

Modelling, Sensing, and Control of Weld Beads in Gravity Aligned and Non-Gravity Aligned Orientations for Wire Arc Additive Manufacturing

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To my amazing wife Haley

Acknowledgments

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Abstract

Wire Arc Additive Manufacturing (WAAM) has recently developed into a viable manufacturing process for large, complex metal parts. The WAAM process uses a Gas Metal Arc Welding (GMAW) torch mounted to an automated motion platform to execute a predetermined path plan based on a desired CAD geometry. As the desired geometry becomes more complex, it is advantageous to utilize out-of-position welding techniques used by human welders to stabilize the weld pool during the deposition of large overhangs. To ensure part accuracy and quality, adding layers of real-time control to manage various aspects of the WAAM process is critical. First, a controller is developed to maintain the contact-to-workpiece distance in the GMAW process to control the layer height of the deposited weld bead. Next, through exploring the relationship between base plate inclination angle, welding torch orientation, and bead shape, a system is developed to monitor the profile of the deposited weld bead and calculate the shape of the current bead to compare the current shape to a desired bead shape. Finally, the effect of interpass temperature on the geometric conformity of a deposited part is explored to improve the efficiency of the WAAM process and ensure geometric conformity and process stability.

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Chapter 1

Introduction

Additive manufacturing continues to grow as a viable manufacturing process for fabricating both prototypes and final products. While the initial, commercially available additive manufacturing systems primarily deposited polymers, recent developments have opened a path to depositing various metals. The now commercially available metal additive manufacturing systems typically use a powder form of a given metal that is then melted in specific patterns to create a final geometry. The metal powder is generally melted by either a laser or an electron beam that scans across the surface of the powder based on a part plan generated from an analysis of the desired final part geometry. After each scan across the powder surface, the entire bed of powder is shifted down by a set distance (called the layer height) and a new layer of non-melted powder is raked across the top surface and the process is repeated until the final part is created.

A standard issue with the powder bed approach to metal additive manufacturing is the restriction on part size due required process constraints. The electron beam must process must occur in a vacuum and the laser welding process must occur in inert environments. This is achieved through either pulling a vacuum in the build chamber or flooding the entire build chamber with an inert gas (such as Argon). With this requirement, a larger build chamber that accommodates building larger parts becomes expensive to implement due to the volume of vacuum or inert gas needed to support the welding process.

To build larger metallic structures, another form of metal deposition is needed. Gas Metal Arc Welding (GMAW) is a traditional manual welding process widely used to join

metals through the use of an electric arc. Rather than using a metal powder, GMAW uses a wire form of the metal as the feed material. A schematic of a basic GMAW setup can be seen in figure 1.1. GMAW does require an inert environment for proper functionality, but rather than needing to control the entire build chamber, only local inert shielding is required. This is achieved through a flow of inert gas (typically argon, and sometimes mixed with another gas such as carbon dioxide) from the torch that covers the area directly around the electric arc.

As the wire is fed through the welding torch, electrical current is passed through the wire and the electric arc is created through ionization of the shielding gas and the electric potential between the tip of the wire and the work-piece. The wire is continuously fed through the torch at a constant wire feed speed as the torch is moved along the welding path with a given travel speed. The combination of wire feed speed, travel speed, wire diameter, and wire composition yields the deposition rate for a set of welding parameters.

The electric arc heats the tip of the wire as it is being fed, melting the tip into a droplet of molten liquid metal. This droplet continues to grow until either the gravitational effect on the droplet overcomes the surface tension holding the droplet to the wire and thus the droplet falls onto the base metal (a phenomenon called globular or spray transfer), or the droplet contacts the base metal in a short circuiting event (referred to as short circuit transfer).

As more droplets of molten metal are deposited onto the surface of the base metal, a pool of molten metal forms called the weld pool. This weld pool travels along the surface of the base material at the same rate as the travel speed of the welding torch. As the weld pool exits the influence of the electric arc, the pool solidifies into a deposited weld bead. It is this bead that is used as the basis of Wire Arc Additive Manufacturing (WAAM).

A part built using WAAM is created by stacking multiple weld beads one on top of the next. Some examples of WAAM built parts can be seen in figure 1.2. While WAAM is very similar to seam welding in how beads are stacked to join material, some key differences arise in the execution. First, generally in seam welding, deep penetration into the base material is desired to ensure strong fusion between the materials. While fusion between layers is necessary in WAAM, excessive penetration can lead to issues such as over part overheating and inconsistent layer heights. Second, low heat input is greatly preferred in WAAM (as

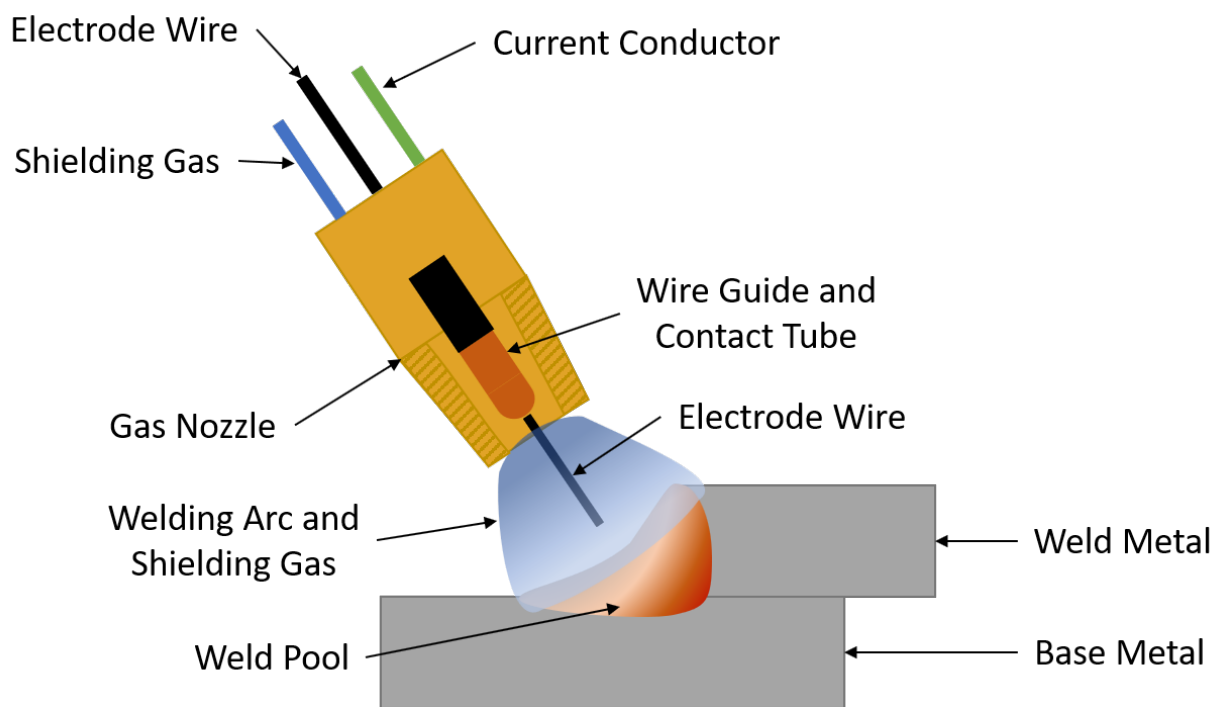


Figure 1.1: Schematic of the basic Gas Metal Arc Welding process based on [26]

too much heat input can structurally weaken the part and cause it to collapse), so only certain GMAW sub-processes can be used. Of the three primary GMAW material transfer modes (Spray, globular, and short-circuit), short-circuit transfer provides the lowest heat input and therefore is most widely used for WAAM. Finally, the tool paths in WAAM move the welding torch through open space with complex moves based on the desired geometry. More traditional groove welding keeps the weld pool and bead more contained through the side walls of the base material. This is not present in WAAM as the entire part geometry is created through the deposition of weld beads apart from an initial base plate to deposit the first layer. Thus, maintaining a detailed level of control over the WAAM process is needed for a successful build.

One advantage to using GMAW for metal additive manufacturing is the ability to use the forces from the welding process to counteract gravitational forces acting on the weld pool. Skilled human welders are able to weld in many different orientations including up and down vertical walls and overhead using GMAW. Through manipulating the force vector produced by the GMAW process relative to the welding orientation, a dynamic force balance can be reached which results in the weld pool remaining stable until it solidifies.

This property of GMAW can be implemented in WAAM to increase the achievable part complexity. This quickly becomes an active control issue since human welders are constantly manipulating the welding torch to maintain the stability of the weld pool through observing the process in real-time. Implementing this technique in WAAM requires an additional layer of real-time control in the robotic system.

The control system must be able to react to several outside disturbances to maintain a steady-state WAAM process. Some of these disturbances include surface waviness of the previous layer, temperature of the previous layer when depositing the current layer, and the build direction. Ideally, all layers are deposited exactly as planned and have no deviations causing humps or dips along the weld path. This can occur for several reasons including improper welding parameters, gravitational effects, or wire-feed errors. If this occurs, the next layer must react to these layer height deviations to settle the process back to a steady-state. The temperature of the previously deposited layer is also important. If the surface is too hot, adding additional heat through the welding process can cause the part as a whole

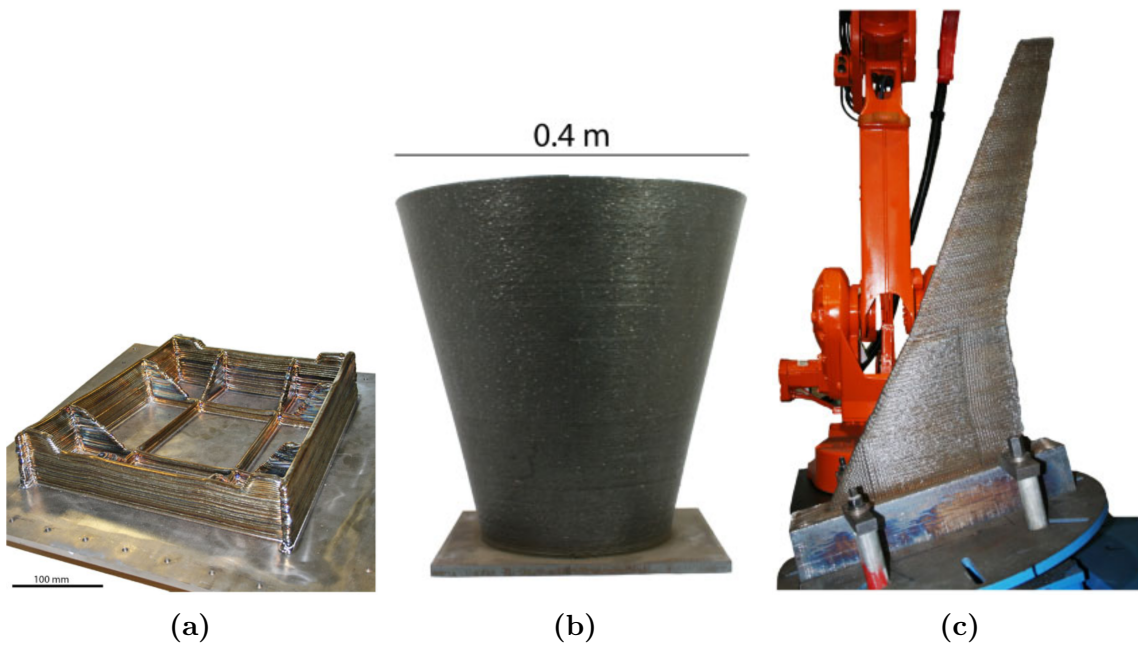


Figure 1.2: Examples of WAAM built parts [48]

to begin to melt, potentially leading to a full build failure. If the previous layer is too cold, insufficient fusion between layers may compromise the final part structural strength. Finally, if the build direction changes, the gravitational effect on the weld bead also changes. As previously stated, if the gravitational force on the weld pool is larger than the surface tension and arc forces combined, then drooping or even dripping of the weld pool can occur. This can also introduce additional surface waviness to the weld bead that disrupts the steady state process.

This work strives to improve the WAAM process through the following fundamental contributions. The first contribution is a model of the weld bead, describing how the shape of the weld bead is affected by gravity when deposited in non-gravity aligned orientations. Second is a method of interpreting data from multiple sensors monitoring the GMAW process as well as the weld bead shape to determine if correctional action is needed to maintain a steady state WAAM process. Third, based on the interpreted sensor data, is a real-time control structure which regulates the weld bead shape with respect to gravity and other disturbances to the WAAM process.

Finally are two more general contributions that are results of the previous contributions. First is an expanded understanding of gas metal arc weld pool dynamics under the influence of gravity; particularly in non-gravity aligned orientations. Through the development of a weld bead model and the analysis of data describing the real-time WAAM process, new, quantitative knowledge can be gained as to how weld beads are disturbed by external factors and formed in non-gravity aligned WAAM. Second, through the implementation of a real-time control structure that reacts to changes in the WAAM process to allow more precise and consistent weld bead depositions, the construction of more complex geometries can be explored.

The WAAM system used in this research consists of a KUKA KR 6-2 six-axis robotic arm (see figure 1.3) for positioning the GMAW torch welding torch in space and a Miller AutoAxxess E450 GMAW system (see figure 1.4). The specifications of the KUKA KR 6-2 robot can be seen in table 1.1 and figure 1.5. The robot is controlled using a KUKA KRC4 controller running KUKA System Software v8.3.

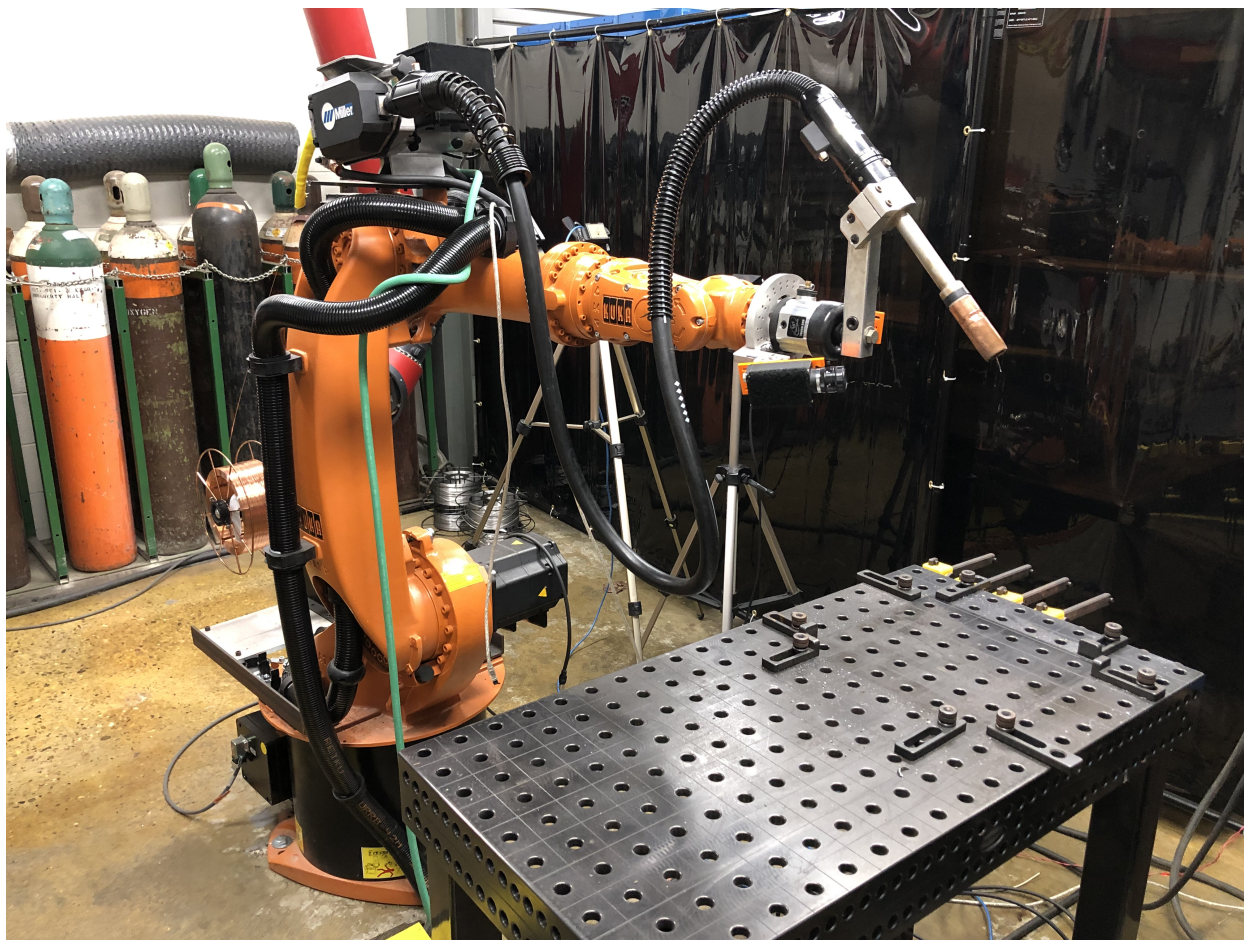


Figure 1.3: KUKA KR 6-2 six-axis robot used to perform Wire Arc Additive Manufacturing research



Figure 1.4: Miller AutoAxcess E450 Gas Metal Arc Welding power supply

Table 1.1: Basic Technical Data for KR 6-2 [13]

Property	KR 6-2
Rated Payload	6 kg
Maximum Reach	1611 mm
Pose Repeatability (ISO 9283)	± 0.05 mm
Volume of Working Envelope	14.5 m ³

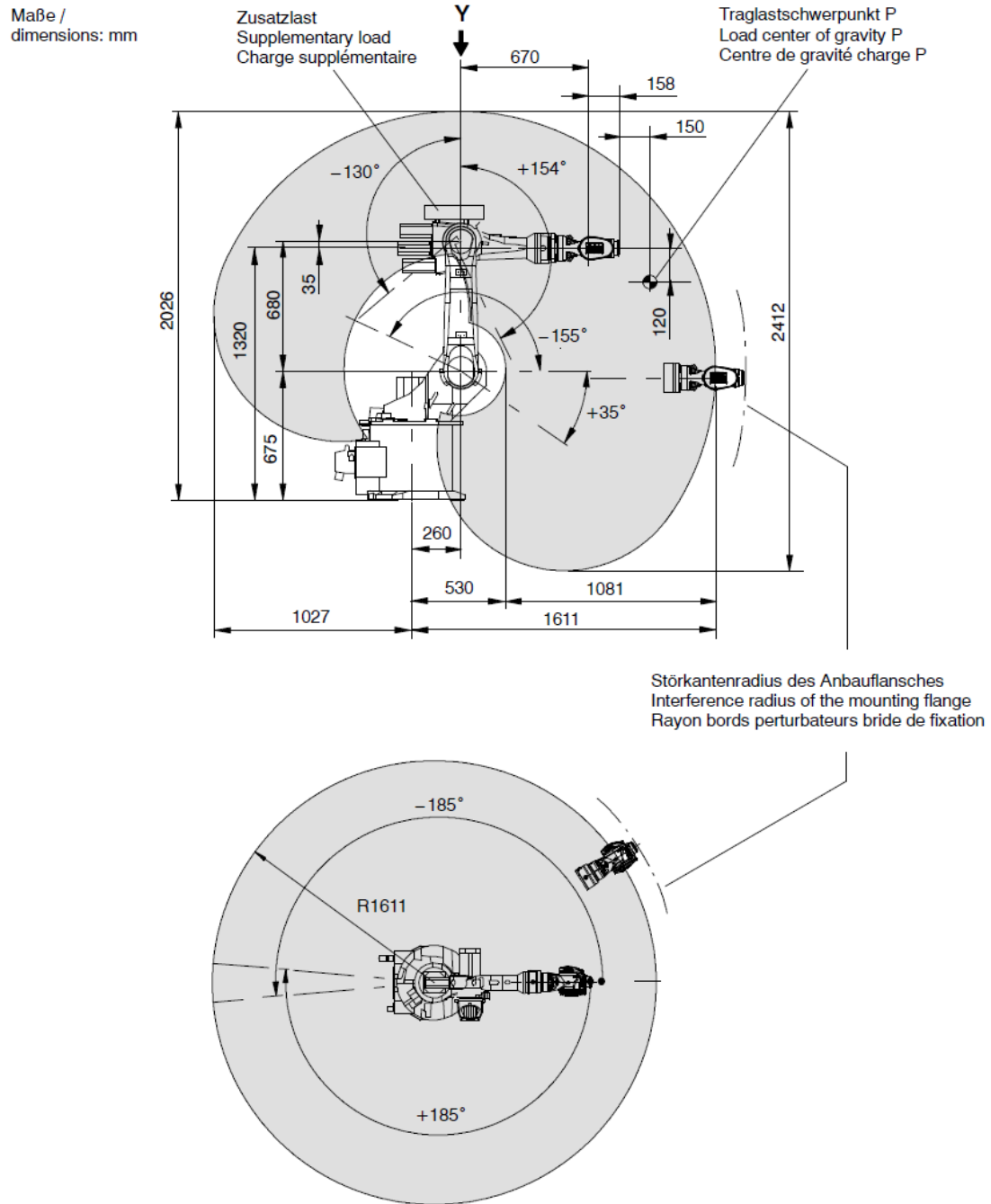


Figure 1.5: Workspace dimensions and axis limits for the KUKA KR6-2 robot [13]

The Miller AutoAxxess E450 power supply offers a low heat input, short circuiting process called Regulated Metal Deposition (RMD). This process is a proprietary waveform process (see figure 1.6 for an overview of the waveform shape) that uses active short circuit sensing to control the voltage and current. This process is ideal for WAAM as the overall heat input is lower than standard pulse, globular, or spray processes. Due to the lower heat input, the overall bead size is also smaller, which allows for smaller features to be deposited.

