimensions of 120.65 mm by 19.05 mm by 395.60 mm (L x W x H). The height of the arms were determined by considering the height of the B-axis motor, which was 290.50 mm, with additional space for wiring and maintenance. In addition, the extension arms attached directly to the gearbox of the B-axis motor through free-fit holes for M6x1 mm screws with a length of 25 mm. As part of the enclosure, a base plate (Appendix A6) and two side plates (Appendix A5) kept the motor parallel to the bottom. The base plate was fixed to the extension arms from the bottom using 5/16”-18 screws with a length of 1”, while the side plates were attached to the extension arms and the base plate by 1/4”-20 screws also with a length of 1”. In addition, the side plates had a hole with a diameter of 28.575 mm for the shaft of the motor to rotate freely.

The gearbox of the motor that attached to the base plate was dual shaft, meaning that the rotation of the motor was transferred to two shafts that protruded from the gearbox. The shafts were connected using flanged collars for 15 mm shafts. These flanged collars then connected to a
plate that interfaced with the rest of the tool (Appendix A4) This plate for the flange had free-fit holes for 5/16”-18 screws which matched the holes on the flanged collars. In addition, this plate also had a rectangular profile to decrease overall weight. An isometric view of the CAD for the B-axis configuration with the components previously discussed can be found in Figure 3.12.

![Isometric view of the B-axis configuration](image)

**Figure 3.12:** CAD of the isometric view of the B-axis configuration with its major components (Section II)

Figure 3.13 shows the bottom view of the B-axis configuration showing the base plate for the motor and the flanged collars for the 15 mm shaft.

![Bottom view of the B-axis configuration](image)

**Figure 3.13:** CAD of the Bottom view of the B-axis configuration with the rest of the components (Section II)
3.2.3. Section III (C-axis)

The interface between Section II and Section III required a connection plate (Appendix A3) that served as an adapter similar to the interface between Section I and Section II. This connection plate had dimensions of 228.6 mm by 19.0 5mm by 76.2 mm (L x W x H) and joined the B-axis flange collar connection plates from Section II to the C-axis arms. There were six free-fit holes for 5/16”-18 screws that attached the connection plate to the B-axis, three on the left side and three on the right side. In addition, the middle portion of this connection plate had six free fit holes for 5/16”-18 socket head screws with counterbores that kept the screw heads flush with the plate’s surface. The C-axis arms (Appendix A2) were attached to the connection plate and had dimensions of 218.44 mm by 19.05 mm by 76.2 mm (L x W x H). Just as the B-axis arms, the length of the C-axis arms was determined by the length of the C-axis motor which was 182.70 mm with additional length for wiring and maintenance. At the end of the C-axis arms was the mounting plate for the C-axis motor. The mounting plate had six counterbored holes for 5/16”-18 screws to attach onto the arms while the motor attached using four 10-32 screws. Lastly, the shaft of the motor had a flanged collar for a 16 mm diameter shaft with a keyway. The end effector attached

![Figure 3.14: Isometric CAD of C-axis configuration (Section III)](image-url)
onto the flanged collar with three M5 tapped holes. A CAD of the Section III assembly can be found in Figure 3.14.

3.3 Wire Delivery Tool as End Effector

The end effector (wire delivery tool), required different mechanisms and components to automate the wire embedding process. Detailed drawings of the machined components can be found in appendix B which are referred to throughout this section. The main plate consisted of a plate made of aluminum 6061 which had a 45° angle to avoid collision between the substrate and components of the tool during the embedding process. A detailed drawing for this plate can be found in Appendix B, figure B1. This aluminum plate contained the components necessary to make the tool functional, first of which is the spool holder. The spool holder had a spool of 14-American Wire Gauge (AWG) copper wire with a diameter of 1.6281 mm (0.0641 in). The main part needed to make this mechanism was an aluminum L-bracket with dimensions of 76.2 mm by 76.2 mm (L x H) as a holding base. The copper wire spool was on the L-bracket which attached to the aluminum main plate using two 1/4”-20 button head screws. The spool rotated on a 3½” long threaded rod with a thread size of 5/16”-18. Additionally, to retain the spool on the holder, a wing

![Figure 3.15: CAD of the spool mechanism with its respective components attached to the main plate of the wire delivery tool](image)

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nut with the same thread as the threaded rod was used on one side and a nut on the other. The wing nut also helped with easy removal of the spool itself. Figure 3.15 shows a CAD of the spool mechanism completely assembled and attached to the main body of the tool.

The second mechanism is a V-grooved bearing that attached to the main plate that guided the wire to the straightener section. An 80 mm double threaded shaft was placed on the main plate and attached using M12x1.75 nuts. Figure 3.16 shows the V-groove bearing assembled CAD with its required components.

![V-grooved bearing CAD](image)

**Figure 3.16:** CAD of the V-groove bearing section with its respective components attached to the main plate of the wire delivery tool

The third mechanism for the end effector was the wire straightener designed to maintain the copper wire straight until it reached the end of the tool. Figure 3.17 shows the CAD assembly with the identified components. Four U-groove bearings were placed to straighten and pull the copper wire, two of them were stationary and the other two were adjustable. The U-groove bearings had a radius of 2 mm for the groove, 30 mm and 11.608 mm for outer and inner diameter respectively, and 14mm of thickness. Each bearing was secured with an M8x1.25 mm hex head shoulder screw with a total length of 17.50 mm, shoulder length of 9.50 mm, and diameter of 10 mm. The two adjustable bearings were attached with T nuts to allow for adjustability. The
aluminum main plate had the T-slots that matched the T nuts. The T nuts are held in place by a cover plate (Appendix B2) that attached to the main plate with 8-32 screws. Adjustability was done through 10-32 screws that threaded into the cover plate and pushed against the T nuts. Additionally, a driving roller for the wire was implemented using a DC motor with an encoder that pinched the wire with the help of one of the U-groove bearings. The custom driving roller (Appendix B8) was made of 302 stainless-steel with a keyway that matched the shaft of the DC motor. The driving roller was also knurled to help grip the wire against the U-grooved bearing. The shaft had a thin layer of Teflon to electrically insulate it from the high current. The shaft had a thread size of M4x0.70 at each end which was used to secure the custom roller onto the main plate using plastic screws of the same size.

![Diagram of the Wi
te straightener section with its respective components assembled to the main plate of the wire delivery tool](image)

**Figure 3.17:** CAD of the Wire straightener section with its respective components assembled to the main plate of the wire delivery tool

The application roller mechanism pressed the hot copper wire against the plastic substrate which melted the polymer surrounding the wire, therefore mechanically bonding the wire and the substrate once cooled. Figure 3.18 Shows the location of the application roller mechanism attached
to the main body of the tool. In addition, Figure 3.19 shows a cross-sectional view of the mechanism as well as the components used

![Application Roller Mechanism CAD](image)

**Figure 3.18:** CAD of the application roller mechanism completely assembled to the main body

Four 1/4”-20 double sided threaded shafts with lengths of 38.10 mm (1.5in) were required to constrain movement to the desired displacement direction of the application roller, in this case vertically. Each of the four threaded shafts were threaded into the main plate with locking nuts at the opposite ends to hold the application roller and compression springs. The compression springs were used to maintain a constant pressure across an uneven substrate and to keep the roller perpendicular to the substrate. The compression springs were made out of Zinc-plated steel and had a total length of 19.05 mm (0.75 in) and an inner diameter of 9.906 mm (0.39 in) which fit around the double threaded shafts. The two aluminum shaft guide blocks (Appendix B3) had cavities sized for insulation caps (Appendix B3) that held the 5/8” application roller shaft made of 420 stainless-steel. The purpose of the insulation cups between the 5/8” shaft and the aluminum shaft guide block was to electrically insulate the application roller. The insulated cups were 3D printed using ULTEM 1010 from Stratasys which had a range in resistivity of 1.0*10^14 -
8.96*10^15 ohm-cm. The application roller (Appendix B7) sat in the center of the stainless-steel shaft. The roller was centered by two 5/8” shaft collars which prevented any lateral movement of the roller along the shaft. The roller had an outer diameter of 50.8 mm (2 in) and inner diameter of 16.256 mm (0.64in) that fit over a 5/8” shaft. The roller was fitted over a 5/8” bearing which was on the 5/8” shaft. The roller also had a U-groove on the outer surface which had a radius of 0.40702 mm (0.16025 in) which was half the radius of 14 AWG copper wire. The purpose of the U-groove was to keep the wire centered.

**Figure 3.19:** Cross-Sectional view of the application roller mechanism

Figure 3.20 shows the side view of the complete CAD of the wire delivery tool with every mechanism including motor that drives the knurled roller and arc torch mount. The dotted line represents the path of the wire through the assembly.
The arc welding torch served as the heating source for the wire. The assembly for the welding torch consisted of an adjustable block (appendix B4) and the welding torch mount which were both 3D printed with PC. The adjustable block was designed to control the distance between the copper wire and the tip of the weld torch and was attached to the main body using a 10-32 screws. The mount for the welding torch was also adjustable and controlled the height of the torch tip with respect to the wire. Figure 3.21 shows a bottom view of the complete CAD of the wire delivery tool. Figure 3.21 also shows mounting screws with spacers that were used to connect the wire delivery tool to the articulated arm. The screws used had a 3/8”-16 thread size and were 1-5/8” long. The unthreaded spacers were19.05mm in length and had an inner diameter of 10.31mm for the screws to pass through it freely. The main aluminum plate of the wire delivery tool was tapped for the 3/8”-16 screws which fastened the tool onto an A-shaped mounting plate (Appendix B10). The A-shaped mounting plate was secured with the aforementioned screws and attached to