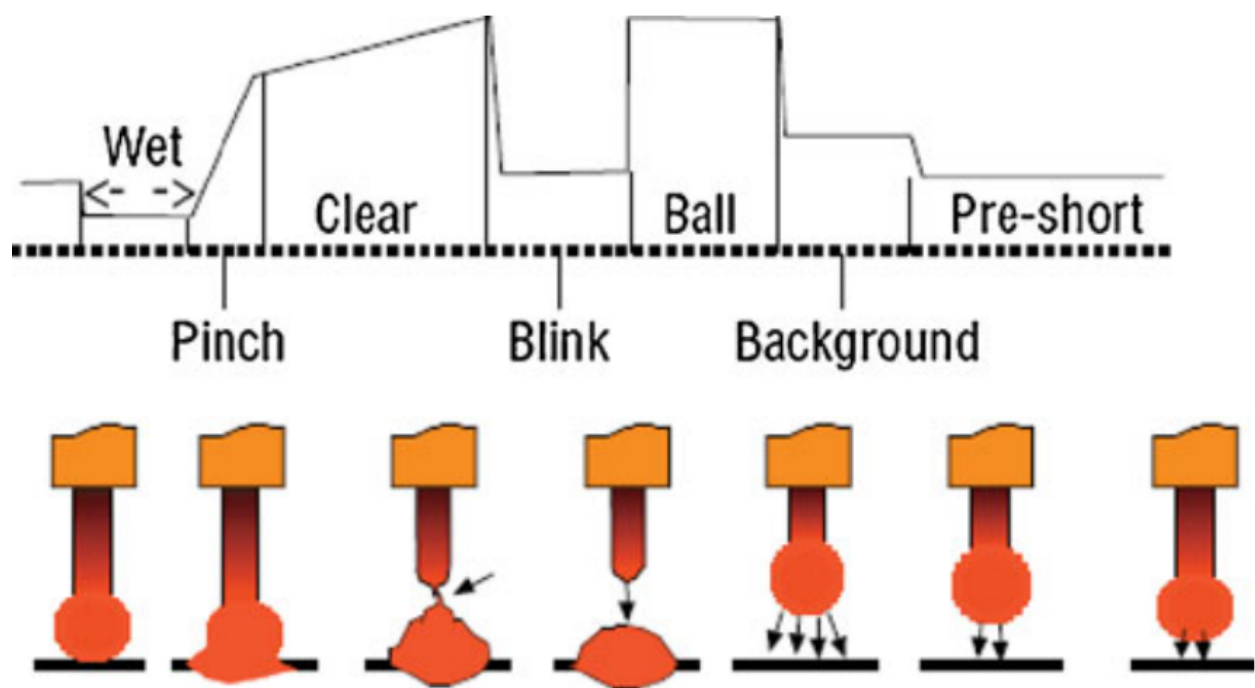


Figure 1.6: RMD Current wave form and droplet illustration

Chapter 2

Background and Literature Review

2.1 Introduction to Wire Arc Additive Manufacturing

There are currently two primary methods of depositing metal using a wire in Additive Manufacturing: Laser Wire and Wire Arc. Laser Wire [1, 41, 5] uses a high powered laser to deliver energy to a desired location with the filler wire inserted into the weld pool separately, similar to tungsten inert gas welding, and thus melts the wire as well as the top surface of the substrate. This deposition method allows for the deposition of some materials that may not cooperate with the arc welding process. It also allows for finer control over the melting area through manipulating the laser power and laser spot size and location. Some downsides to the laser-based processes include the cost of the laser head and power supply as well as the need to operate in a completely inert environment. This often limits the size of parts the system is capable of building. Also, the weld head with a separate wire feed usually has a much greater physical envelope thus reducing maneuverability adjacent to the build part.

Wire Arc Additive Manufacturing (WAAM) uses a standard welding process, typically Gas Metal Arc Welding (GMAW), to deposit the material delivered via wire [32, 48]. The WAAM process, while somewhat limited in the materials it can deposit based on a given material's weldability, uses less expensive equipment and only requires local shielding of the deposition area, meaning it operates in an open atmosphere. Additionally, the GMAW weld torch is considerably more compact than the laser head.

2.1.1 Initial Development of WAAM

The initial concept of stacking weld beads one on top of another to create a part was originally patented in 1925 by Ralph Baker [2]. Baker's patent set the stage for building free-form metal parts using an electrically based welding process. With the improvements made to welding power supplies and the innovations in robotic welding, Baker's method can now be used to build production level parts not possible with manual welding.

Song et al. in [39] and [38] uses a GMAW processes to explore fabricating molds for the injection molding process. Song shows that WAAM is a viable process for depositing structures is proper path planning and parameter development is performed to ensure a stable process. It is noted that alternating layer direction greatly impacted the tensile strength of part test specimen.

In [11], a low cost WAAM system is developed using a GMAW power supply and a CNC gantry milling system. By retrofitting the milling system with a GMAW torch, the torch could be moved in pre-planned motions to create a desired geometry. This work shows two important needs for a successful WAAM system: an accurate torch positioning system and a method of creating torch trajectories based on the desired final geometry.

2.1.2 Gas Metal Arc Welding Processes

There are several types of Gas Metal Arc Welding (GMAW) available in modern welding power supplies. These include Spray, Globular, and Short Circuit transfer methods. The primary differences in these transfer methods revolve around the amount of heat input into the filler wire.

Spray transfer uses the most power of the three primary transfer methods. It is characterized by a stream of metal droplets propelled from the tip of the filler wire to the base material. This is the result of the high welding currents used which heat the filler wire far above its melting temperature, which results in a decreased surface tension. With such a low surface tension at the tip of the electrode, smaller droplets are dispatched at a high frequency to the base material.

Globular transfer requires less power than spray transfer and deposits larger droplets at lower temperatures to the base material. The droplet detachment is still a function of the surface tension of the liquid droplet growing at the tip of the electrode as it is heated, but rather than a stream of smaller droplets, a single larger drop is deposited at a time. These larger drops detach from the filler electrode when the gravitational force pulling on the liquid mass overcomes that of the surface tension between the liquid drop and solid electrode.

The short circuit transfer method requires the least amount of power of the GMAW transfer methods. In this transfer method, the heat input is low enough that the droplet does not detach from the filler rod and free fall to the base material. Rather, as the filler electrode is fed at a given Wire Feed Speed, the droplet grows due to the continuous melting of the wire tip. When the drop grows a sufficient size and translates a sufficient distance towards the base material, the drop contacts the weld pool. This is referred to as the short circuit event. When this occurs, the surface tension between the droplet and the weld pool, usually accompanied by a spike in current from the power supply, detaches the droplet from the filler electrode and the melting process begins again. Due to the low heat input characteristic of the short circuit transfer mode, it is ideal for use in WAAM [10].

An interesting feature of GMAW is that can be performed in different orientations. Work has been done in examining these out-of-position techniques for groove welding [33, 31, 30, 7] as well as additive manufacturing [56, 55]. Yuan et al. shows in both works that using out-of-position welding techniques is useful in WAAM for building more complex geometry, but the process contains no closed loop control and thus is limited in deposition speed compared to nominal gravity aligned WAAM speeds used to achieve a similar bead shape.

2.2 Modelling of Wire Arc Additive Manufacturing

According to [40], one of the key aspects to achieving closed-loop control of the robotic welding process is having a model of the process. While many detailed analytical models of the GMAW process have been developed, many of them must be numerically solved, which is not ideal for a real-time control problem. It is necessary then to look towards the

development of computationally efficient, control-oriented models to understand the WAAM process.

2.2.1 Modelling the welding process

In modeling the weld pool, strong consideration is often given to improving the original model for a moving weld pool developed by Rosenthal in 1946 [34]. Wu and Tsao in [44] improve the Rosenthal model by adding consideration for the fluid flow inside the weld pool, and thus the convective heat transfer of the weld pool. This model more accurately matches experimental temperature values for a certain point on the base material that experiences a thermal cycle generated by a weld pool moving over that point.

In [46], Wang and Tsai construct a model of the GMAW process, particularly how a weld pool is formed from droplets of molten filler metal. Their model takes many different forces (including surface tension, arc force, gravity, and electromagnetic force) into account to determine how multiple, subsequent droplets form a moving molten weld pool. While this work provides great insight into the welding process and the formation of the weld pool, the nonlinear mathematical complexity precludes closed form analysis and requires sophisticated numerical solution approaches for any detailed analysis. Such methods are generally not useful for the implementation of practical real-time control.

2.2.2 Modelling the deposited geometry

For WAAM to successfully build a near-net shape representation of a designed part, it is essential to understand the geometry of the weld bead produced by the GMAW process. The bead dimensions feed into the path planning process to inform the path planning software how many layers are needed when slicing a given geometry into layers. If the model of the deposited weld beads is not accurate, then the final deposited geometry will most likely not be accurate and in the worst case, the build may not provide a near net shape that encompasses the part design due to errors in the GMAW process.

In [27], Panda et al. use a machine learning approach to model the non-linear relationships of weld bead geometry and welding parameters. Using a genetic algorithm

based approach, a model was trained from experimental data of measured peak current, commanded wire feed speed and travel speed with post weld measured bead height and width. This model allowed for a baseline prediction of the bead height and width based on a set of welding parameters and showed that the peak current had the greatest effect on the bead shape.

As the WAAM process produces a near-net shape part rather than an exact desired geometry, predicting the amount of overbuild or under-build due to the waviness of the stacked weld bead surface provides useful data to inform possible future machining processes. In [50] Xiong et al. examine how changes in the welding process parameters change surface waviness of a deposited multi-layer WAAM wall. It was found that the inter-pass temperature between layers is inversely proportional to surface waviness while both wire feed speed and travel speed are directly proportional to surface waviness. Thus, to produce the most consistent bead layer-to-layer, long inter-pass wait times (resulting in a lower temperature for the previous layer) along with a high travel speed and low wire feed speed should be used.

The interaction between adjacently placed weld beads is also of interest in WAAM as many desired geometries are not thin-walled structures, but rather solid parts. A model to identify how much overlap is required to build a smooth surface is developed in [16]. This model identifies material shortage areas, particularly when multi-layer beads are deposited to build sloped surfaces. This model proved quite accurate in its prediction of how beads should be deposited to build solid structures and is helpful in the path planning phase of WAAM to determine the best strategy for building solid parts.

2.3 Controlling Wire Arc Additive Manufacturing

Controlling the WAAM process can have many different connotations. Control could imply modification to the GMAW process, striving to maintain a desired weld bead geometry, or controlling how a robot moves the welding torch during deposition. For the purpose of this work, control looks to maintain a desired weld bead geometry, as this is the first step in achieving a stable, and consistent deposition process.

2.3.1 Determining the state of the welding process

To control the WAAM process, it is important to accurately monitor the process. Many sensing modalities have been developed for monitoring the traditional GMAW process as well as the WAAM process. It is important to capture the state of both the welding process and the deposited geometry. As discussed in [3], the GMAW process and weld pool is highly coupled with the resulting geometry. Thus understanding the state of both the welding process and the deposited bead is critical to the controllability of the WAAM process.

To view the shape of the weld pool, several methods using different sensing modalities have been proposed. First are vision based systems which use some form of video camera to capture the weld pool in-situ. Since it is desirable to capture the three-dimensional shape of the weld pool, stereo vision techniques are often used. [21] used two cameras with known positions and orientations relative to each other to reconstruct the weld pool. While a good approach, mounting two cameras at the torch tip can cause collision issues if welding in tight areas. Or, as is the case in WAAM, the actual part geometry may not be fully known at the time of welding and including a model of the cameras at the path-planning stage could limit the geometric complexity of the desired part. Standard cameras must also be outfitted with special filters to block out the intense light produced by the welding arc or, in the case of short circuit welding, time the image capture with the short circuit event when the arc light is lessened.

To minimize the number of sensors needed to view the weld pool, some have developed a passive stereo vision setup which uses a single camera and a biprism to manipulate the image. [54, 52, 51] all use this technique to extract a three-dimensional reconstruction of the weld pool.

Another sensing modality for extracting a three-dimensional image of the weld pool is to project a structured laser pattern onto the weld pool and capture the reflections of the laser off of the weld pool using a special camera. The topology of the surface can be computed from distortions in the structured light pattern. This is done by [47, 22], using different laser patterns. While a generally efficient method of viewing the weld pool shape, this laser projection method does not translate well to WAAM due to its reliance on a constant travel

direction. If the travel direction changes, the location of the laser array and camera must also change to maintain a constant orientation relative to the weld pool. If the orientation changes, then the reconstruction algorithm must be re-calibrated as the laser reflections captured by the camera will change.

2.3.2 Controlling the welding process

Work has not only been done to develop an off-line model of a GMAW pool, but also to more tightly control the process. This has been done in several ways; some using simplified model based approaches and others using heuristic rules to interpret sensor data. Steele et al. in [40] discuss what would be necessary to control the robotic welding process. They suggest that an accurate model that is capable of running in real-time, but is still accurate enough to make correct predictions is essential. They also note the impact that changing the orientation of the weld torch has on the shape of the weld pool. The subject of the gravitational effect on the shape of the weld pool is not well discussed in the welding literature, and will require more study to fully understand the dynamics at work so that the gravitational effects can be mitigated by the controller.

In [9], Shen et al. implement a classical PID controller for wire feed rate along with a fuzzy controller for current to control the Gas Tungsten Arc Welding (GTAW) process. They also implement a model for predicting the amount of reinforcement present in a joint welded by GTAW through a conservation of material volume method. Essentially, Shen et al. control the wire feed speed to control the mass transfer flux, thus controlling the temperature of the weld pool to prevent burn through in the joint and to ensure a strong weld.

A classic issue in GMAW control is identifying the amount of penetration into the substrate by the weld pool and modulating the welding parameters to control this depth. [18, 37, 20] all develop various methods of determining the weld pool depth, using audio signatures, visual images of the underside of the weld pool in groove welding, or top surface views of the weld pool to infer penetration. From these identifiers, various parameters of the GMAW process can be tuned including the voltage, current, wire feed speed, and travel speed. Controlling the process parameters of the GMAW process is key to ensuring the

deposition of the desired weld, and also ensuring that the deposited bead maintains the structural strength required for a given application.

2.3.3 Controlling the deposited geometry

Controlling layer height

If the bead height used as the baseline layer height during the slicing process is incorrect or if the cooling time between layers is not long enough to prevent excessive penetration into the previous layer, the final deposited geometry may not meet desired dimensional requirements. To that end, some methods have been developed to control the layer height of the deposited weld bead to ensure geometric accuracy.

In [35], a model is developed using the sensed current during deposition and relating that current to the contact-to-workpiece distance. As each layer is deposited, the through arc sensing analyzes where the previous layer is in relation to the planned layer height. If the layer is too short, an updated path plan is updated with additional layers to compensate for the under-build. This controller is implemented on a gantry style robot and therefore is limited in overall possible part complexity. Also, the re-planning process is not ideal as this could dramatically increase the printing time if the slicing height is incorrect.

Xiong et al. use a vision-based approach to control the layer height in Gas Tungsten Arc Welding (GTAW) based WAAM [53]. The field-of-view of the camera is positioned such that both the current layer being deposited as well as the previous layer are visible in a single frame. The difference between the measurements of both layers is used as the input to the control which manipulates the wire feed speed to adjust the material deposition rate. While the method works well for a single-bead width straight wall, it would be difficult to implement this method when building more complex structures.

A method has also been developed and patented by welding company Lincoln electric [6]. In this method, the CTWD is determined from through arc sensing methods. Then, using a 3-dimensional model of the welding robot, the height of the previous layer is determined relative to the path plan. From this measurement, a correction is made to the wire feed speed and travel speed of the robot to change the mass transfer rate of the current layer.

This allows for under-built areas to have more material deposited to bring the current layer back into alignment with the path plan and overbuilt areas to receive less material towards the same goal.

Controlling bead geometry

Work in controlling the size of the weld pool was done as early as 1994 by Boo and Cho in [4]. In their work, a pyrometer was used to measure the temperature of a GMA weld pool (the input to the control system) and then used fuzzy self-organizing control to manipulated the heat input, through adjusting the weld current and voltage. They showed that due to the nonlinear nature of the welding process, a standard PID controller was not able to keep a uniform bead cross section compared to the more complex fuzzy self-organizing controller. This suggests that to accurately control the welding process, a more complex control algorithm is necessary to account for the non-linear nature of the GMAW process.

Liu et al. control the geometry of the weld pool through manipulation of the welding current and welding speed in response to the change in sensed weld pool topology of a GTAW puddle [19]. In their experiments, the current and welding speed commands were determined by comparing data collected from a weld pool reconstruction using an array of laser dots and a predictive model of the 3-dimensional weld pool shape based on the previously commanded current and weld speed.

Non-Gravity Aligned WAAM Considerations

As mentioned earlier, the welding literature addresses the Non-Gravity Aligned problem in the context of orbital welding. In orbital welding, a welding torch is mounted to a track (typically a cylindrical track matched to the size of pipe being welded) and moves around the circumference of two pipes to join them.

In this vein, Tipi analyzed a GMAW pipe welding system and developed a state-space model of the process [43]. Using this model, Tipi developed a control system that manipulated the current of the welding process to control how the metal droplets were transferred from the tip of the welding wire to the weld pool. This approach works in orbital pipe welding due to the constricting geometry of the groove. While the structure of the

controller and state-space model are more ideal for a real-time application, the unrestricted part geometry of WAAM makes overhangs more difficult to deposit.

In gantry style systems (only three degrees of freedom of motion available), the welding torch must remain in a gravity aligned orientation. Thus, to build large overhangs, the effects of process parameters have been studied to understand how to use the welding process deposit more complex geometries. Xiong et al. in [49] found that increasing the travel speed of the welding torch from 2.5 mm s^{-1} to 10 mm s^{-1} increased the maximum possible inclination angle from 30° to 45° . Li et al. investigated what was possible in depositing thick walled structures with large overhangs in [16]. Li found that the deposition order of the beads greatly contributed to internal voids caused by drooping as the melt pool was still solidifying.

It has also been found that using a more highly actuated robot system allows for moving the welding torch out-position (similar to what occurs in orbital pipe welding) to more successfully control the shape of the non-gravity aligned weld bead. [12, 56, 55, 17] all use an approach where the welding torch is aligned with the inclined build direction to deposit larger overhangs. This technique gives better results than pure manipulation of process parameters with torch in the gravity aligned orientation.

An issue is that these are all open-loop processes with little or no control over the WAAM process. This work focuses on the introduction of the previously discussed modelling and control techniques to the NGA WAAM process. The addition of these techniques will allow for increased part complexity with a higher assurance of geometric conformity in the final part near net shape.

Chapter 3

Modelling the Gas Metal Arc Weld Bead

To understand the effects of gravity on the GMAW weld bead, a simplified model will be developed to demonstrate the effects of gravity, surface tension, and welding forces on the shape of the weld pool in an NGA orientation. The shape of the weld bead is a direct result of the shape of the weld pool generated by the welding process. Since WAAM moves the welding torch along a given path, the heat source provided by the welding arc only remains in one area for a comparatively short amount of time. As the heat source moves along the path, the liquid metal deposited begins to cool and solidify.

As described in chapter 2, recent GMAW bead models utilize a form of regression or machine learning to determine the relationship between welding parameters and the deposited geometry. While these models tend to produce good results for welding parameters at or around the experimental data used to develop the model, they tend to break down when new parameters are used or new disturbances are introduced into the system. One such disturbance is the change in orientation of the gravitational field with respect to the weld pool when welding in non-gravity aligned orientations.

The model developed here will be used in a control strategy to manipulate the force system acting on the weld pool to maintain a consistent bead shape. It has been observed in [29] that when welding in a non-gravity aligned (NGA) orientation, gravity causes the weld pool to lose its symmetric shape, thus distorting the final shape of the solidified weld bead.