Figure 3.20: Complete CAD of the wire delivery tool (Side view)
the end effector mounting plate (Appendix B9), which was designed to match the flanged collar from the shaft of the C-axis motor. The A-shaped plate was tapped for 5/16”-18 screws and this attached to the end effector mounting plate. Lastly, the end effector plate had a total of six holes in the center, three of them were tapped holes for 10-32 screws, and the remaining three were free-fit holes for M5 screws. The 10-32 screws secured the flanged collar from the collar side and the M5 screws from the end effector side. Figure 3.22 shows the components previously described that enable motion to the end effector from the C-axis motor.

**Figure 3.21:** CAD of the wire delivery tool (Bottom view)

**Figure 3.22:** CAD of the End effector mounted to the A-shaped plate and the end effector plate (Left). A shaped plate and the end effector mounting plate without the wire delivery tool (Right)
Chapter 4: Experimental Methodology

4.1 Fabrication, Installation and Limitations of the 6DOF Tool

The mechanical design for the 6DOF articulated arm previously mentioned in Chapter 3 presents a completed conceptual framework for the transition from CAD design to the fully realized assembly of the tool, and required an extensive period of machining design and accommodation. All previously mentioned design components (Appendix A, B) were machined on either a HAAS Super Mini Mill 2 CNC machine or additively manufactured using an industrial grade, fused deposition modeling, Fortus 400mc machine. The machining process alone consumed a large portion of the fabrication process as a number of parts proved more challenging to replicate than others. The criteria being used to evaluate the complexity of the system’s mechanical components was based on the number of features required for each individual piece and its geometric intricacies. For instance, some pieces were rectangular and only required two tapped holes; a component previously described as Slip Ring Block 1 (Appendix A18). In contrast, there are components which require numerous design features like that of the A-axis Pulley Mechanism Mount (Appendix 11), which provided additional fabrication challenges due to the need for specific tooling and orientation in accommodation for particular design features. Figure 4.1 shows a comparison between Slip Ring Block 1 and the A-axis Pulley Mechanism Mount.
Mechanism Mount. Block 1 is an aluminum block with two holes drilled the thickness of the component. The A-axis Mount shows a more complex geometry that required the use of different tools and orientations in order to machine it.

All components for this system were designed on Solidwork’s 2019 computer-aided design software (CAD). Depending on the method of manufacturing and simulation capability of a particular CAD software, machining instructions for the hardware can be generated. Although all components were designed on Solidwork’s CAD platform, the Computed-Aided Manufacturing (CAM) feature from Fusion 360 (also a CAD software) was used to generate the toolpaths for every specific tool in a G-code (a generic name for a control language) format that a CNC machine can interpret and execute. In the case of 3D printing a component, a slicing processor software is needed in order to generate the toolpaths depending on the geometry of the part. Slicing a 3D model drawing effectively translates that 3D drawing into readable information that a 3D printer can understand and print. During the fabrication period, the manufacturing process was conducted concurrently with the assembly process within a means; completed components most critical to the design were test-fit and assembled first, as components with less complexity were manufactured last.

As mentioned before, Cincinnati Incorporated (CI) assisted in the development and installation of the 6DOF arm. After completion of the design and assembly of the tool, the system was sent over to CI facilities where they then designed a mounting structure to accommodate its integration on to their system, and which also provided an offset for the tool with respect to the gantry in order to position the tool in front of the extruder as previously stated in Chapter 3. In addition to design assistance in positioning the tool, CI tested and ensured proper function of the A, B, C, and V motors. They also modified the Human-Machine Interface (HMI), which controls
the BAAM, in order to add the capabilities of the 6DOF arm and allow it to work in tandem as one system.

The steel mounting structure for the 6DOF arm developed by CI gave way for sufficient offset from the BAAM’s gantry, ultimately enabling increased mobility and versatility of the tool, and provided a larger printing distance along the Y-axis as previously discussed in Chapter 3. For the purpose of simplicity in visualization, the mounting structure will be dived into Part A and Part B for discussion (Figure 4.2).

**Figure 4.2:** Part A (left) and Part B (right) mounting structures for the 6DOF articulated arm

Part A consists of a railing and carriage system needed to move the articulated arm along the Z-axis and retains the system perpendicular to the X and Y axes, as previously discussed in Chapter 3. Part B attaches to the BAAM’s gantry and keeps the distance between the extruder and the articulated arm free from collision. Part B also contains features to avoid contact with adjacent components on the gantry. For instance, the hopper which delivers material to the extruder was considered a feature to avoid. In combination with the additional operating space due to the offset and additional redesign, now allows an ease of access for maintenance purposes. Also, it is
important to note that Part A is secured to Part B in order to provide integration of the tool’s full assembly within the BAAM system.

During the installation process of all electrical cables, it was found that the Slip Ring, which was designed to gather and route all cables through its interior, was not designed to withstand high levels of current passing through it. Therefore, the Slip Ring was not used and all electrical cables pertaining to the motors, arc starter and air valves were connected normally and left suspended within expendable bundlers and fasteners throughout the tool’s fixtures and mounts (Figure 4.3).

**Figure 4.3:** Left side view of the 6DOF articulated arm during the installation process showing the electrical cables routed in fasteners traversing through and around the system.

Due to this development, the arm still has movement but it is not free to move within a full 360° motion. Limits on the rotational axes had to be implemented to avoid entanglement of the wires and possible wear and tear to create possible failure of the tooling system. The limits are expressed in degrees and were implemented within the HMI; once the motor reaches that particularly defined limit, it will not move any further. For the A-axis there is a limit of ± 180°, the B-axis has a limit of +110° and -80°, and ±180° for the C-axis. The tool shown in Figure 4.3 is oriented in its stowed
position for the 6DOF Arm, and the reasoning for this particular default position is to allow preservation of the maximum allotted printing volume already present before the tool’s integration, and to avoid collision with the walls of the BAAM’s build space or the extruding head which deposits material during the printing process. Additionally, a subroutine was implemented to position the extruding head above a customized purging station before beginning a print, which is located inside the build chamber just in front of the build platform upon entering. This station acts as a preliminary cleaning step to rid the extrusion nozzle of stringing plastic and to collect all purged material to ensure the quality of the material is uniform across each layer. Since the tool’s defaulted stowed position faces the front door, it does not have enough room for the extruder head to reach the purging station. Therefore, every time the gantry approaches the purging station, the subroutine will rotate the A-axis + 90°, positioning the arm of the B-axis parallel to the front door, ultimately avoiding possible collision.

CI also designed and manufactured a Control unit Box containing the PLCs (primary logic controllers) for the A, B, C, and V motors. This Control Unit Box also contains a power supply unit which delivers a desired voltage and current for the embedding process. The control unit box is next to the BAAM machine, and Figure 4.4 shows the control unit box.

Figure 4.4: Control unit box next to the BAAM machine
4.2 Modified Human-Machine Interface and G Code

With new capabilities implemented into the BAAM machine, CI required modification of their system’s HMI in order to control a revised printing process which could integrate control of our 6DOF articulated arm within their existing software. The HMI includes buttons for the additional axes added to the tool, which now has the option to be moved in the positive and negative directions. It also denotes the current position of each motor (A, B, C and V) axes based on their particular angle of function. In the case of the V-axis motor, responsible for feeding the wire, contains an additional section of reportable outputs which currently reports the length of wire being fed. Figure 4.5, shows the HMI with new interactable features added to the interface in order to control the 6DOF tool.

![Modified HMI main window used to control the BAAM + the 6DOF Articulated Arm](image)

**Figure 4.5:** Modified HMI main window used to control the BAAM + the 6DOF Articulated Arm

Within the wire controls display, options to control the wire embedding process can be seen and are discussed. This series of interfaces only apply to the end effector. Starting with the shielding gas tab, which has two options: flow or purge where flow is to control how much argon gas is flowing outwards in terms of L/min, and purge is to ensure that there is gas flowing out.
These two options are still in an experimental methodology stage, with ongoing testing and development in order to ensure proper gas line connection. Secondly, the wire heating tab which also has two options, arc power supply and arc starter, provide the option to be in an on, off, or auto-phase condition, and enables a safeguard to deactivate supply of any current or voltage to the system if the power supply is manually activated. Selecting the ‘On’ indicator will keep the power supply delivering power as long as this is activated. Lastly, selecting ‘auto’ will wait for a command within the code before delivering power automatically. The substrate tab contains information about the pyrometers located in front and behind the wire delivery tool as well as the selectable option of trailing substrate cooling, which enables air flow towards deposited material and newly embedded wire for cooling. It is important to note that these options are also still in an experimental phase in addition to the ‘Tool Standoff’ and ‘Wire Spool’ interface controls. Figure 4.6 displays all selectable tabs and options as previously described within the HMI.