This model aims to inform the path planning process as well as future control algorithms with knowledge as to the magnitude and direction of this drooping and what actions can be taken to mitigate the distortion of the weld bead.

3.1 Modeling Approaches

In early work on modelling the weld pool and weld bead, a simplification was made to look at a two-dimensional model rather than the more complex three-dimensional model [15]. In [15], Lancaster discusses a two-dimensional model which describes the cross-sectional shape of a deposited bead using two governing equations:

$$\frac{\gamma}{R} = \frac{\gamma}{R_0} - \rho g y \quad (3.1)$$

$$\frac{1}{R} = \frac{d^2 y / dx^2}{[1 + (dy/dx)^2]^{3/2}} \quad (3.2)$$

where γ is the surface tension of the liquid metal, ρ is the density of the liquid metal, g is the acceleration due to gravity, x and y are the coordinate system used to define the cross-sectional curve, R is the radius of curvature of the section, and R_0 is the radius of curvature at the origin (see figure 3.1).

What is not accounted for in this model is any sloping of the base material under the weld bead or the orientation of the torch relative to the weld bead surface. As seen in figure 3.2, when the base material under a deposited weld bead is at a given slope and the GMAW torch is kept in a vertical, gravity aligned orientation, the profile of the weld bead shifts due to the gravitational pull on the liquid metal.

To predict this shift, a more comprehensive model is needed than that given by Lancaster. In the fluid dynamics literature, Higashine et al. develop a 3-dimensional model for the shape of a static liquid droplet on a known surface under the influence of gravity [8]. This model assumes that the droplet is stationary on the plate. The droplet is evaluated at the critical point where the droplet is statically balanced between surface tension and gravity. For the quasi-static case of the weld pool, this will also include the arc forces derived from the welding process.

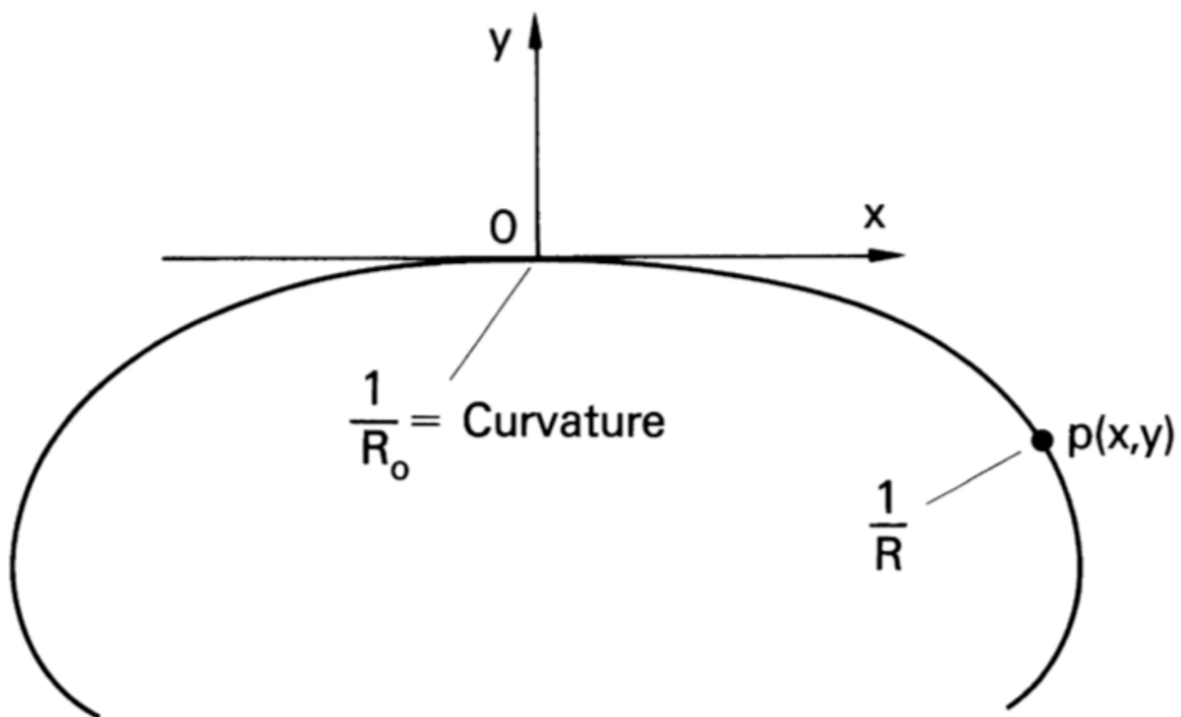


Figure 3.1: Bead cross-section model described in [15]

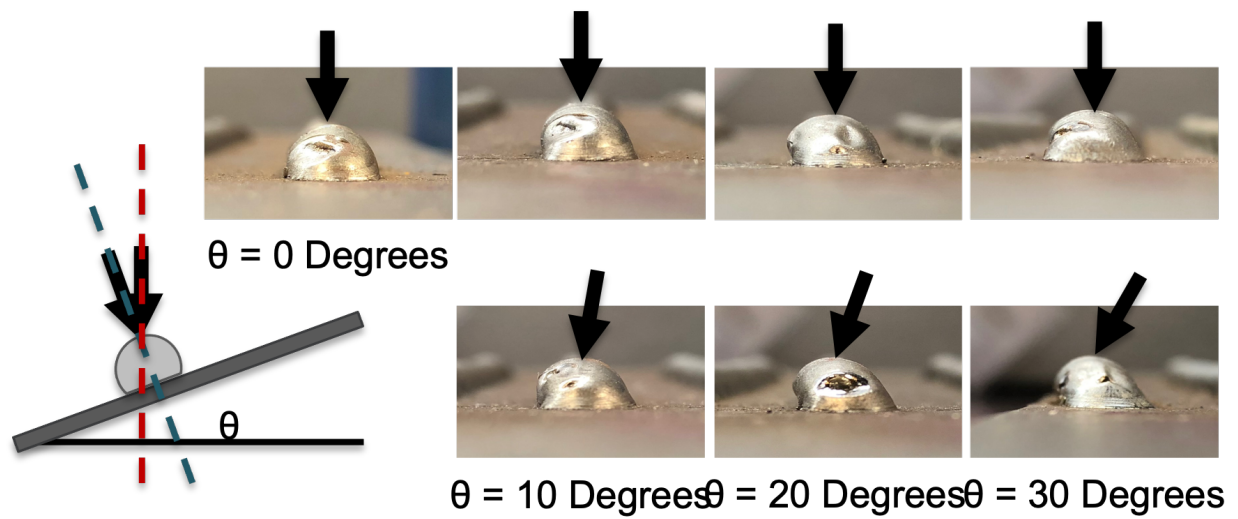


Figure 3.2: Progression of drooping in the GMAW bead as the inclination angle of the base material is incrementally increase and the torch orientation remains gravity aligned.

The surface of the droplet is described by the three-dimensional Laplace equation shown in equation 3.3, where y_x etc. are the partial derivatives of $y = f(x, y)$, P_0 is the static pressure at the origin of the drop, and ΔP_F is the change in pressure on the drop due to external forces.

$$\sigma \frac{-(1 + y_z^2)y_{xx} + 2y_x y_z y_{xz} - (1 + y_x^2)y_{zz}}{(1 + y_x^2 + y_z^2)^{3/2}} = P_0 + \Delta P_F \quad (3.3)$$

It is assumed that the cross-section of the droplet at each x value is a circle with an origin below the xz plane (similar to the model shown by Lancaster). The equation describing this circle can be seen in equation 3.4.

$$\left(y + \frac{b^2 - h^2}{2h}\right)^2 + z^2 = \left(\frac{h^2 + b^2}{2h}\right)^2 \quad (3.4)$$

Since $y_z = 0$ at $y = h$ (with h being the peak of the droplet for a given value of x), and by substituting (d^2h/hx^2) and (dh/dx) for y_{xx} and y_x , respectively; then equation 3.3 can be simplified to equation 3.5

$$\sigma \left[-\frac{\frac{d^2h}{dx^2}}{\{1 + (dh/dx)^2\}} + \frac{2h}{(h^2 + b^2) \sqrt{1 + (dh/dx)^2}} \right] = P_0 + \Delta P_F \quad (3.5)$$

In this more simplified form, the ΔP_F term is defined by equation 3.6, which describes the gravitational force acting on the droplet.

$$\Delta P_F = -\rho g \sin(\phi) \cdot x - \rho g h \cos(\phi) \quad (3.6)$$

Thus, by solving equation 3.5 for h , the the profile (and subsequently the topology) of the droplet for a given incline angle (ϕ) can be determined.

Theoretically, Higashine's model translates well to a weld pool model, as a weld pool is a specified volume of molten metal (the acting fluid) and many external forces are acting on this volume to manipulate its shape. To update this droplet model to a model of a weld pool, the forces acting on the weld pool must be considered and the material properties of the liquid must be updated to that of the given material used in the welding process.

3.2 Model Development

The weld pool model developed here follows the quasi-static approach used by Higashine. The quasi-static assumption does not include slipping observed in welds performed with very steep overhangs. Utilizing this assumption points to modelling the drooping resulting from the influence of the forces on the fluid surface and not a slippage of the entire weld pool in the gravitational direction.

Another aspect of the quasi-static state assumption is that the travel speed of the weld pool is ignored due to the placement of the main coordinate frame of the model. It is assumed that the observed weld bead profile has a fixed coordinate frame with respect to the moving welding torch. Thus, the bead profile is moving at the same speed as the weld torch and the effects of the travel speed appear static, assuming that, for a given set of welding parameters, the travel speed is constant.

As discussed previously, the short circuit transfer GMAW process is the most ideal transfer method for WAAM. There are two primary phases in a cycle of the short circuit process: the arcing phase and the short circuiting phase. As discussed in [45], during the arcing phase the tip of the welding wire is melted by the electric arc, forming a droplet of molten liquid metal. As the wire continues to feed, the droplet moves closer to the weld pool surface and continues to grow in size due to continued melting.

As this droplet is formed, several forces are acting upon it and the established weld pool dictating each of their respective shapes. The droplet experiences four primary forces: Surface Tension, the force due to gravity, the electromagnetic force, and the plasma jet force of the electric arc. In addition, the droplet experiences both a heat and mass transfer due to the heat produced by the arc. This heat melts the solid wire material which then joins the growing droplet at the tip of the wire.

During the arcing phase of the short circuit process, the weld pool has a similar force system dictating its shape. Surface tension, gravity, the electromagnetic force, and the plasma jet pressure are all exerting force on the top surface of the weld pool. The gravitational force on the weld pool is higher than that of the gravitational force on the droplet due to the larger mass of liquid in the weld pool.

Once the droplet has reached a sufficient size and has traveled a sufficient distance, contact is made with the top surface of the weld pool. When this contact is made, the arc momentarily extinguishes as the short circuit occurs. This simplifies the force balance of the system to include the following primary forces: the gravitational force acting on the mass of the weld pool (F_g), force due to the momentum transfer of the droplet impacting the weld pool (F_m), the surface tension of the liquid metal (F_{ST}), and the normal force of the previous bead or base plate (F_N). For the bead to remain stationary (i.e. the weld pool remains stationary in the direction perpendicular to the travel direction), the sum of these forces should be zero.

These three forces are the only forces considered for several reasons. The plasma jet force or "arc force" described by [15] is equal to zero during the short circuit phase as the arc is extinguished. The electromagnetic forces on the weld pool and droplet are comparatively small and also neglected due to the low voltage and current inherent to short circuit transfer.

Figure 3.3 shows how these three primary forces are applied to a weld pool in the gravity aligned orientation. It can be seen that since the droplet impact force and the gravitational force are aligned in the z-direction, the surface tension of the droplet is the driving force for the shape of the weld pool.

As discussed in [45], the moment when the droplet collides with the surface of the weld pool, the surface deforms due to the droplet impact force. Since this force is applied for a very short time interval, the weld pool recovers to a natural state during the arcing phase. As the weld pool moves with a velocity of the travel speed of the torch, the weld pool solidifies, leaving a bead with a cross-sectional profile that is primarily dictated by the surface tension.

The non-gravity aligned case is somewhat more complex due to the rotation of the torch based on the amount of overhang dictated by the part plan. The free body diagram for the non-gravity aligned case can be seen in figure 3.4.

The vector directions of both gravitational and droplet impact forces are important. The gravitational force is considered to be applied at the center of gravity of the weld pool, while the droplet impact force is applied to a point on the surface of the weld pool. The direction of the gravitational force is always in the negative z-direction in the global coordinate frame.

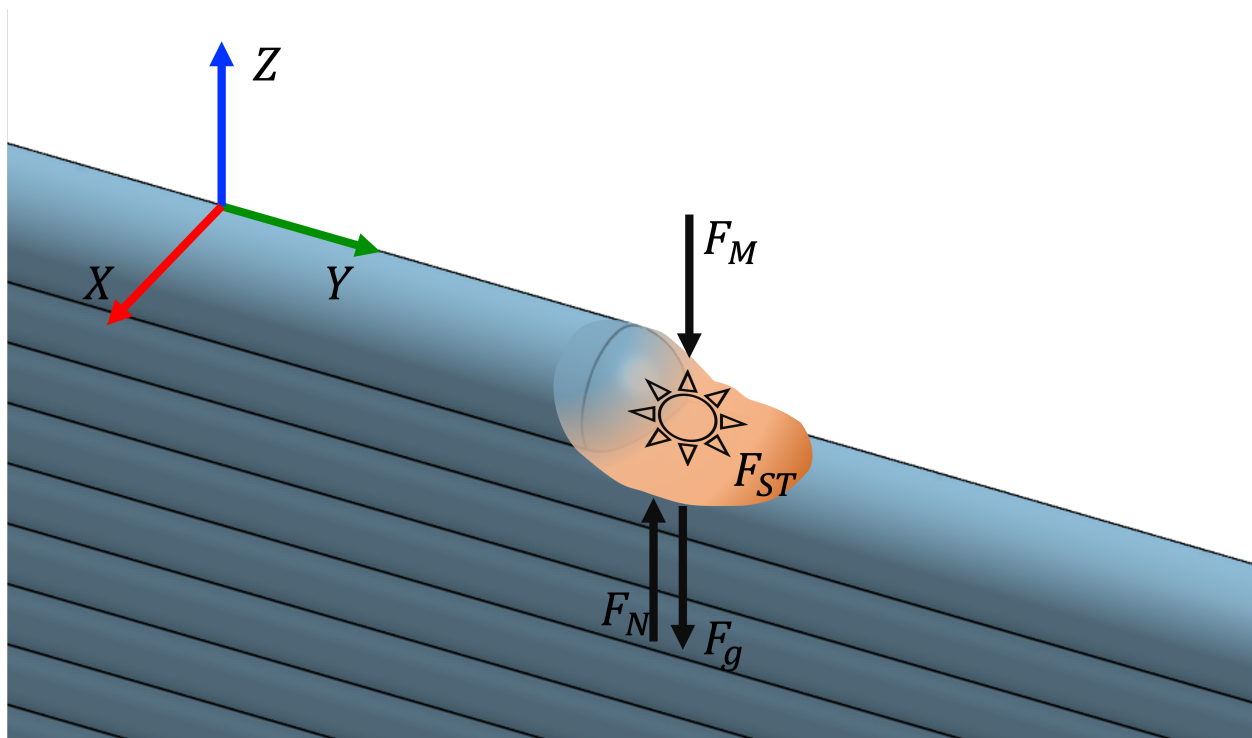


Figure 3.3: Free body diagram of a short circuit transfer weld pool in the gravity aligned orientation during the short circuit phase

The droplet impact force, however, depends upon the orientation of the welding torch relative to the global coordinate frame. The orientation of the welding torch relative to the weld pool is dictated in WAAM in the path planning process. In previous research, it was found that the non-gravity aligned weld pool is most stable when the torch is aligned with the build direction [29].

Upon further inspection of the non-gravity aligned free body diagram, this heuristic rule can be explained in theory. When welding in the non-gravity aligned orientation, the center of gravity of the weld pool is no longer directly supported by the normal force of the previous layer. Thus, the gravitational force has a greater effect on the profile of the weld pool. If the welding torch is kept in a gravity aligned orientation (i.e. in line with the global z-direction shown in figure 3.4), the droplet impact force exacerbates the influence of the gravitational force on the weld pool. This effect was shown in figure 3.2.

If the welding torch is re-oriented to be in-line with the build direction (as is shown in figure 3.4), the x-direction component of the droplet impact force (F_M) is now directed in such a way as to move the center of gravity of the weld pool more in line with the normal force exerted by the previous layer. In addition, the surface tension of the weld pool is supplemented by the x-component of the droplet impact force, thus further lessening the effect of the gravitational force on the weld pool shape.

This force balance, and the droplet impact force vector orientation influences the shape of the weld pool, and is useful in informing both the path planning process and control scheme for non-gravity aligned WAAM. In path planning, by orienting the torch in the build direction, it is possible to support the weld pool shape up to an inclination angle (ϕ) of 105° (see figures 3.5a to 3.5c).

As can be seen in figure 3.5c, even with orienting the droplet impact force to supplement the weld pool surface tension, some shifting and drooping of the weld pool still occurs. This indicates that for very large overhangs, the normal force is significantly reduced. Thus the effect of gravity on the weld pool shape is more apparent.

The first principles discussed here show that by controlling the force balance acting on the weld pool, it is possible to control the shape of the weld pool and subsequently the shape of the solidified weld bead.

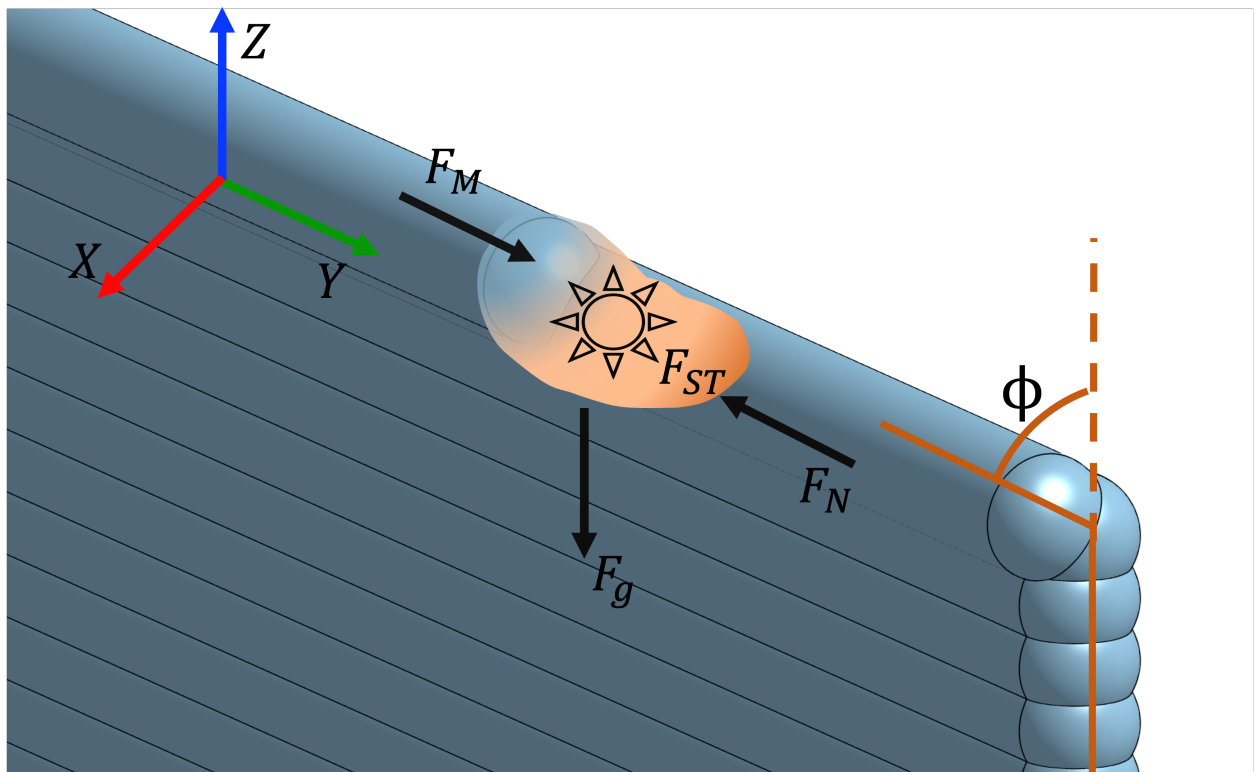
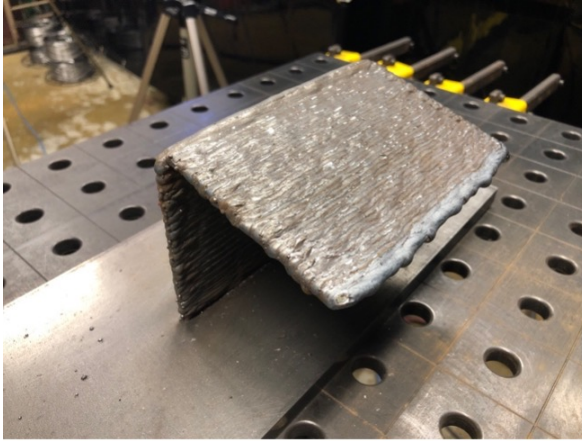


Figure 3.4: Free body diagram of a short circuit transfer weld pool in the non-gravity aligned orientation during the short circuit phase



(a) Iso view of a 105° WAAM overhang



(b) Side view of a 105° WAAM overhang



(c) Underside of the NGA portion of a 105° WAAM overhang

Figure 3.5: WAAM built wall with a 105° overhang produced using the heuristic rule for supporting the weld pool by reorienting the droplet impact force through the orientation of the welding torch

Chapter 4

Layer Height Control in WAAM

An important facet of WAAM is maintaining a consistent layer height throughout a build. This ensures that each planned weld bead is deposited as planned and that the final part geometry will match the desired geometry and dimensions within acceptable tolerances as the part is created by stacking the beads. Layer height is defined as the distance from the peak of the previous bead to the peak of the bead being actively deposited (see figure 4.1).