![Wire tool controls](image)

**Figure 4.6:** Wire control options for the heating method used in the end effector

Other areas of the main HMI screen contain additional informative controls and indicators; controls for the V-axis motor, actuator, and the position of the tool can be found within the ‘Set up/ Test’ display. The V-axis motor, which drives the wire on the wire delivery tool, has three
options: ‘Wire load, Wire feed and Wire retract.’ Selecting ‘Wire load’ will grasp a section of the wire and load it between the custom driving roller (previously described in Chapter 3) in order to control it. ‘Wire feed’ is the option to supply wire to the application mechanism and ‘Wire retract’ pulls the wire backwards towards the driving roller. For the actuator, two options display and control its current state. ‘Actuator up’ and ‘Actuator Down’ enables pneumatic output motion of the tool in the Z-axis, enabling the extruder to be free of collision during the printing process and the latter to move the 6DOF arm down when it will be in use. In addition to the ‘Setup/Test’ display, there also exists an option called ‘Stowed Position’ which translates the 6DOF arm to its stowed default position previously mentioned which serves mainly to avoid any possible collision between the printing bed and the arm during the process.

For the A, B, C and V motors, there is optional informational displaying current positions expressed in degrees, velocity expressed in deg/sec, as well as torque expressed in lb-in. Figure 4.7 contains an image of the Set up/Test display interface with the options for the wire, actuator and stowed position control.

**Figure 4.7:** Modified HMI used to control the BAAM + the 6DOF Articulated Arm
and stowed position controls shown. In addition, Figure 4.7 also contains the ‘Secondary Axes Info’ which can be alternatively accessed under the Tools Option from palette on the bottom edge.
Chapter 5: Results and Discussion

5.1 USE OF THE 6DOF ARTICULATED ARM

After finalizing installation of the 6DOF tool and witnessing the initial limitations previously observed, a need for analysis was required. The 6DOF arm measures 1164.65 mm from the highest planar surface of the actuator to the bottom base plate of the B-axis motor, and 642 mm from the lower, inner-plate to the outer, external end of the tool, also known as the application mechanism of the end effector (Figure 5.1). These measurements were noted when the articulated arm was in its stowed default position.

![Image](image.jpg)

**Figure 5.1:** Dimensions of the 6DOF articulated arm already installed

The Z-axis actuator is operating with a pressure of 827.37 kPa (120 Psi) and must travel a distance of 385 mm in the +Z-axis to allow the remaining axis free roam space and to avoid collision. To demonstrate working success of the adjustment, Figure 5.2 shows the 6-DOF tool in
its stowed position on the left-most image in contrast to the right-most image which displays an unactuated, displaced, and fully extended articulated arm.

![6DOF Arm in stowed position (left). Extended arm after the actuator was activated with the arm extended (Right) (Figure 5.2)](image)

For further demonstration, the 6DOF arm will perform movements on the XY, XZ and YZ planes to ensure performance of the arm allows for operation on different planes other than the XY plane. It was decided that the end effector would need to be positioned parallel to any particular plane to be embedded on, and the wire delivery tool would need to be travel in the opposite direction of wire pathways to be embedded (Figure 5.3).

![Wire delivery tool with the application roller mechanism parallel to a plane (Figure 5.3)](image)

To accomplish this, the 6DOF arm will perform linear movements at four different points, making a rectangular shape...
of 141.4mm by 254 mm (41” by 10”) in the case of the XZ and YZ planes while keeping the 254 mm distance along the Z-axis. For the XY plane it will be 609.6 mm by 889 mm for the X and Y axes respectively. Figure 5.4 denotes a visual representation of the XY, XZ, and YZ planes to be traversed by the 6DOF articulated arm, with red arrows representing the direction and linear movements the arm will be reproducing. Staging assignments of numbers in between 1 to 5, with 1 representing the starting point and other subsequent numbers representing the steps required to get to the final point which is number 5. The tool was instructed to rotate 90° at every stage during the process in order to keep the application roller mechanism in the same direction as the direction of travel.

![Figure 5.4: Visualization of the XY, XZ and YZ planes along with the path used to demonstrate the capabilities of the 6DOF arm](image)

In order to give directions to the arm G-code was used and wrote manually. In the code it was specified the positions for every axis that the arm should follow, rotations and velocity of movement. First the movement demonstration on the XY plane was performed with a velocity of 148.16 mm/s (350 in/sec). As a result, pictures of the 6DOF during the demonstration were taken and are shown on figure 5.5 which has the steps done by the tool while going through each position.
There are four images showing the process. The first image was taken from the tool while it was traversing from point 1 to 2 and it continued until the end of the travel. In addition, it also contains red arrows which are showing the direction of the travel done by the tool. The images were taken from the door which is the YZ plane. That is the reason why the tool is extended towards the printing bed.