This chapter describes a new approach to monitoring the layer height in-situ and the development and implementation of a control system to maintain a desired layer height in real-time. The layer height control algorithm is the first piece of the overall control structure contribution. The ability to deposit consistent layers for an entire build is critical to ensuring that the desired geometry is achieved.

The algorithm presented here was developed using Miller Electric's Regulated Metal Deposition (RMD) process, which is a short circuit GMAW process. Other short circuit, waveform-based GMAW process exist including Surface Tension Transfer (STT) by Lincoln Electric and Cold Metal Transfer (CMT) by Fronius Welding. To use this layer height control algorithm with either of these additional process (or others not listed), the described experiments should be performed to generate new data to train a model specific to the welding process. Then, the remaining control system should be tested and re-tuned to appropriately react in-situ to control the deposited layer height.

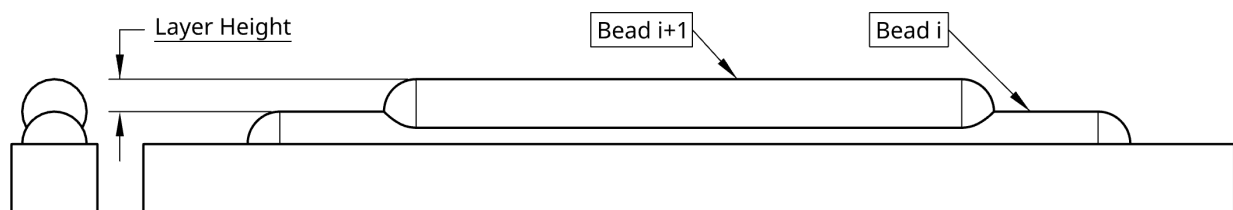


Figure 4.1: Definition of WAAM Layer Height

4.1 Approach to Layer Height Control

The first aspect of introducing layer height control into the WAAM system is to identify the layer height of the previously deposited layer to know if it deviated from the planned layer height. This can be done by measuring the contact-to-workpiece distance (CTWD) or filler wire stick-out. The CTWD is defined as the distance from the contact tip in the welding torch to the top surface of the workpiece where material will be deposited (see figure 4.2).

Several approaches can be used to measure the CTWD in real-time. First are indirect approaches which measure cues not directly controlled by the welding power supply. These can include laser measurement of the location of the workpiece, analysis of the sounds produced during welding, and spectral analysis of the arc light [26]. Second, the CTWD can be deduced by measuring the voltage and current of the active welding process. This is possible due to the mathematical relationship between the process voltage, current, and CTWD.

For a constant current GMAW process, the model can be approximated as a linearized first-order system [25]. This simplified model (as described by Oglivie) takes the wire-feed speed (WFS) and outputs the arc length using the following equation:

$$\frac{\Delta l(s)}{\Delta W(s)} = \frac{-K_w}{\tau_w s + 1} \quad (4.1)$$

where l is the arc length, W is the WFS, K_w is the weld process model gain, and τ_w is the weld process time constant. This time constant is defined as:

$$\tau_w = \frac{1}{K_O^* n m} \quad (4.2)$$

where K_O^* is the linearized melting rate constant, n is the slope of the welding power supply characteristic curve at the linearization point, and m is the slope of the arc length-arc voltage characteristic curve. For this model to be successfully used, many of the parameters must be experimentally determined for a given set of welding parameters. In addition, since the model is fully linearized, it neglects many non-linear aspects of the constant-current welding

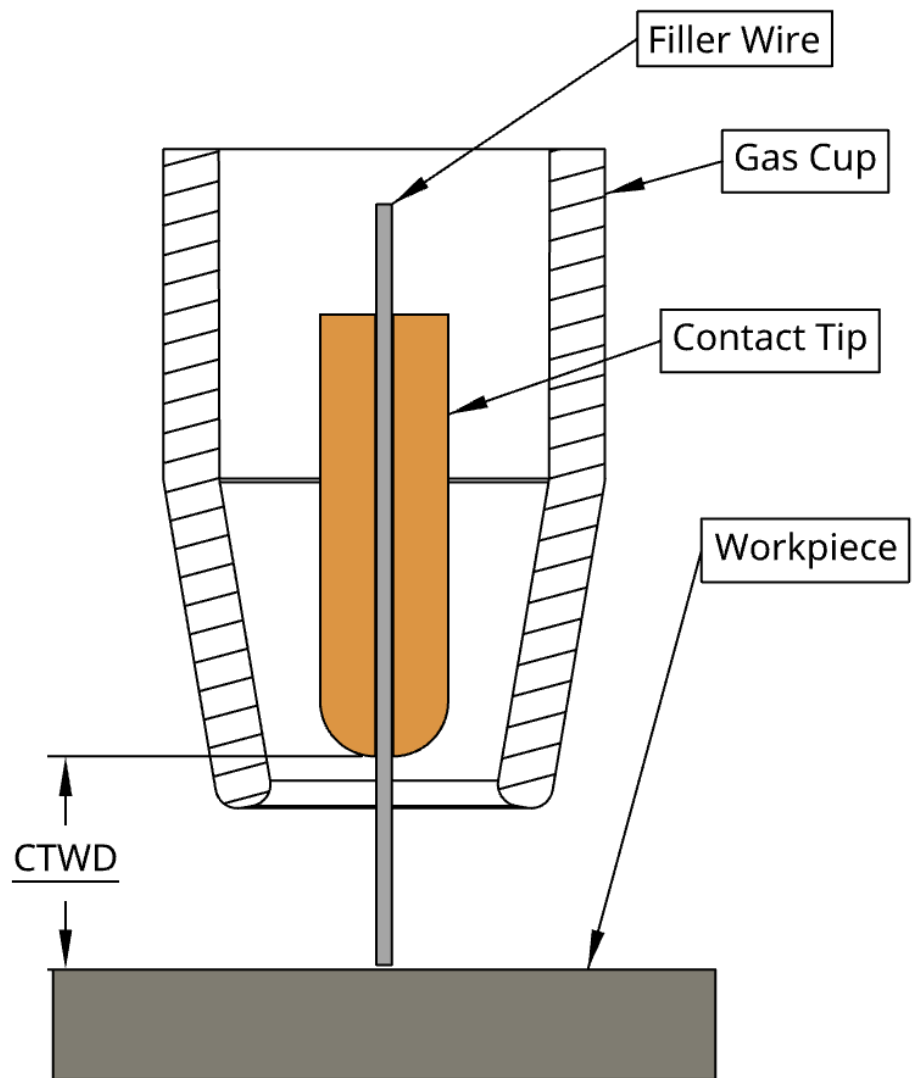


Figure 4.2: Definition of Contact-to-Workpiece Distance (CTWD)

process and therefore is not a good fit for estimating CTWD when using a short circuiting, waveform-controlled GMAW process.

To fully model the non-linear components of a waveform-controlled process, a component model of the welding system should be used as described in [57]. Zeng et al. model the full power supply system in great detail, using non-linear elements to describe the melting of the electrode as it is heated by the arc and how the drop is deposited into the weld pool when a short-circuit event occurs. While the model agrees well with the experimental results, the computational complexity of the model does not make it a good fit for real-time applications such as that presented here.

To measure the voltage and current of the active welding process, a special sensor system capable of sampling the voltage and current at high frequencies is needed. The sensor system used is called a LEM Box (see figure 4.3, graciously donated by Miller Electric). The LEM box has two internal sensors, one for voltage and one for current, that are integrated into the welding circuit. The voltage sensor is placed in parallel across the terminals of the welding power supply and the current sensor is wired in series (see figure 4.4).

The LEM Box samples the voltage and current waveforms of the RMD process at 20 kHz. By sampling the voltage and current at this rate, the waveforms shown in figure 1.6 can be analyzed. An example of the captured waveforms can be seen in figure 4.5. While the waveforms are not particularly useful by themselves, they contain important information about the welding process, namely the rate at which droplets are deposited into the weld pool (namely for short circuit processes) and the average voltage and current used to create those droplets.

The LEM box is connected to a desktop computer via USB and LabVIEW is used to interface with the LEM Box and store the captured data. For this implementation of layer height control, the average voltage and current must be found to then calculate the CTWD. Since the voltage and current waveforms are periodic signals, a digital Fast Fourier Transform (FFT) can be used to extract the DC component of the signal (the amplitude of the 0 Hz frequency band). The DC components of the voltage and current must then be correlated to the CTWD. This is done through a Support Vector Regression model [28].



Figure 4.3: LEM Box voltage and current sensor

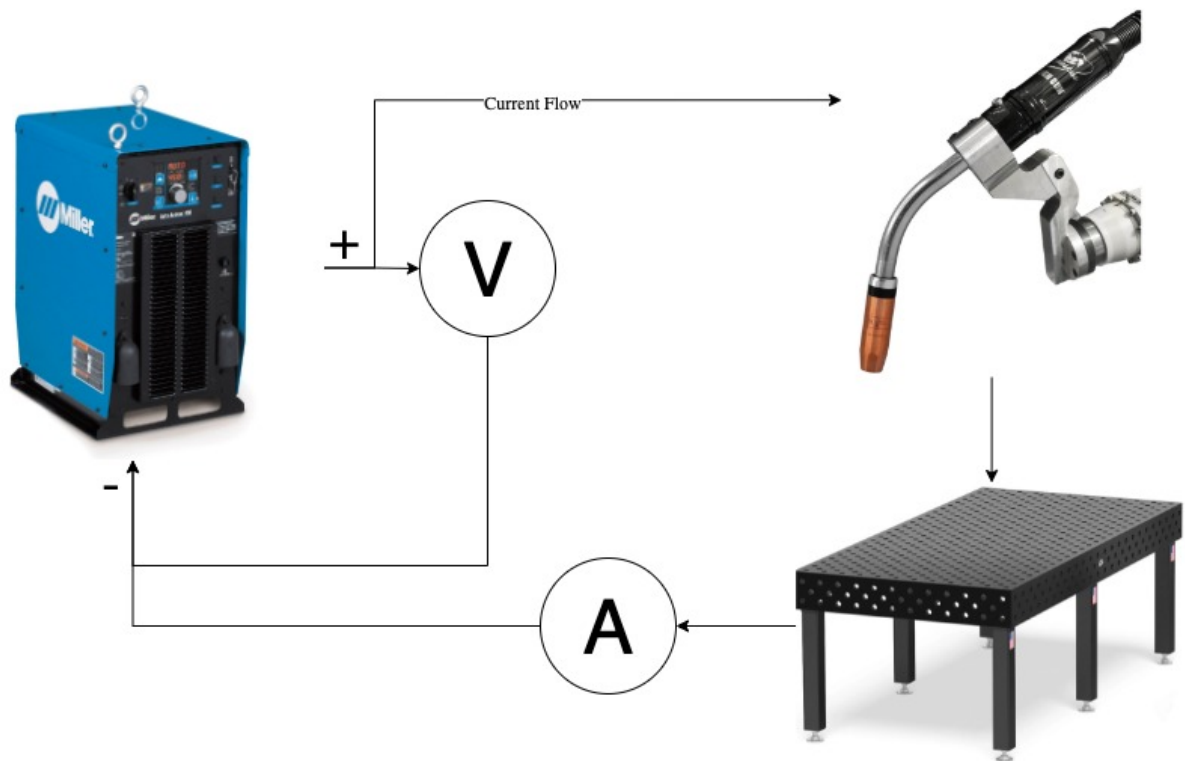


Figure 4.4: Circuit diagram showing the location of the LEM Box voltage (V) and current (A) sensors in the overall welding circuit

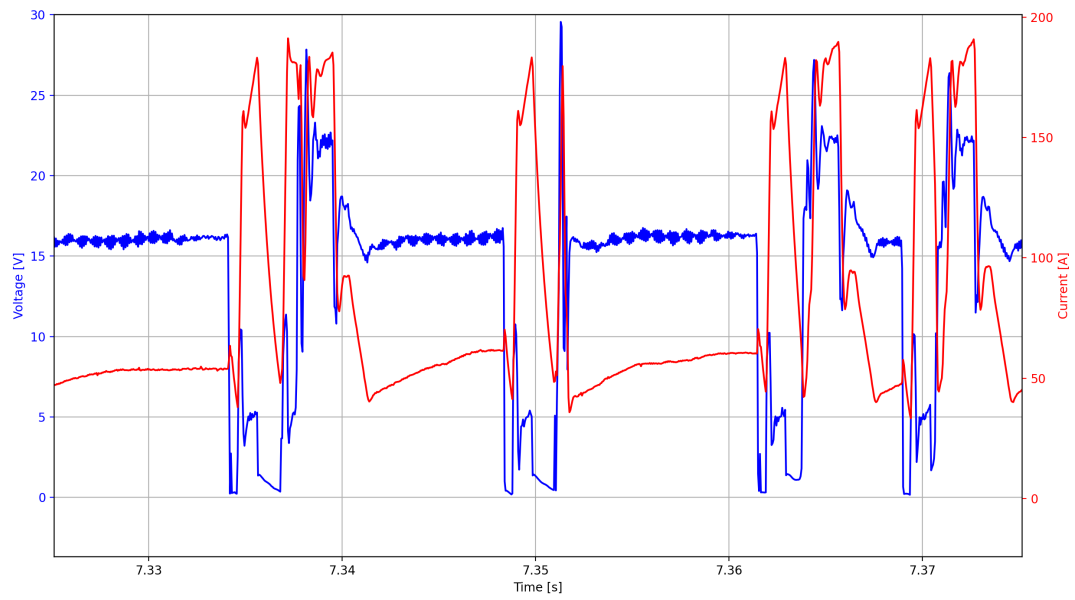


Figure 4.5: Example of the voltage and current waveforms generated by the RMD process and captured by the LEM box.

4.2 Development of Support Vector Regression Model

Due to the complex nature of the RMD process and the voltage and current waveforms it employs to control the GMAW process, it is difficult to use a direct, first principle approach to calculate CTWD from the measured voltage and current. To this end, a Support Vector Regression model was implemented to correlate measured voltage and current values with a CTWD.

The Support Vector Regression method uses a defined acceptable error within which predictions will be made based on a given input. This model is trained through experimental data to generate the necessary coefficients. At its heart, SVR tunes the coefficients of the fitted curve to satisfy the following two equations:

$$\text{MIN} \frac{1}{2} \|\mathbf{w}\|^2 \quad (4.3)$$

$$|y_i - w_i x_i| \leq \epsilon \quad (4.4)$$

where $\mathbf{w}$ is a vector of the coefficients of the fitted curve, ϵ is the desired maximum error, and x and y are the inputs and outputs of the function respectively [36]. SVR attempts to satisfy the objective function equation (4.3) while maintaining the constraint in equation (4.4). Since, as described above, the relationship between welding process and CTWD is a linear first order system, the SVR method is a good fit for modelling the relationship with experimental data.

To generate the voltage and current inputs to the CTWD model for layer height control, several experiments were executed. Figure 4.6 shows the layout of weld beads that were deposited to generate the voltage and current data to feed the SVR model. The nominal desired CTWD is 12 mm. In the KUKA control software, the set maximum deviation allowed from the programmed position in the tool direction is ± 5 mm. Thus, to develop the model, CTWD deviations of ± 4 mm were introduced manually for certain deposited beads. The experimental parameters can be seen in table 4.1.

The data generated from these beads was then fed through the SVR algorithm implemented in Python with the SciKit Learn library [28]. The input vector consists of

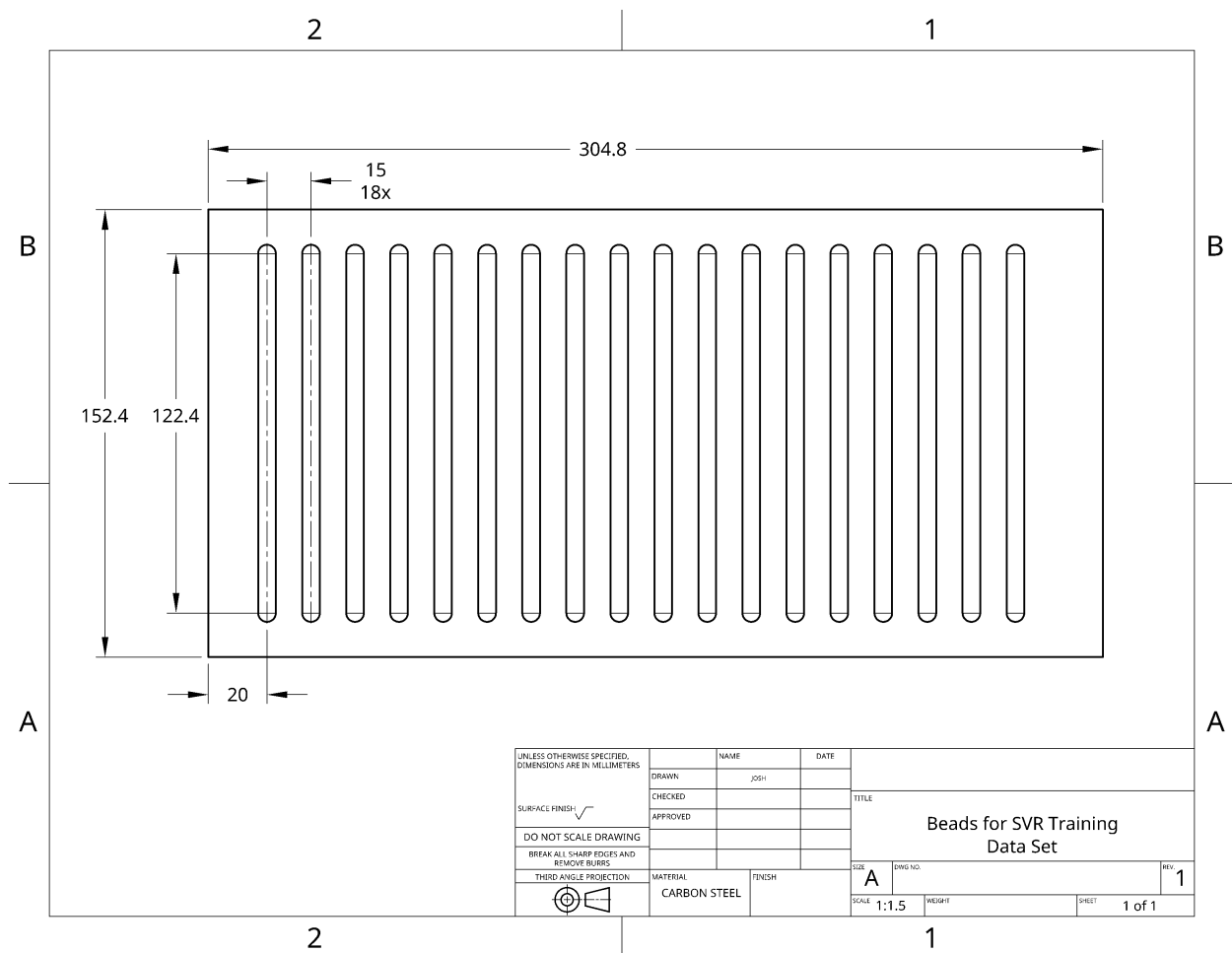


Figure 4.6: Drawing of the test beads deposited to generate data for the SVR model development

Table 4.1: Bead experiment parameters for generating data for SVR model

Bead	CTWD [mm]	WFS [in min ⁻¹]	TS [in min ⁻¹]
Bead 01	12	130	6.5
Bead 02	9	130	6.5
Bead 03	13	130	6.5
Bead 04	11	130	6.5
Bead 05	8	130	6.5
Bead 06	14	130	6.5
Bead 07	16	130	6.5
Bead 08	10	130	6.5
Bead 09	15	130	6.5
Bead 10	13	130	6.5
Bead 11	8	130	6.5
Bead 12	11	130	6.5
Bead 13	16	130	6.5
Bead 14	14	130	6.5
Bead 15	18	130	6.5
Bead 16	9	130	6.5
Bead 17	15	130	6.5
Bead 18	10	130	6.5

the DC gain values for both the voltage (in Volts) and current (in Amperes). The desired output value is the robot z-position in the base coordinate frame of the part. The data is split into training and testing sets with eighty percent of the data used for training and twenty percent used for testing. The Python code used to train the model can be found in appendix [A.1](#).

The resulting SVR model scores a 0.918 using the testing data set to validate the accuracy of the model generated through the training data set. This score is the coefficient of determination R^2 for the trained function and is defined by [\[28\]](#) as:

$$\begin{aligned} R^2 &= \left(1 - \frac{u}{v}\right), \\ u &= \sum (y_{true} - y_{pred})^2 \\ v &= \sum (y_{true} - \bar{y}_{true})^2 \end{aligned} \tag{4.5}$$

The score represents how well the trained function predicts values of y . This is where the split testing data is fed into the model. If the trained model perfectly predicts the output (i.e. $y_{pred} = y_{true}$ for a given input $\mathbf{x}$, then the score will be 1. Thus, the model trained here is quite accurate at predicting the CTWD for given values of voltage and current. Figure [4.7](#) shows the data used to train the CTWD SVR model and figure [4.8](#) shows the data used to test the model for accuracy.

4.3 Implementation of Layer Height Control

To implement the developed SVR voltage and current model, a LabVIEW program was written to read and process the voltage and current data from the LEM box, evaluate the SVR model using the measured values to obtain a CTWD, then apply a position correction to the robot in real-time to compensate for deviations in the CTWD. The data is passed from LabVIEW to the KUKA robot controller over a local Ethernet connection and received by KUKA's Robot Sensor Interface (RSI) package. This package runs in the background of the KUKA System Software (KSS) and enables interaction with outside hardware and software to influence the motion of the robot.

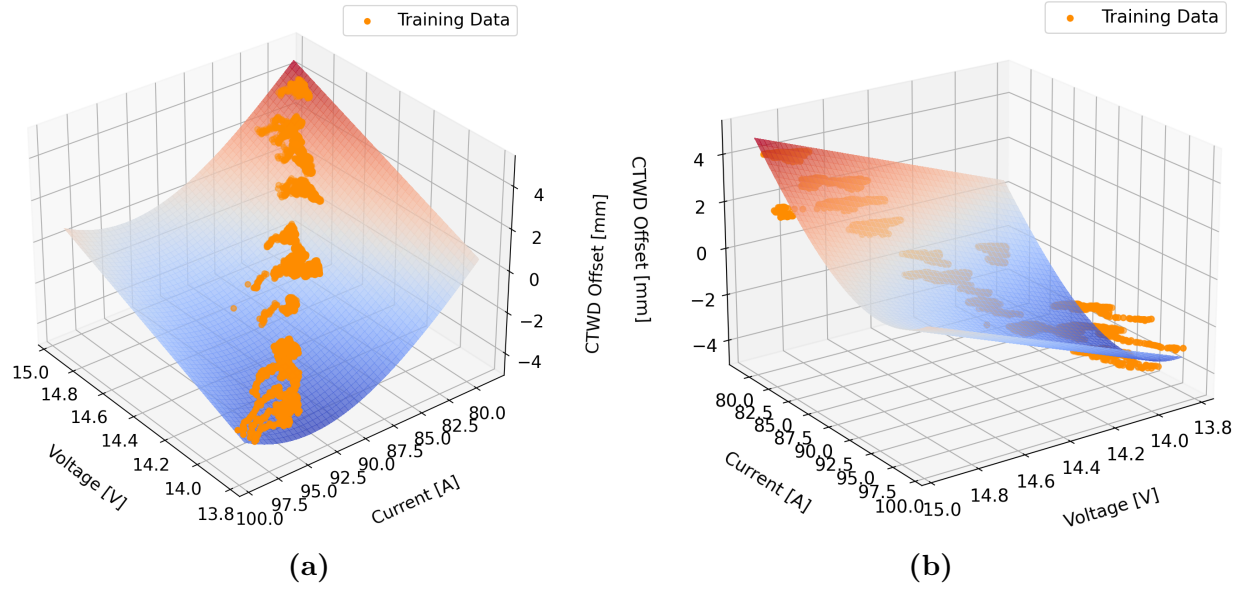


Figure 4.7: Data used for training the CTWD SVR model along with the resultant SVR surface

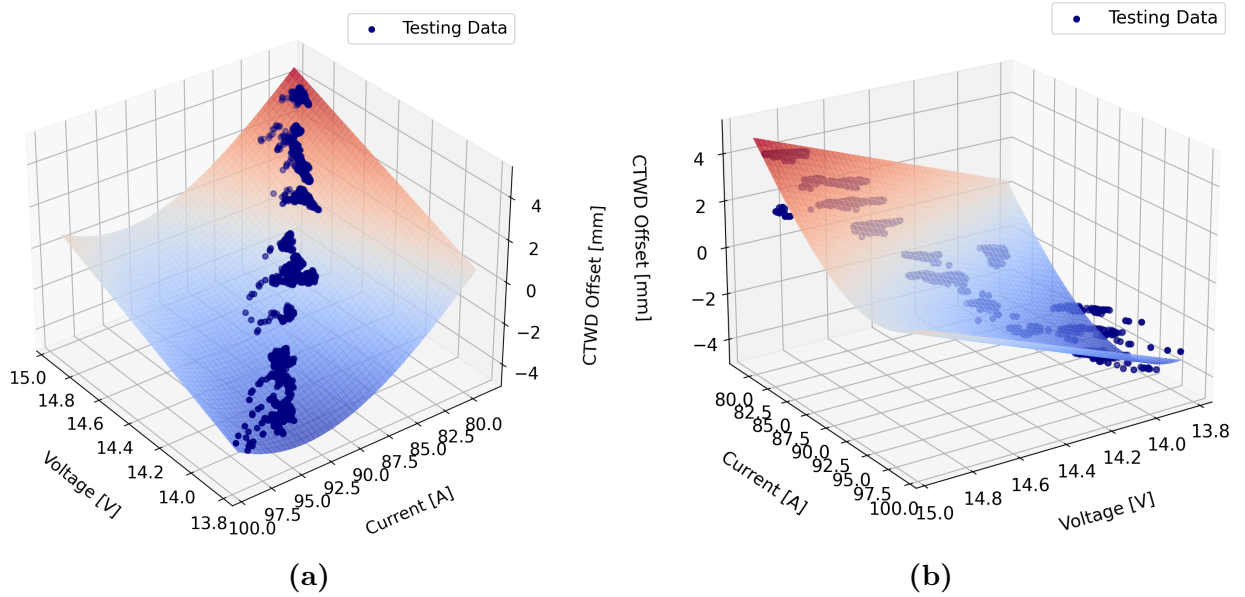


Figure 4.8: Data used for testing the CTWD SVR model along with the SVR model

Within LabVIEW, a python script is implemented to run the SVR model. Then, a Proportional, Integral, Derivative (PID) controller is implemented to process the CTWD error generated by the SVR model and produce an error signal to pass to the robot controller. This control loop can be seen in appendix [B.4](#).

4.4 Experimental Validation

To test the validity of this Layer Height Control algorithm in the gravity aligned direction, two sets of experiments are conducted. First, the same single bead-on-plate experiment used to generate the training data for the SVR model is re-run with the Layer Height Control algorithm. Then, several multi-layer walls are built to validate the algorithm in the context of WAAM.

4.4.1 Bead on Plate Validation

The experiment described in table [4.1](#) is conducted again, but now with the implemented layer height control algorithm. The desired outcome is two fold. First, the layer height control algorithm should drive any error between the nominal CTWD (12mm) and the measured CTWD to zero. Second, all beads deposited, regardless of initial programmed CTWD, be the same height.

As shown in figures [4.9](#) to [4.17](#), the controller accomplishes the first goal of attempting to drive the error to zero. With 12mm being the desired CTWD, figure [4.13](#) shows that the control algorithm is reacting to fluctuations in the voltage and current waveforms, but is ultimately oscillating around the desired set-point.

As the CTWD continues to become larger than 12mm (see figures [4.9](#) to [4.12](#)), the layer height controller continues pulling the robot Z position closer to zero. It is seen that there is a steady-state error that continues to grow larger proportionally with the initial CTWD. It is likely that with more tuning of the PID parameters, this steady state error could be reduced. Another limiter on the maximum amount of correction the controller is able to make is the internal saturation limits within the KUKA robot controller. When configuring the Robot-Sensor Interface package [\[14\]](#), limits are set on the maximum amount of deflection

in each Cartesian direction that can be made. For the safety of the robot and workpiece, this limit was set to 5 mm to keep the welding torch from contacting the workpiece.

For the cases where the initial CTWD is less than the 12 mm set-point (see figures 4.14 to 4.17, a similar steady-state error occurs as in the above case. An interesting feature of the shorter CTWD is a higher stability of the welding process as shown by the decreased oscillation in the controlled robot positions. The instability in the beads deposited with a higher CTWD is due to a phenomenon called "Long Arcing". In long arcing, the time between short circuit events becomes longer as the melting rate of the wire is relatively unchanged and the distance the droplet must travel is larger. Due to the waveform nature of the voltage and current, and the active control of these waveforms performed by the welding power supply, as the arc grows longer, the process becomes more unstable.

For the second goal of producing the same bead height at all times, the developed layer height controller performs well. This can be seen in figure 4.18. Each bead was scanned using a Keyence VR-5000 3D scanner. Using these scans, the average height of the bead was found, then, since two beads were produced for each CTWD both in the controlled and uncontrolled cases, the average heights of the two beads were averaged to give a single average bead height for a given CTWD. To determine the consistency of the controlled vs uncontrolled beads, a simple linear regression was performed (the black lines in figure 4.18). It can be seen that the fit line for the controlled data has a significantly lower slope than that of the uncontrolled data. This indicates that the layer height control does accomplish the second goal and produces a relatively consistent bead height regardless of initially dictated CTWD. The 15 mm and 16 mm beads are not used due to the process instability. The level of instability seen in these two beads show that these distances are too great to provide a stable process.

4.4.2 Multi-Layer Validation

While bead-on-plate tests provide good information to validate that the controller is behaving in a desired manner, the true test of the layer height controller comes in a multi-layer application. To this end, two thirty-layer walls are built, one without layer height control and the other with layer height control. The part plan for both walls is exactly the same, using