**Figure 5.5:** Demonstration of the 6DOF tool moving on the XY plane

Demonstration for the XZ plane shown in Figure 5.6 was performed at a feed rate of 42.33 mm/s (100 in/min). Again, the images in this figure were taken parallel to the plane being tested, as it provided improved visualization of rotation of the C-Axis which can be seen on the end effector. Figure 5.6 also shows the tool while traversing from a specified location to sequential locations as well as red arrows signifying the direction of linear movement of the tool, similar to
that of Figure 5.5. As a result, it was noticed that the tool could not adequately traverse from position 4 to position 5 since the tool had stalled and remained stagnant in the middle of the linear movement. Speculation of a reported error within the HMI warns of the potential for the B-axis to exceed predefined torque conditions, which is suited only to withstand 637 N-mm, thus leading to a possible reason for the sudden pause occurring during the translation from position 4 to position 5. The B-axis operating on the XZ plane was exactly 90°, and may not have been able to compensate for the combined weight of the tool for extended periods of time. This behavior also observed during the demonstration of the YZ plane.

![Figure 5.6](image)

**Figure 5.6:** Demonstration of the 6DOF tool moving on the XZ plane.

Lastly, the demonstration of the tool on the YZ plane, which can be seen represented in Figure 5.7, also contains the stages and the direction of the travel similar to figure 5.5 and 5.6. The
images for this demonstration were taken parallel to the YZ plane from the entrance of the build chamber, with movements and placements of the end effector at each position.

![Demonstration of the 6DOF tool moving on the YZ plane.](image)

**Figure 5.7:** Demonstration of the 6DOF tool moving on the YZ plane.

5.2 **Prescribe Parameters through the Custom HMI Developed in Collaboration with Cincinnati Incorporated (CI)**

As part of the project, it was previously mentioned that the HMI needed to be able to control the 6DOF arm, and contributed greatly from CI’s assistance in the design and development of the options presented in Chapter 4, and ultimately enabled control and synchronization between the BAAM and the 6DOF arm. CI also provided support in the development of a code interpretation program for controlling the additional axes implemented in to the machine, as well as with the
features added to the HMI shown in Chapter 4. In order to give instructions to the 6DOF arm to demonstrate its capabilities on the XY, XZ and YZ planes, a code for each case was manually input for each particular movement and orientation of each individual axes. Figure 5.8 shows a sample G-code used to test the movements on the YZ plane, previously discussed in Section 5.1. Within the code, activated commands are reported in inches, and the notation referred to as ‘G1’ is used to call and activate linear movement of the machine. The G-code also contains the position for the Y-axis and the Z-axis. Also, at every stage previously described for the C-axis, it contains values to account for the rotation at every step and maintains the end effector in a simulated path for embedding. At the end of the code, the tool returns to the zero position for each individual axis and upon completion, extends towards the printing bed.

```
[YZ drive - Notepad]
File Edit Format View Help
(YZ drive)
G20 (IN)
G1 F350
G1 Y54 Z-11
G1 B90
G1 C180
G1 Y54 Z-1
G1 C90
G1 Y13 Z-1
G1 C0
G1 Y13 Z-11
G1 C-90
G1 Y54 Z-11
G1 C-180
G1 Y54 Z-1
G1 C0
G1 B0
G1 A0
```

Figure 5.8: G-code used to demonstrate desired movements on the YZ plane
5.3 Demonstrate the Capabilities of Printing and the Use of the 6DOF Articulated Arm While Printing

The printing process was not affected by the incorporation of the 6DOF arm due to extensive review of design considerations and tactics at the beginning of the project. As mentioned previously in Chapters 3 and 4, the Z-axis actuator is used particularly to avoid interference of the printing process due to the arm’s placement at the same level when it is not being used; when it is required to be in use, the actuator will move it below the level of the extruder. Also mentioned in Chapter 4, a subroutine was implemented to reposition the 6DOF arm and it approaches the purging station next to the system’s front door, therefore, it rotates the arm 90 degrees in order to be parallel with the X-axis and resulting in avoiding any possible collision between the door and tool. On figure 5.9 it can be seen the BAAM during the printing process and the arm next to it without interfering with anything.