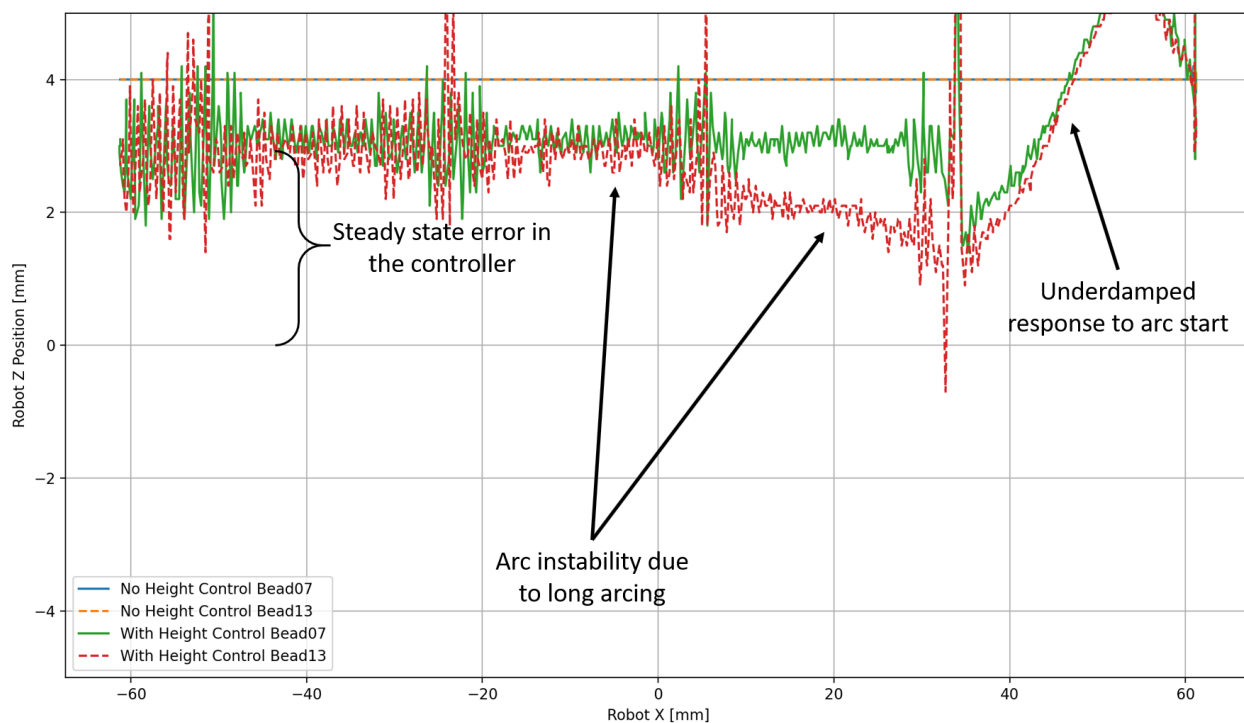


Figure 4.9: Robot Z positions for CTWD = 8 mm

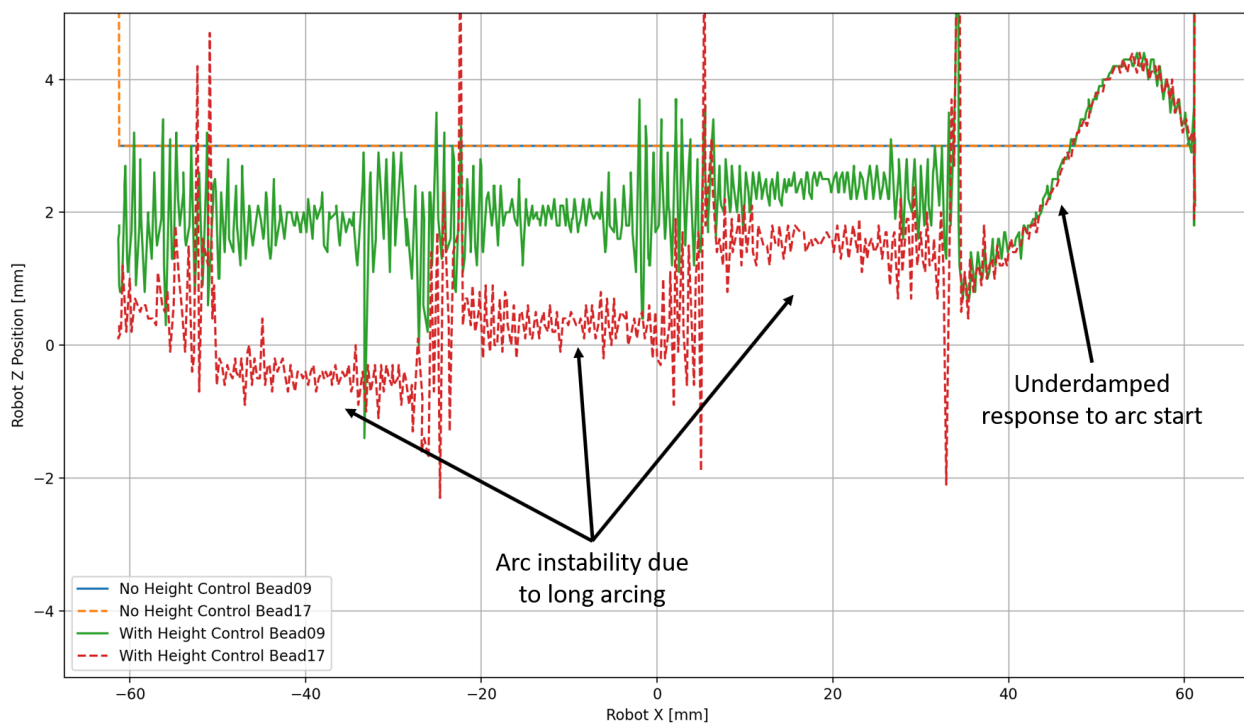


Figure 4.10: Robot Z positions for CTWD = 9 mm

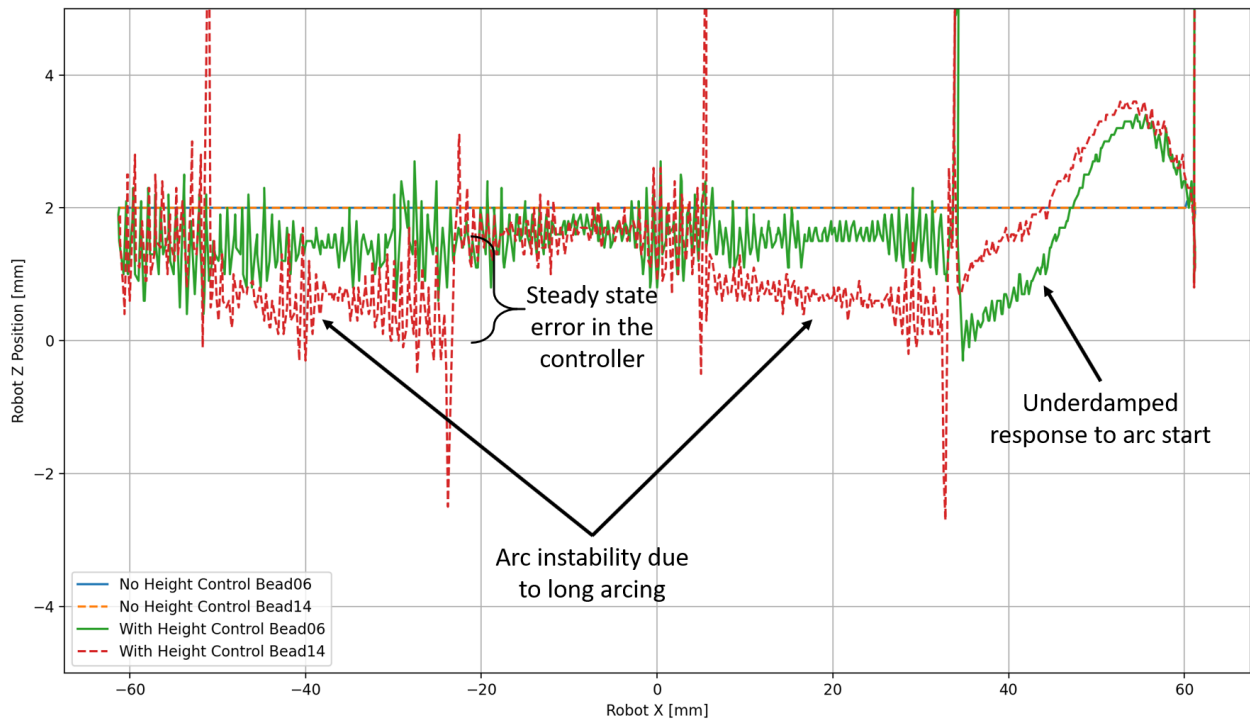


Figure 4.11: Robot Z positions for CTWD = 10 mm

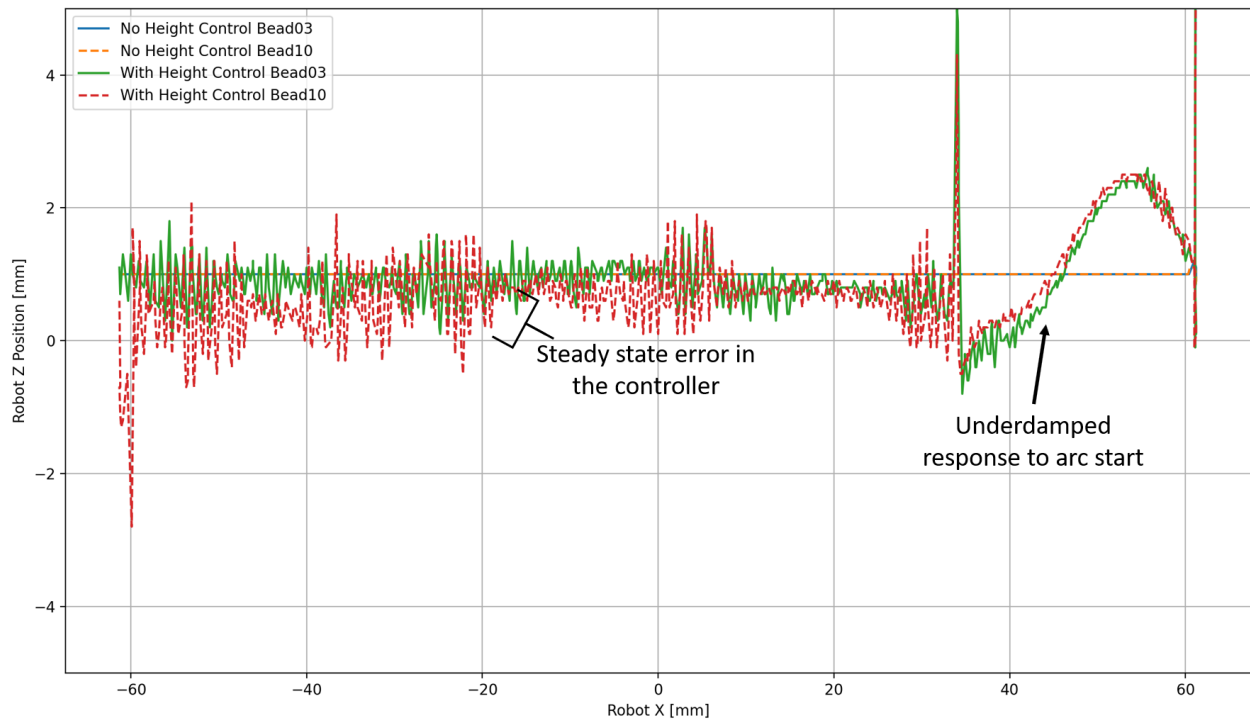


Figure 4.12: Robot Z positions for CTWD = 11 mm

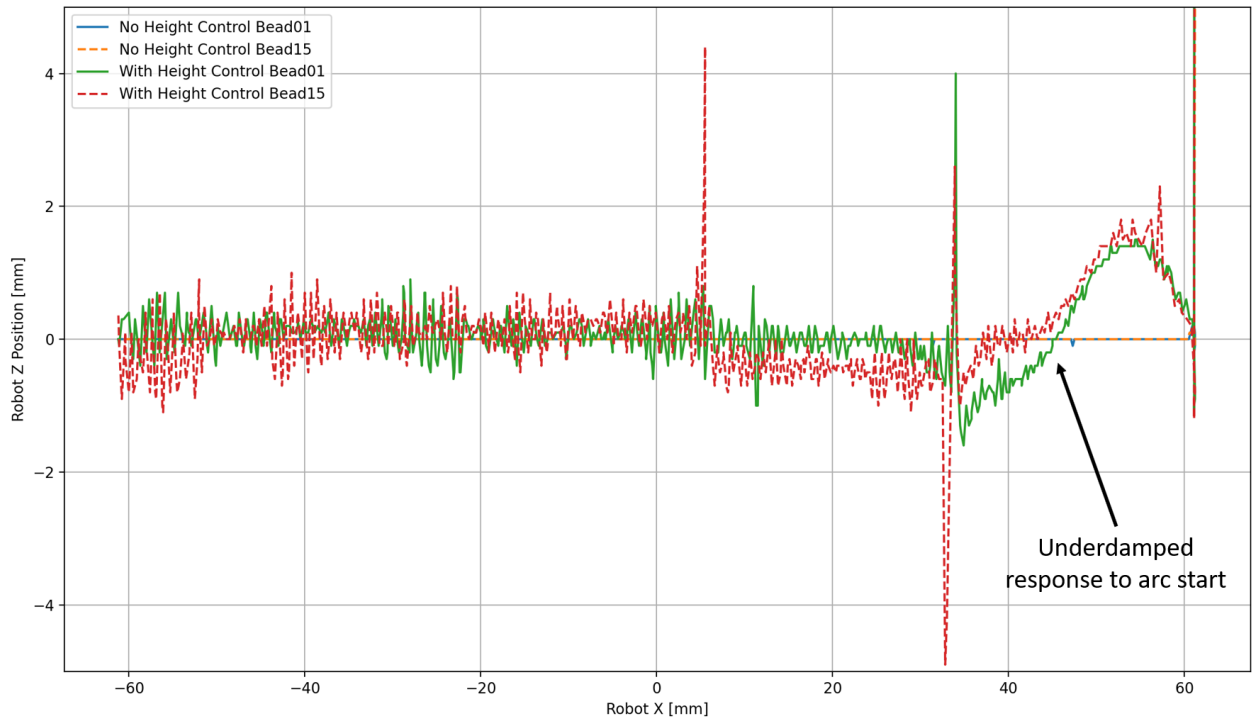


Figure 4.13: Robot Z positions for CTWD = 12 mm

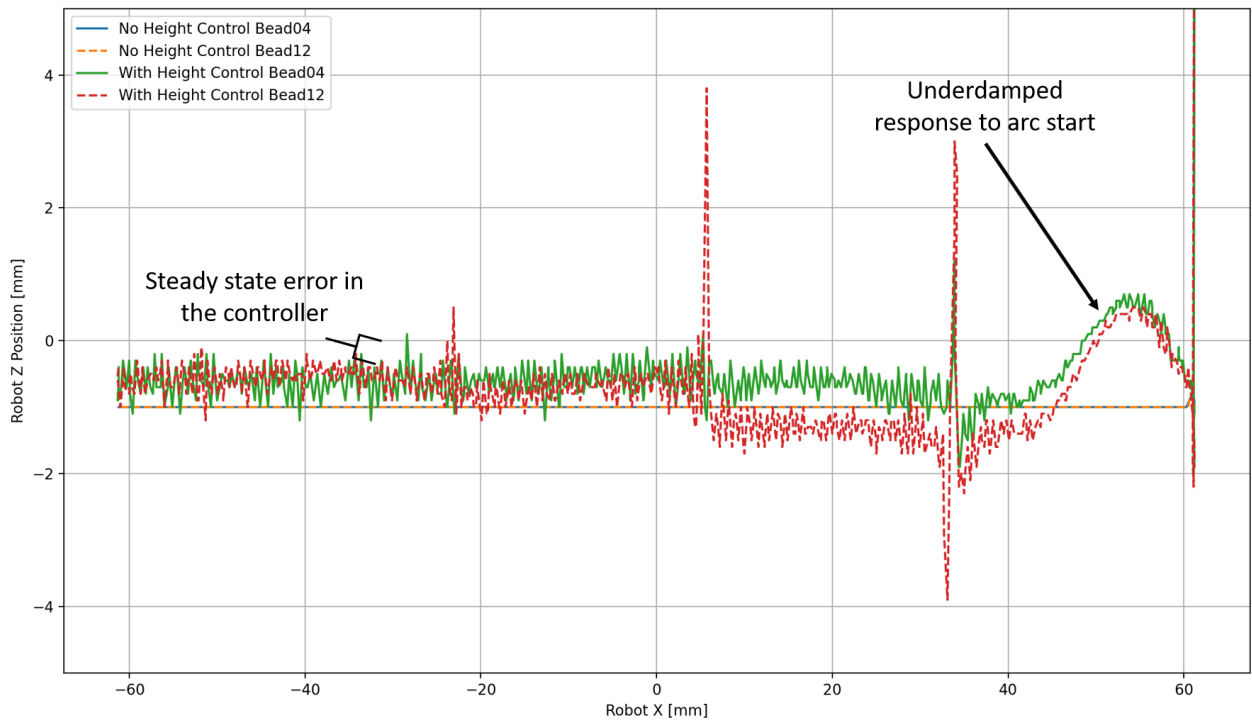


Figure 4.14: Robot Z positions for CTWD = 13 mm

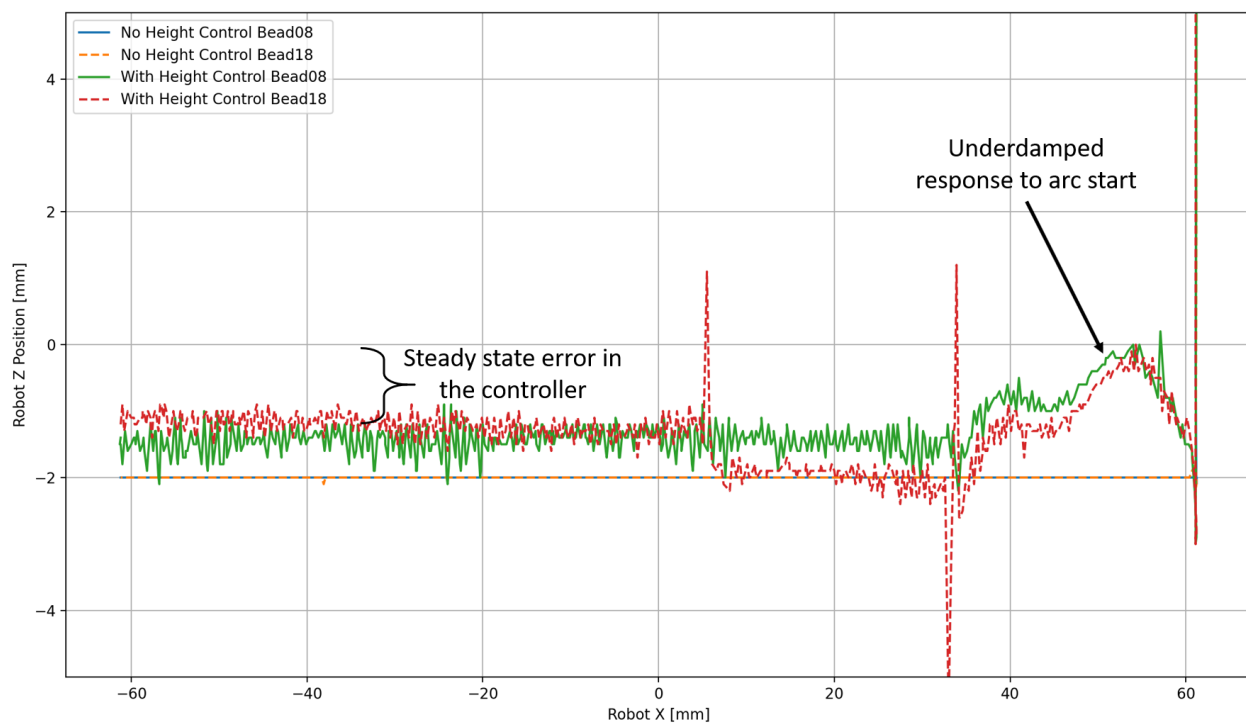


Figure 4.15: Robot Z positions for $CTWD = 14$ mm

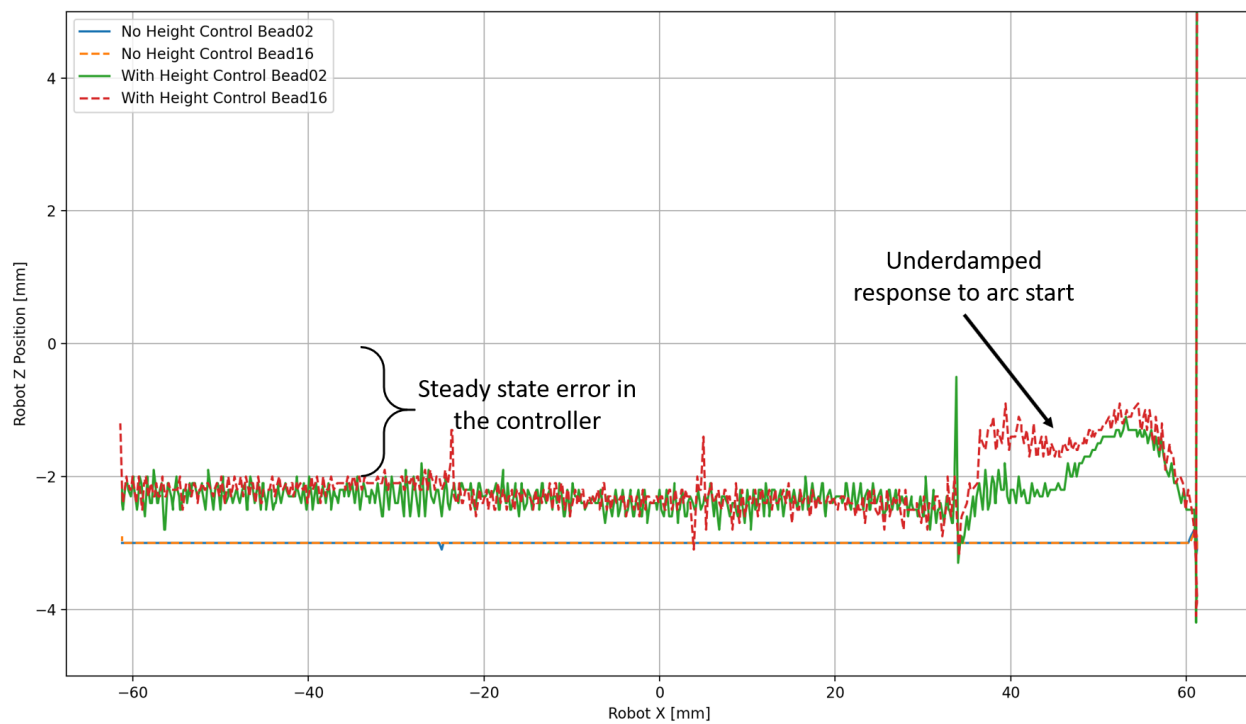


Figure 4.16: Robot Z positions for $CTWD = 15$ mm

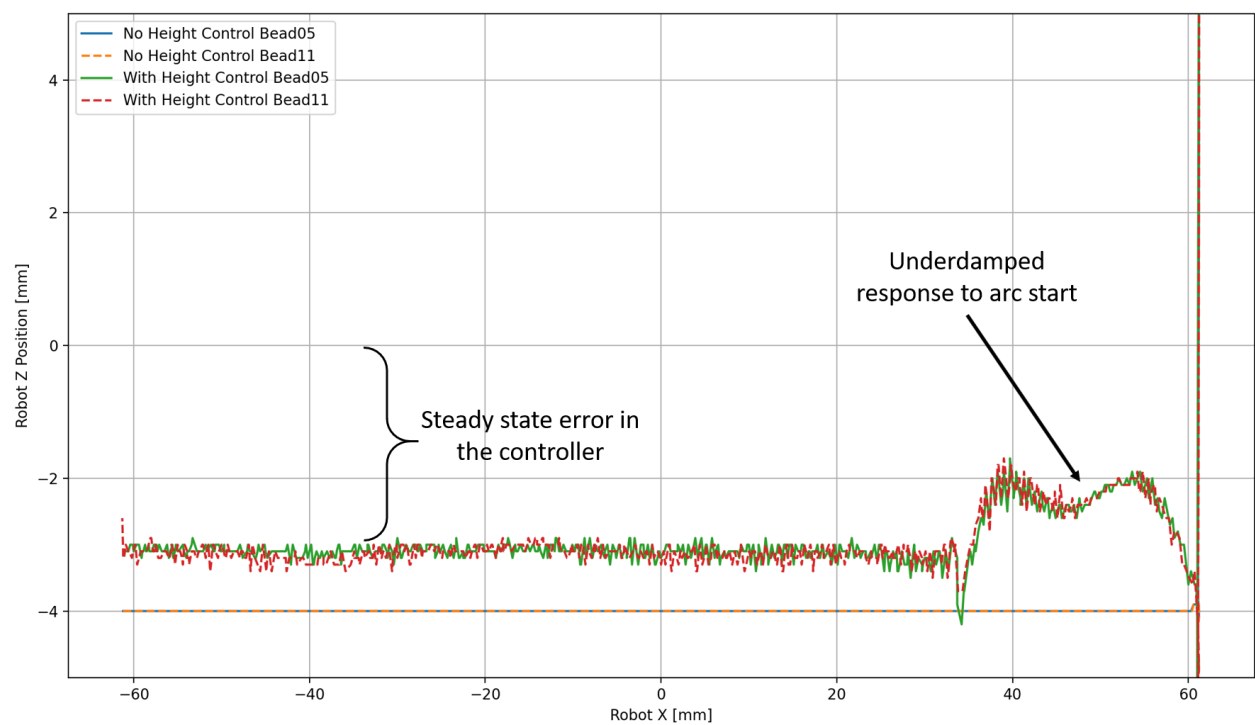


Figure 4.17: Robot Z positions for CTWD = 16 mm

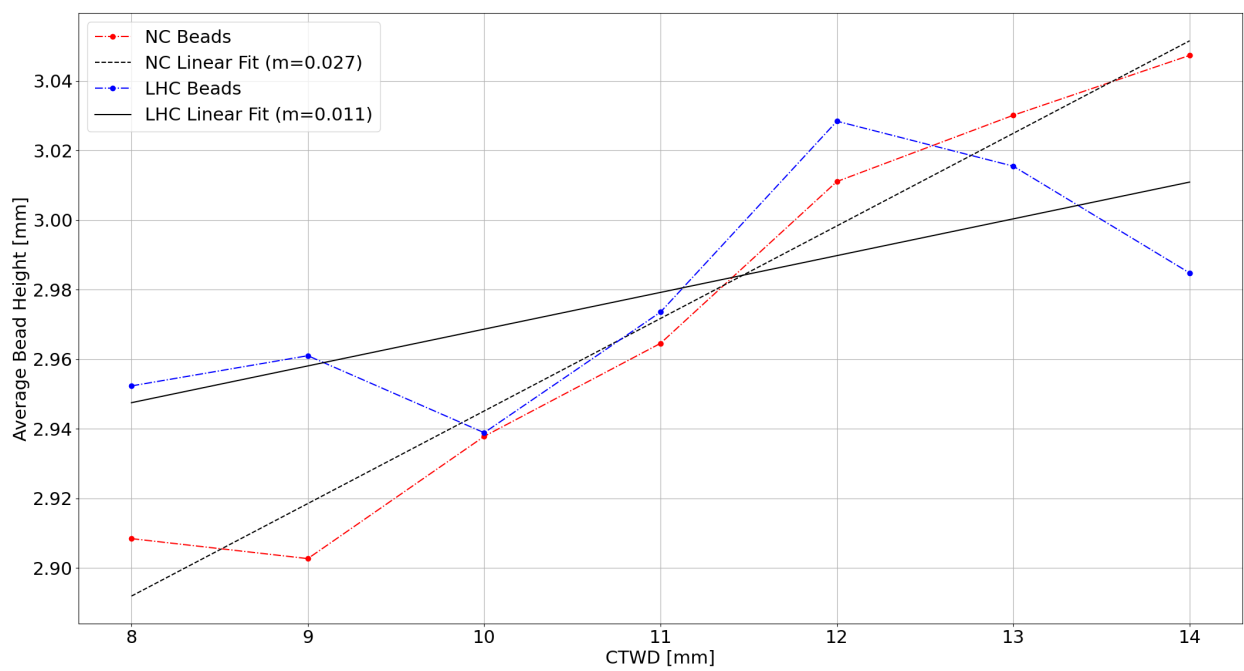


Figure 4.18: Comparison of average bead heights between beads with and without the layer height control.

the same wire feed speed and travel speed shown in table 4.1. The paths were programmed in Octopuz [24], an offline robotic programming software, and the virtual setup can be seen in figure 4.19.

The layer height controller performed similarly to previous, reacting to disturbances in the welding process as well as driving the robot Z position in such a way as to drive the CTWD error generated by the SVR model a close to zero as possible. The z-positions of the robot throughout the entire build can be seen in figure 4.20.

After both walls were deposited, the entire build plate was scanned using a GOM ATOS Q 3D scanner. This scanner was used as opposed to the Keyence scanner mentioned earlier due to its larger field of view. The 3D scan along with the CAD used to analyze each wall individually can be seen in figure 4.21. Using the GOM Inspect software, several points of performance were analyzed for each wall: a surface comparison of the actual wall surface to the desired CAD wall, a profile of the printed wall along the centerline of the wall to analyze the deviations from the desired CAD in more detail, and fitting planes on each side of the wall to analyze the surface waviness of the walls.

The surface comparisons for the front and back of each wall can be seen in figures 4.22a, 4.22b, 4.23a and 4.23b. The surfaces of both walls are quite similar and show fairly good agreement to the desired CAD model with some areas along the main faces being under-built and some overbuilt consistent with the surface waviness typical in WAAM parts. Some of the areas showing as more severely under-built or overbuilt on both the front and back of each wall could be caused by a misalignment between the 3D scan and the CAD model. The scan is aligned with the CAD model using a local best fit centered on the wall under analysis. While the best fit does a good job aligning the data sets, some alignment issues can occur which lead to additional deviations shown in the data.

By taking a transverse planar cut at the center of each wall, the under-build or overbuild characteristics of the wall as a whole relative to the desired height of the part can be determined. These profiles can be seen in figures 4.24a and 4.24b. The profiles show that both walls are significantly under-built in total height. Further analysis of these profiles show that the overall maximum deviation from CAD is greatest in the wall built using layer height control at -6.1251 mm.