![Image 5.9: Demonstration of the BAAM during the printing process with the 6DOF articulated arm already installed](image)

Also, on figure 5.10 it can be observed that the 6DOF arm is ready to be used, and a printed substrate is on the printing bed. In order to activate the actuator to move the 6DOF tool down, the printing bed should be at a minimum distance of 863.6 mm (34 in).
5.4 INTEGRATION OF A WIRE DELIVERY TOOL WHICH INCLUDES AN ARC WELDING TORCH AS A THERMAL ENERGY SOURCE

The demonstration of the wire delivery tool has been presented in terms of motion and control of the tool at different planes. However, as seen before, it also contains the motor for the V-axis which has the sole purpose of driving the wire. The arc starting torch was installed adjacent to the V-axis motor as shown in Figure 5.11.

As described before; this will supply energy to act as the heating source for the wire in order to be embedded on a plastic substrate. Figure 5.11 also shows the wire delivery tool driving the wire. Some of the findings retrieved from the end effector design that could be improved; when the wire is being driven through the system and makes contact with the...
arc torch, the arc torch displays the tendency to shift and was not considered when designing the torch’s mount. Additional improvements lie within the v-groove guide at the beginning of the wire’s intended path, which also experiences trouble in accommodating to the wire since a spool does not supply copper wire from a specific point.

The heating source was tested in order to demonstrate that the tool is indeed able to heat the copper wire to desired temperatures (Figure 5.12). The process as previously stated is similar to the welding process and the energy input will affect the temperature as well as the ability of the torch to remain on by itself. Since the process has been automated, the following variables are affecting the behavior of the torch and temperature of the wire:

- Mass flow rate of Argon
- Current
- Voltage
- Feed rate of the wire
- Distance from electrode to wire

In Figure 5.12, the following parameters were used in order to create the spark:

- Mass flow rate: 12 l/min
- Current: 25 A
- Voltage: 24 V
- Feed rate of the Wire: 2500mm/min
- Distance from electrode to wire: 2.54 mm

Figure 5.12: Demonstration of the Heating source creating a spark on the copper wire
5.5 HMI Operational Error

After sometime performing experiments with the 6DOF arm and the end effector, no further issues were encountered. The controller box unit previously described in Chapter 4 was disconnected for construction purposes. After disconnecting and reconnecting the unit, an error was found on the HMI that was not allowing any operation of the machine. This error was observed to be due to the existence of absolute encoders (which enable in-situ reporting of current positions) within each motor, and upon disconnection, lost known positions and could not function properly. Consequently, none of the axes were moving at all. Involvement from Cincinnati Incorporated determined the need to reset all absolute encoders and would need to be performed in event the error reappeared. The error the HMI displays can be seen in Figure 5.13. Other errors may appear when the HMI is opened, however, disappear off screen upon activation of all corresponding drivers and performing the home axis operation.

![Figure 5.13: HMI error before resetting the absolute encoders](image-url)
Resetting the absolute encoders for the additional axes added to the BAAM machine should be performed under the following conditions:

• When an “Encoder backup alarm” has been generated

• After the Servopack Power has been turned ‘OFF’ and the encoder cable has been removed

Appendix C describes the necessary steps that should be performed in order to reset the encoders.
Chapter 6: Conclusion and Recommendations

6.1 CONCLUSION

A 6DOF articulating arm was designed and implemented into a BAAM machine adding the capability of independent motion on the A-, B- and C-axis. The implementation of the wire delivery tool as end-effector proved that different tools can be coupled with the arm in order to add capabilities to the system. The modification of the HMI allowed instructions to the arm and end effector through simple instructions and G-code, while synchronizing with the BAAM motion. The implementation of the arm demonstrates potential to new processes addition were complementary functionality is required such as heat treatment, pick and place of components and machining of 3D printed BAAM parts.

The 6DOF arm was demonstrated by moving the end-effector perpendicular to the XY, XZ and YZ planes, however, the B-axis motor reported a torque limit error during fractions of motion within the XZ and YZ planes. Still, the demonstration highlighted the capabilities of the tool while identifying some limitations. In addition, the electrical cords required to power the arm were installed around the arm instead of using the slip ring, therefore limitations had to be applied to each axis. The A-axis was limited to rotations of ±180°, the B-axis to +110° and -80°, and the C-axis to ±180.