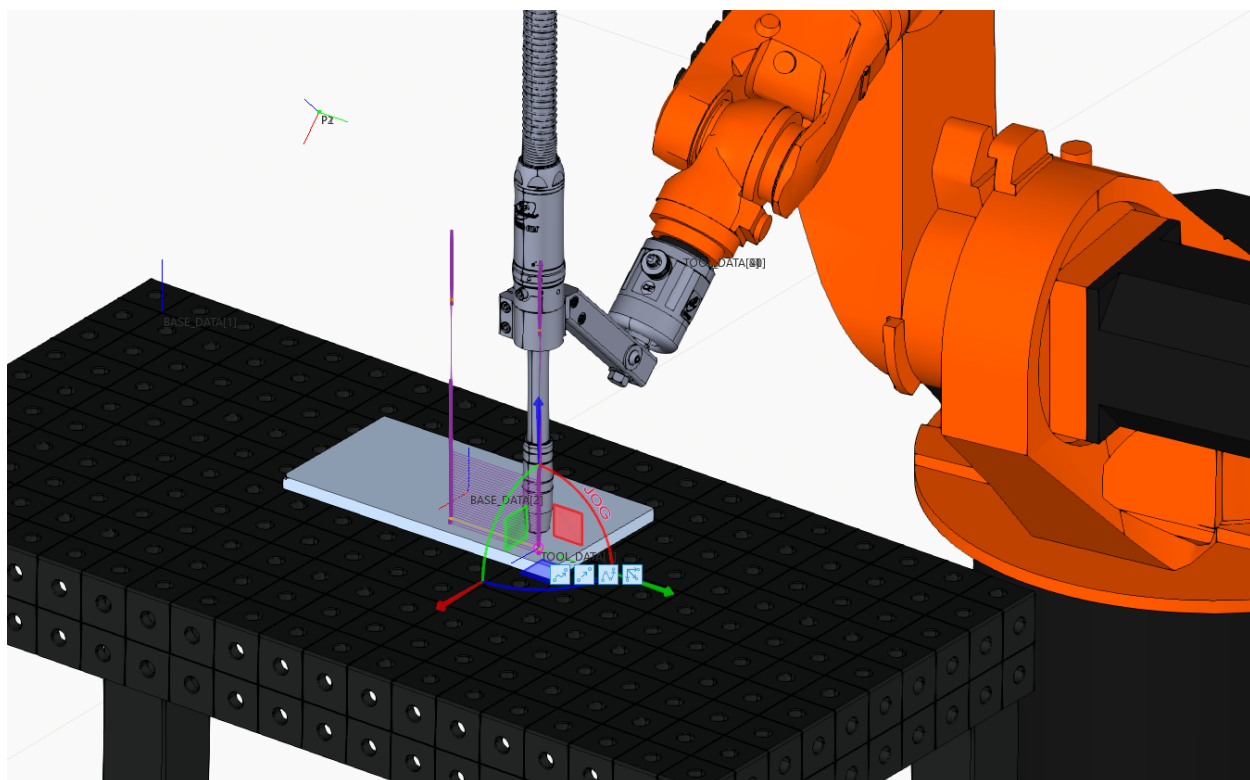


Figure 4.19: Path plan used to 30-layer walls for testing layer height control

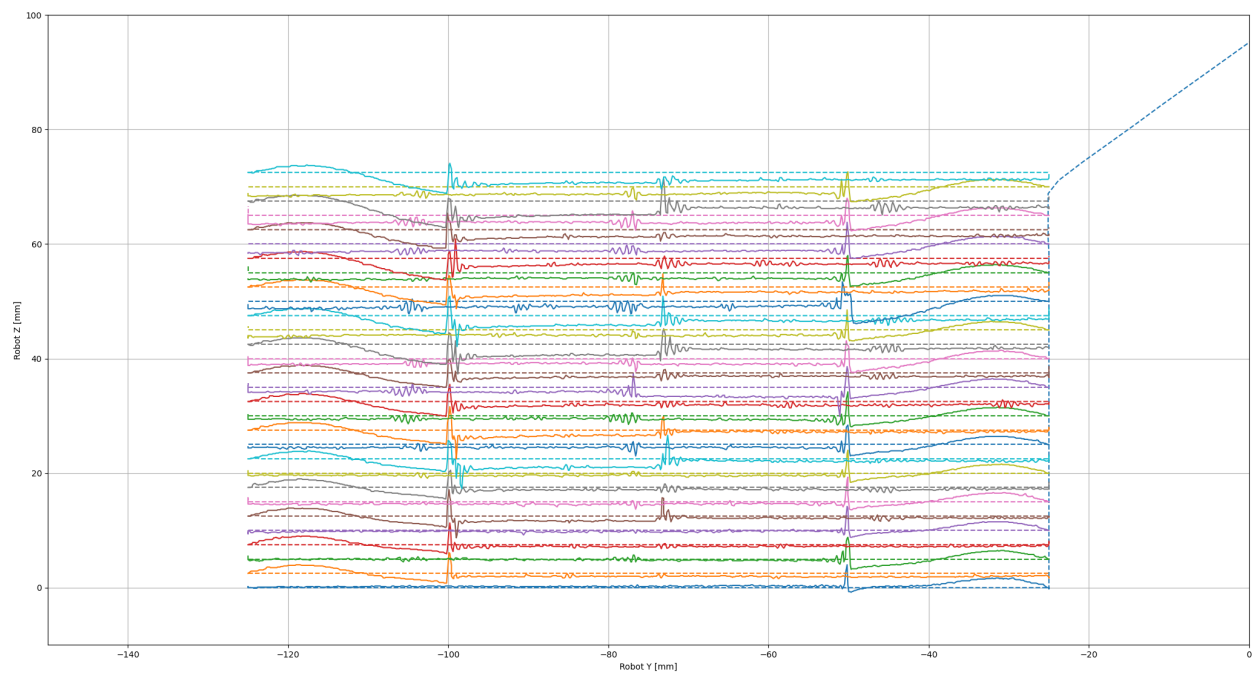


Figure 4.20: Robot positions during the controlled and uncontrolled 30-layer wall builds

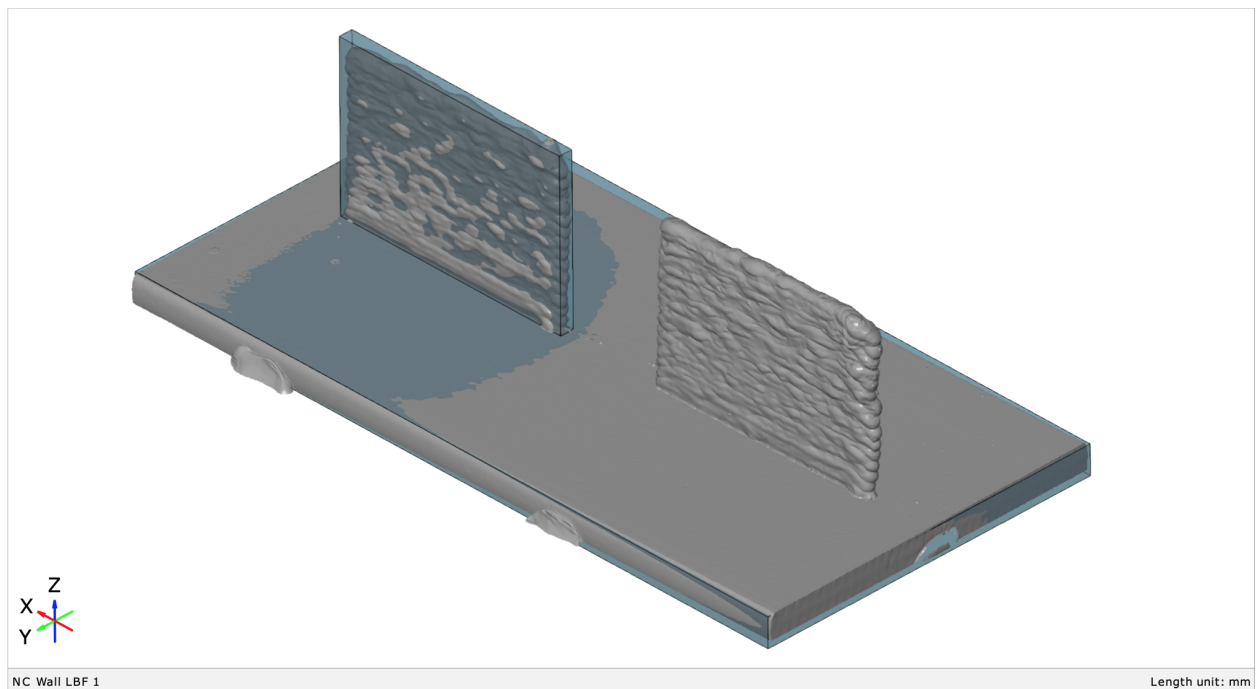
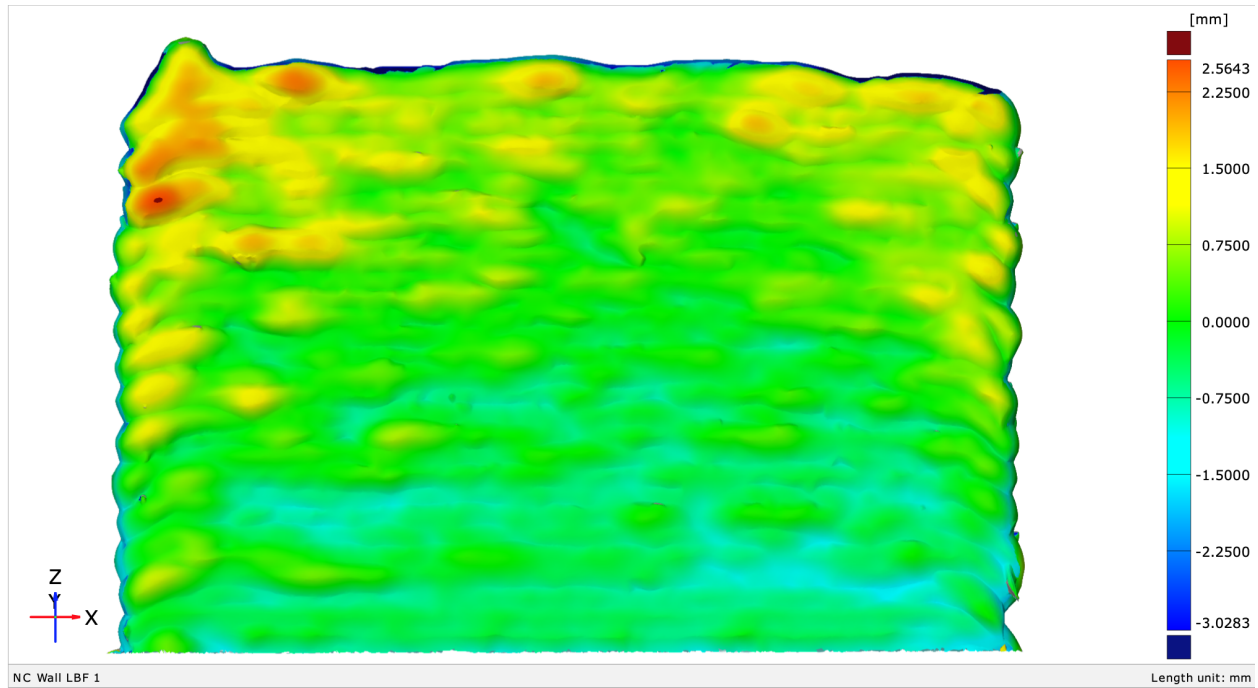
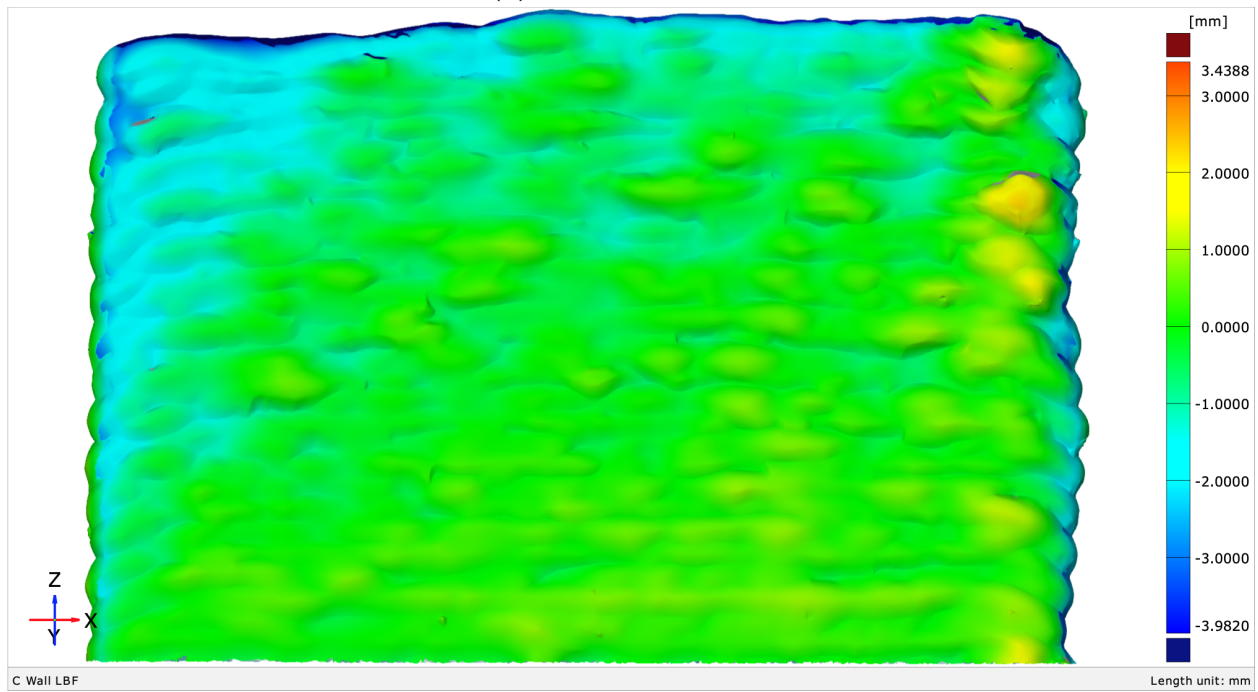


Figure 4.21: 3D scan of the controlled and uncontrolled 30-layer walls along with the CAD for a single wall used to analyze each wall individually

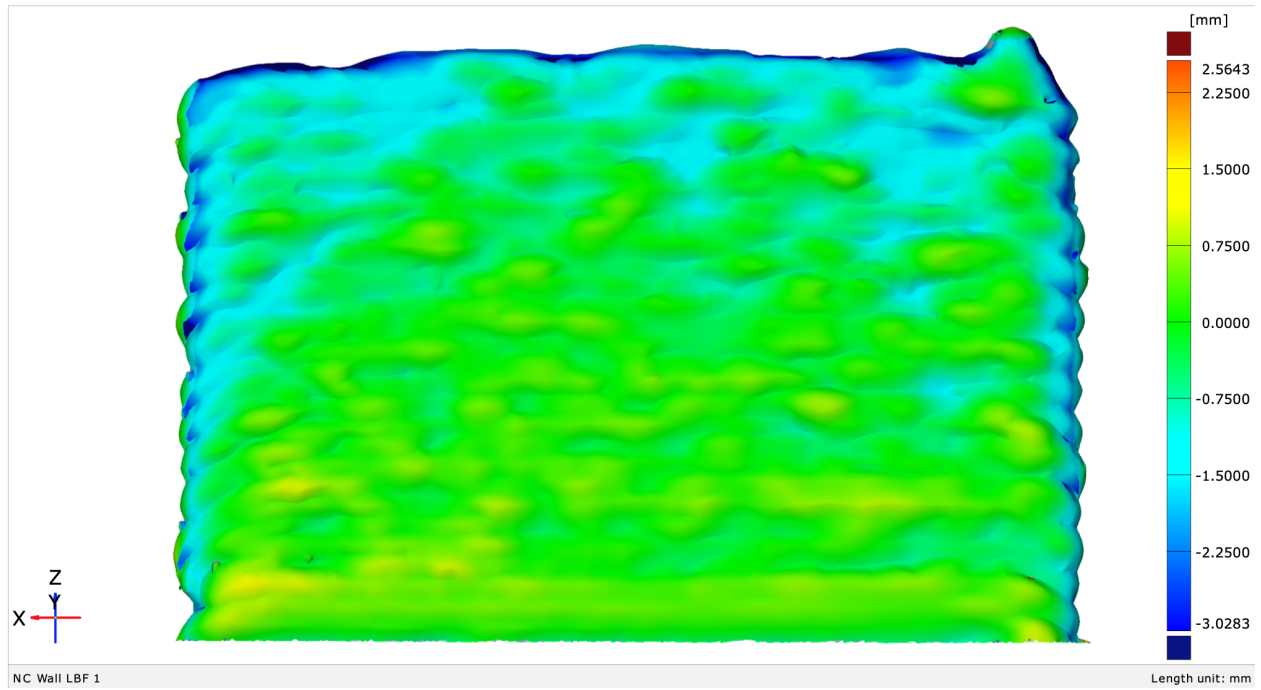


(a) Uncontrolled Wall

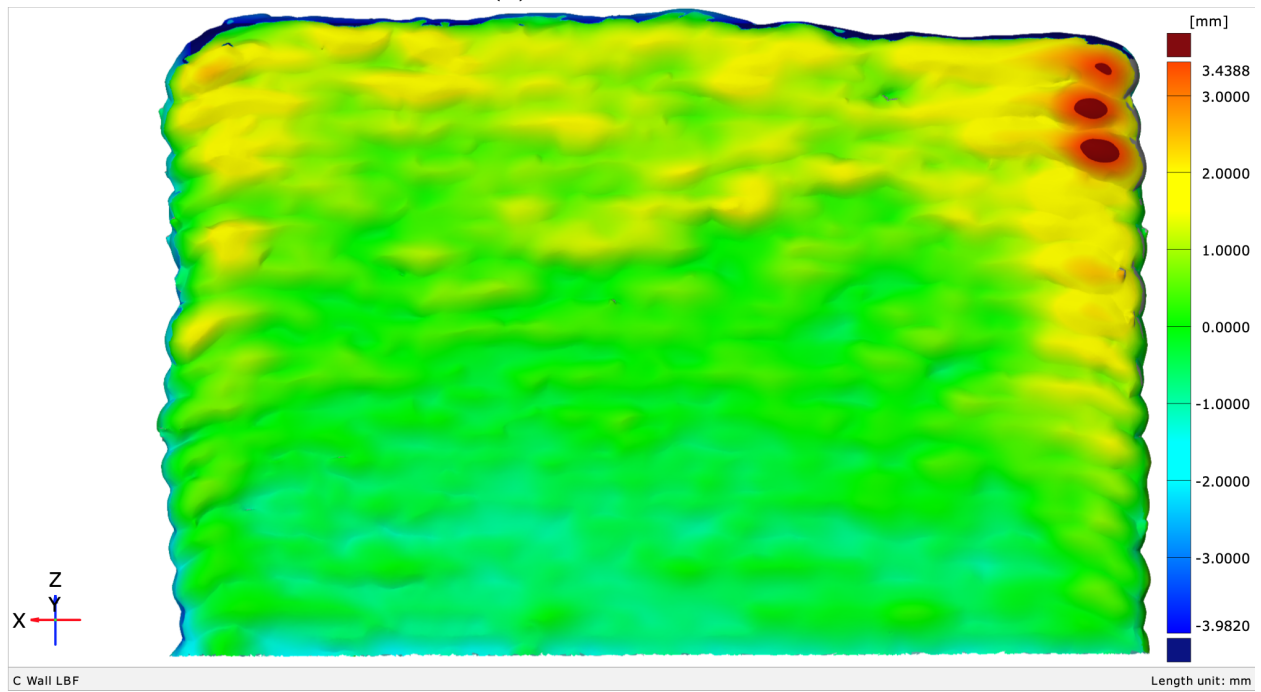


(b) Controlled Wall

Figure 4.22: Surface comparisons of the front surface of 30-layer walls to the desired CAD model