The implementation of the 6DOF arm did not have a negative impact on the printing process. This was confirmed by printing a simple part during which the arm was in a stow position and no collisions were reported. This success was enabled by the arm’s Z displacement and its location relative to the single screw extruder. The actuator for the Z-axis displaced the arm a 385 mm such that interference with the printed part was mitigated during layer stacking. In addition, at the beginning of the printing process it was required to extrude for 15 seconds at the purging
station, which was next to the BAAM door. The purging station’s location made it possible to visually ensure the thermoplastic material was flowing properly. Therefore, since the arm was placed in front of the BAAM’s extruder reducing motion along the X-axis in the stowed position, a subroutine was implemented to rotate the A-axis +90° while in stowed position to ensure clearance between the arm and the doors eliminating the possibility of a collision

6.2 RECOMMENDATIONS FOR FUTURE WORK

Based on the findings and performance of the 6DOF arm, the following future work is recommended:

- Replacement of the 637 N-mm B-axis motor to support the weight of the tool while at a 90° position for long periods of time.
- Regarding the wire delivery tool, the V-groove bearing guiding the wire from the spool did not accomplish its function as expected, therefore a design change is required to reduce driving resistance.
- Further experiments should be performed to find arc heating parameters that result in a stable arc while still embedding wire into the printed part.
- Since parameters have to be found through experimentation with the wire embedding tool, incorporation of a force sensor at the application roller mechanism may help to know the effects of exerted forces between the copper wire and the 3D printed substrates, therefore accomplishing identifying proper parameters for the embedding process.
- The 6DOF articulated arm had the wire delivery tool as end effector but was not limited to only using the one tool. A new design for the end effector for a different application such as pick-and-placement device should be proved to add capability to the arm.
References


Appendix

Appendix A

Figure A1: C-Axis motor base

Figure A2: C-axis connection plate
Figure A3: Connection plate for B and C axes

Figure A4: B-axis plate for flange
Figure A5: B-axis housing side plates

Figure A6: B-axis housing bottom plate
Figure A7: A-Axis extension arm

Figure A8: A-Axis extension arm and flange interface
Figure A9: A-Axis shaft guide

Figure A10: A-Axis shaft guide
Figure A11: A-Axis shaft guide

Figure A12: A-Axis housing front plate
**Figure A13**: A-Axis motor and slip ring base plate

**Figure A14**: A-Axis motor and slip ring base plate
**Figure A14:** A-Axis timing belt pulley for 2in shaft

**Figure A15:** A-Axis timing belt pulley for a 5/8in shaft
Figure A16: Structural plate 1

Figure A17: Structural plate 2
Figure A18: Slip ring block 1

Figure A19: Slip ring block 2
Figure A20: Timing belt adjustable block
Appendix B

Figure B1: Angular wire embedding tool body

Figure B2: Adjustable rollers cover plate
Figure B3: Guide block for application roller

Figure B4: Arc torch adjustable plate
Figure B5: Arc torch adjustable mount

Figure B6: Insulation cups for a 5/8 shaft
Figure B7: Application aluminum roller

Figure B8: Custom driving roller
Figure B9: End effector attaching plate

Figure B10: A-shaped mounting plate
Appendix C

**Figure C1:** Working table should be at a minimum distance of -34 in (At that distance the Z actuator can be activated. 40 in is recommended in order to avoid collision and preserve the tool

**Figure C2:** Arm should be extended vertically. This position is the 0 coordinate for the A, B and C axes. Move it manually
**Figure C3:** Double Click on the SigmaWin+ icon

**Figure C4:** Select all the Axis added to the BAAM System which are A, B, C and V (Do not change anything on the original axes) V is the motor that drives the wire. Click on connect
**Figure C5:** Communication with the motors have been established. Select the Settings option

**Figure C6:** Settings window: Select the option ‘Reset Absolute Encoder’
**Figure C7**: A) Warning about resetting the encoder, if it does not feel safe talk to your supervisor B) Conditions under which circumstances this has to be performed and the execute button C) Caution about the multiturn data within the encoder will be set to 0

**Figure C8**: The absolute encoder reset processing has been performed. Repeat the process for every motor from Step 5 to 8.
**Figure C9**: The Motors will turn green, close the software and power cycle the BAAM machine in order to remove the alarms and have everything working as expected.
Vita

Christopher Jasiel Minjares Reyes is an international student from Ciudad Juarez, Mexico, the sister city of El Paso, Texas. Christopher obtained a high school diploma in June of 2013 from “Colegio de Bachilleres No. 19” located in Ciudad Juárez. He obtained a Bachelor of Science Degree in Mechanical Engineering from the University of Texas at El Paso in May of 2018. During his undergraduate studies, he helped with several projects at the W.M. Keck Center for 3D Innovation where he served primarily in the aspect of mechanical design. While pursuing a graduate degree, Christopher always offered his unwavering support to his colleagues in the lab by showing the proper use of lab equipment or with possible solutions to engineering problems. Furthermore, he worked as a Teaching Assistant under the Department of Mechanical Engineering where he helped students with their classes. Christopher participated at the GradExpo in 2018 and 2019 as a graduate student.

Contact Information: cjminjares@miners.utep.edu