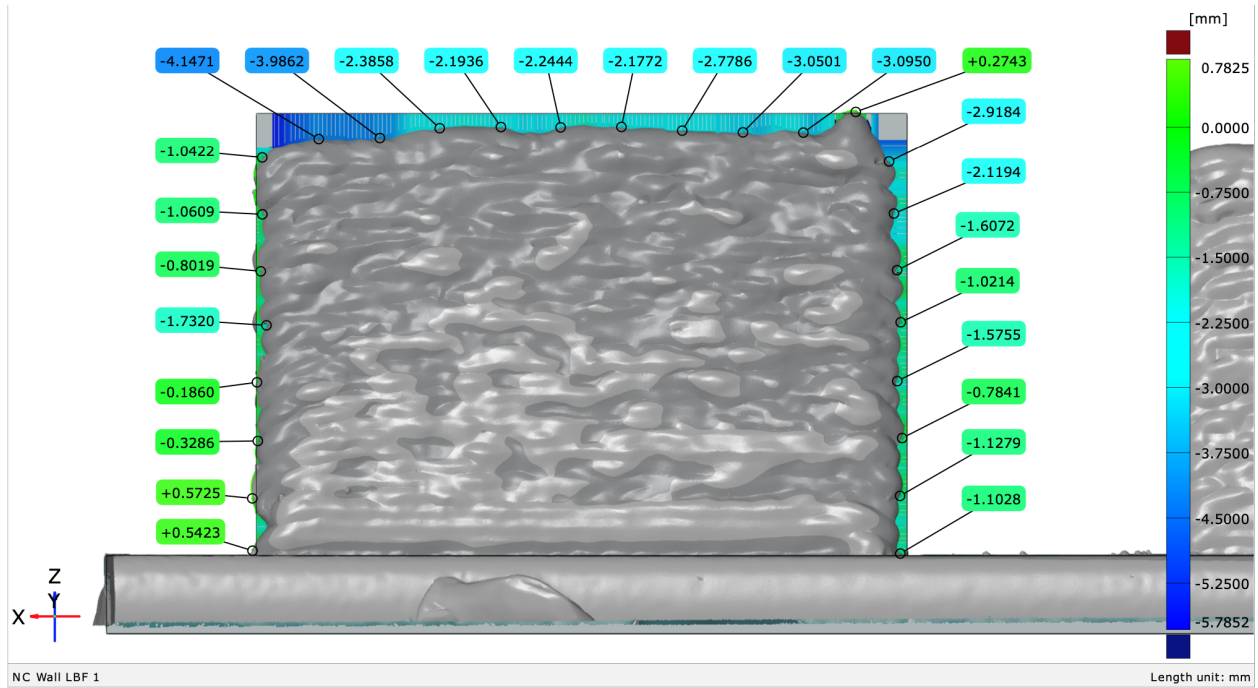


(a) Uncontrolled Wall

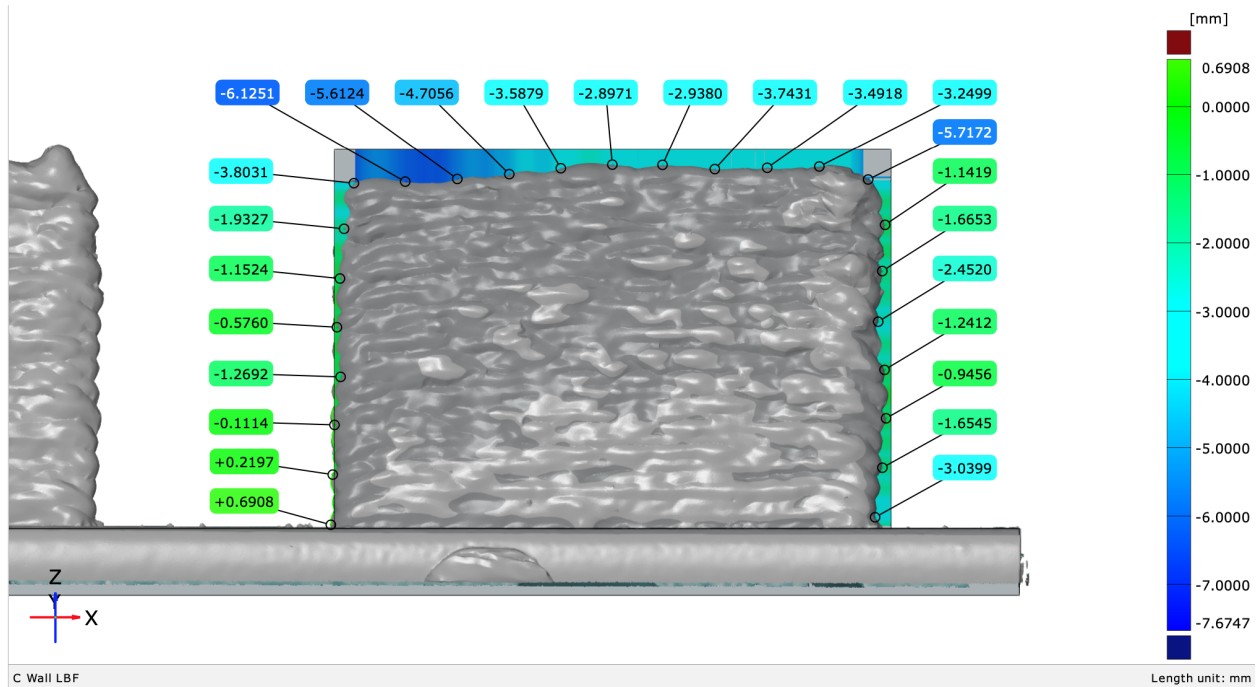


(b) Controlled Wall

Figure 4.23: Surface comparisons of the front surface of 30-layer walls to the desired CAD model



(a) Uncontrolled Wall



(b) Controlled Wall

Figure 4.24: Profile deviations from the desired CAD model at the center-line of the 30-layer walls

While the layer height controlled wall is generally more under-built than the uncontrolled wall, its top surface is more smooth than that of the uncontrolled wall. This can be seen upon a more detailed analysis of each profile as shown in figure 4.25. As shown in the legend of the figure 4.25, the standard deviation of the points along just the top surface of the uncontrolled wall is $\sigma = 1.242\text{ mm}$ while the standard deviation of the points along the top surface of the controlled wall is $\sigma = 1.1214\text{ mm}$. The lower standard deviation indicates a smoother top surface for the controlled wall. This result is consistent with the bead-on-plate results indicating that the layer height control algorithm produces a more consistent layer height regardless of the initially programmed CTWD.

4.5 Validity of Layer Height Control Approach

The experiments conducted using the developed layer height control algorithm and comparing beads and walls built without the controller to beads and walls built with the controller shows that the layer height controller compensates for inaccurate CTWD in a build and improves the quality of the top surface weld beads in WAAM. The uncompensated under-build seen in both the controlled and uncontrolled 30-layer walls can generally be attributed to an inaccurate model of the steady-state layer height. If this is improved, the layer height controller should maintain the desired layer height and also, as already shown, maintain a smooth surface on the top layer of the part, which is central to being able to build large multi-layer parts while assuring that the resulting near net shape properly contains the CAD part design.

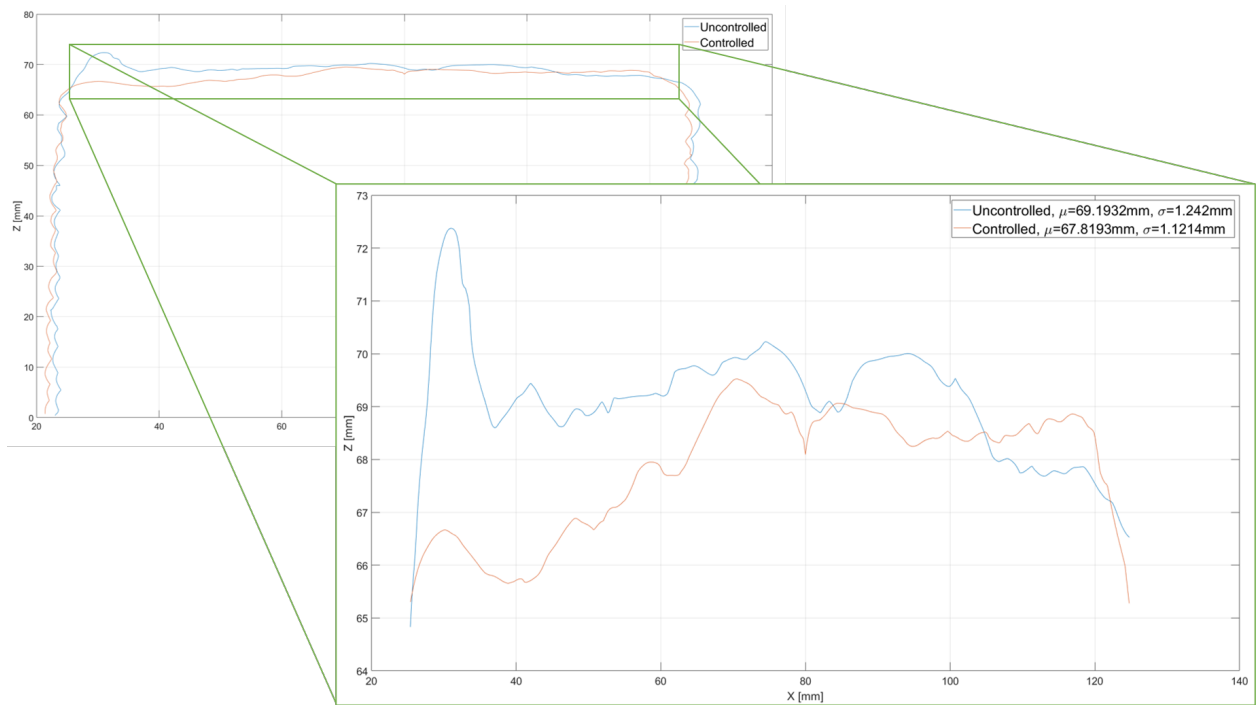


Figure 4.25: Comparison of the top surfaces of the controlled and uncontrolled walls

Chapter 5

Weld Bead Shape Control in NGA WAAM

5.1 NGA Effects on Bead Geometry

As discussed in chapter 3, the shape of the deposited weld bead is dependent upon the inclination of the base material relative to the direction of gravity and the angle of the welding torch relative to the base material. From the understanding of the force balance on the weld pool as well as previous experiments, it was found that positioning the weld torch perpendicular to the surface of the inclined base material produced a stable weld bead that is similar in shape to a bead deposited in the fully gravity aligned orientation.

Here, the gravitational and torch orientation effects on the shape of the weld bead are further examined and a method of determining the shape of the weld bead during deposition is developed. By determining the state of the weld bead shape during deposition, control action can be taken to correct for deviations in the bead shape from the desired profile.

5.2 Monitoring NGA Bead Geometry

To monitor the shape of the weld bead during deposition, a MicroEpsilon 2500-50 red laser profilometer [23] is mounted to the robot end effector in-line with the welding torch (see figure 5.1). With the profilometer in this configuration, the profile of the weld bead can be

measured when welding, but only in a single travel direction. To measure the weld bead profile in any travel direction, either multiple profilometers would need to be mounted to the robot, or a part positioner could be used to rotate the workpiece to allow the torch and profilometer to remain in a constant orientation relative to the travel direction.

Figure 5.1 also shows that there is a 48.48 mm gap between the welding torch tip and the center of the profilometer field of view. With a typical welding travel speed of 6.5 in min^{-1} , that equates to a time delay of 17.6 s between the active weld pool deposition and the sensed profile data. The delay between the active welding process and the sensor data is most evident at the beginning of a weld bead, as it takes approximately 17 s before the current weld bead is visible in the profilometer field of view. In a bead shape control system, this delay (particularly when the weld bead is out of the profilometer field of view) would require the controller to either predict the current bead shape based on the inclination angle and planned torch orientation or run in an open-loop state. For a shallow inclination angle, open-loop control may be appropriate as the gravitational effect on the weld pool is more limited. But, for a larger inclination angle, a predictor may be necessary, possibly monitoring the voltage and current of the welding process to check for process stability.

There are three cases of torch, profilometer, and base material orientation to consider to align the profilometer data for analysis. The first case, presented in figure 5.2, is the fully gravity aligned orientation. Here, the inclination angle (ϕ) of the base plate is zero. As can be seen in figure 5.2, the tool direction of the robot is its x-direction (shown by X_{robot}). In this fully gravity aligned case, the tool direction of the robot is aligned with the z-direction of the base coordinate system (Z_{base}). The coordinate system of the profilometer is rotated 90° from the robot coordinate frame, and thus is fully aligned with the base coordinate system in this orientation.

Next is the fully non-gravity aligned orientation (see figure 5.3). In this case, the inclination angle is non-zero, which, as discussed previously, causes a change in the bead shape due to the re-orientation of the weld pool surface relative to the gravity vector. As this case is fully non-gravity aligned, the welding torch is also re-oriented into a non-gravity aligned orientation. For path planning purposes in WAAM, the ideal non-gravity aligned torch orientation is the same as that of the fully gravity aligned case; where the

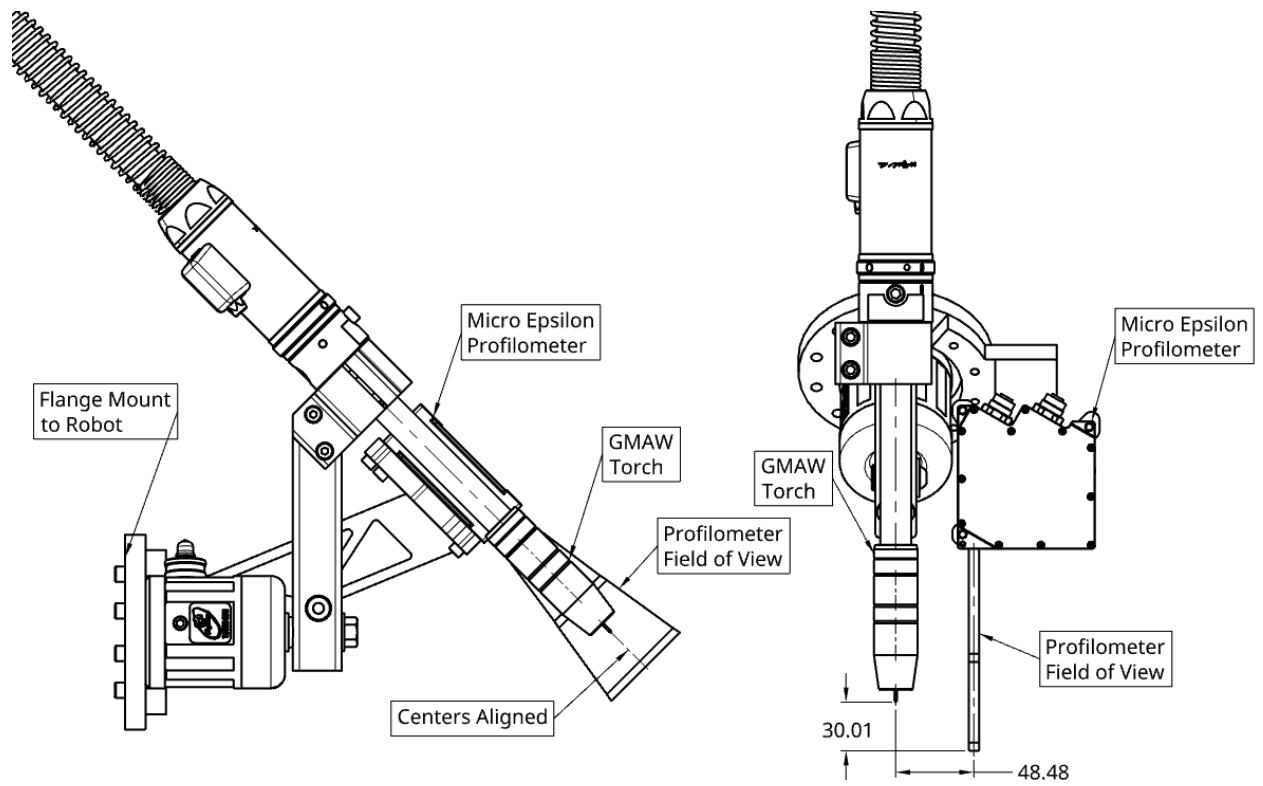


Figure 5.1: Geometric relationship between the welding torch and the profilometer measuring area (dimensions in mm)

tool direction of the robot is aligned with the z-direction of the base coordinate system. Since the orientation of the profilometer coordinate system is constant relative to the robot coordinate frame, the profilometer coordinate frame has the same orientation relative to the base coordinate frame as in the fully gravity aligned case.

Finally, figure 5.4 shows a case where the tool direction of the robot is not aligned with the z-direction of the base plate. In the particular case shown here, the torch is in a gravity aligned orientation while the plate is angled at an inclination angle (ϕ). Since the robot coordinate frame is not aligned with the base coordinate frame, and the profilometer coordinate frame maintains a fixed orientation with respect to the robot coordinate frame, the profilometer coordinate frame is also not aligned with the base coordinate frame.

In order to compare data collected in all three of these cases, the orientation of the profilometer coordinate frame must be aligned with the base coordinate frame. This can be done by describing the relative orientation of the profilometer frame to the base coordinate frame using a rotation matrix, and applying that matrix to the profilometer data to describe the data points in the base coordinate frame.

It can be seen in figure 5.4, to realign the profilometer coordinate frame with the base coordinate frame, the profilometer coordinate frame must be rotated around the y-axis, as the y-axis of both coordinate frames are aligned. This is also the case with realigning the robot x-direction with the base z-direction, and the angle between the robot x-direction and base z-direction about the common y-direction is the same angle needed to realign the profilometer coordinate frame with the base coordinate frame.

The rotation matrix needed to perform the simple rotation about the y-axis by an angle γ is given in equation (5.1).

$$\mathbf{R}_y(\gamma) = \begin{bmatrix} \cos(\gamma) & 0 & \sin(\gamma) \\ 0 & 1 & 0 \\ -\sin(\gamma) & 0 & \cos(\gamma) \end{bmatrix} \quad (5.1)$$

By treating each data point in the profile as a vector represented in the profilometer coordinate frame, $\mathbf{p}' = [p_x p_y p_z]$, then each data point can be rotated into the base coordinate

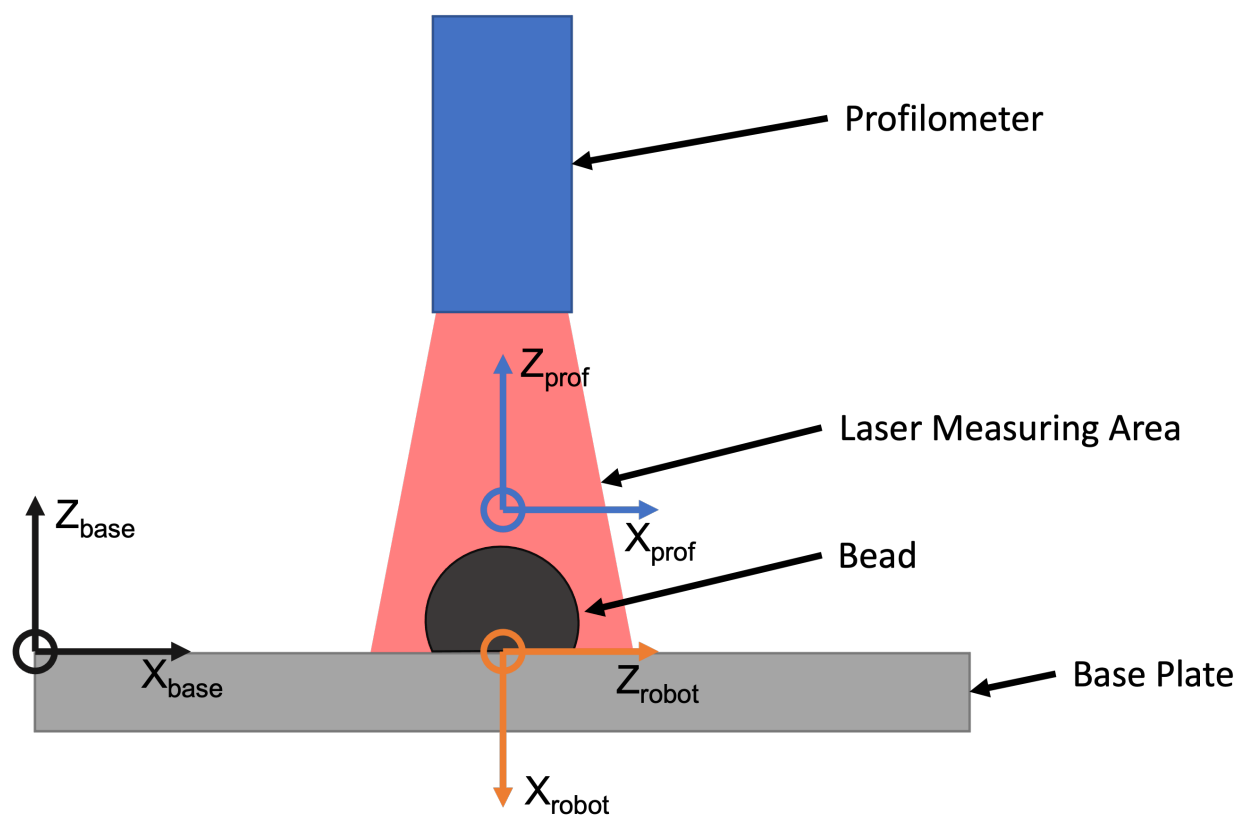


Figure 5.2: Profilometer orientation when both the base plate and torch are in the gravity aligned orientation

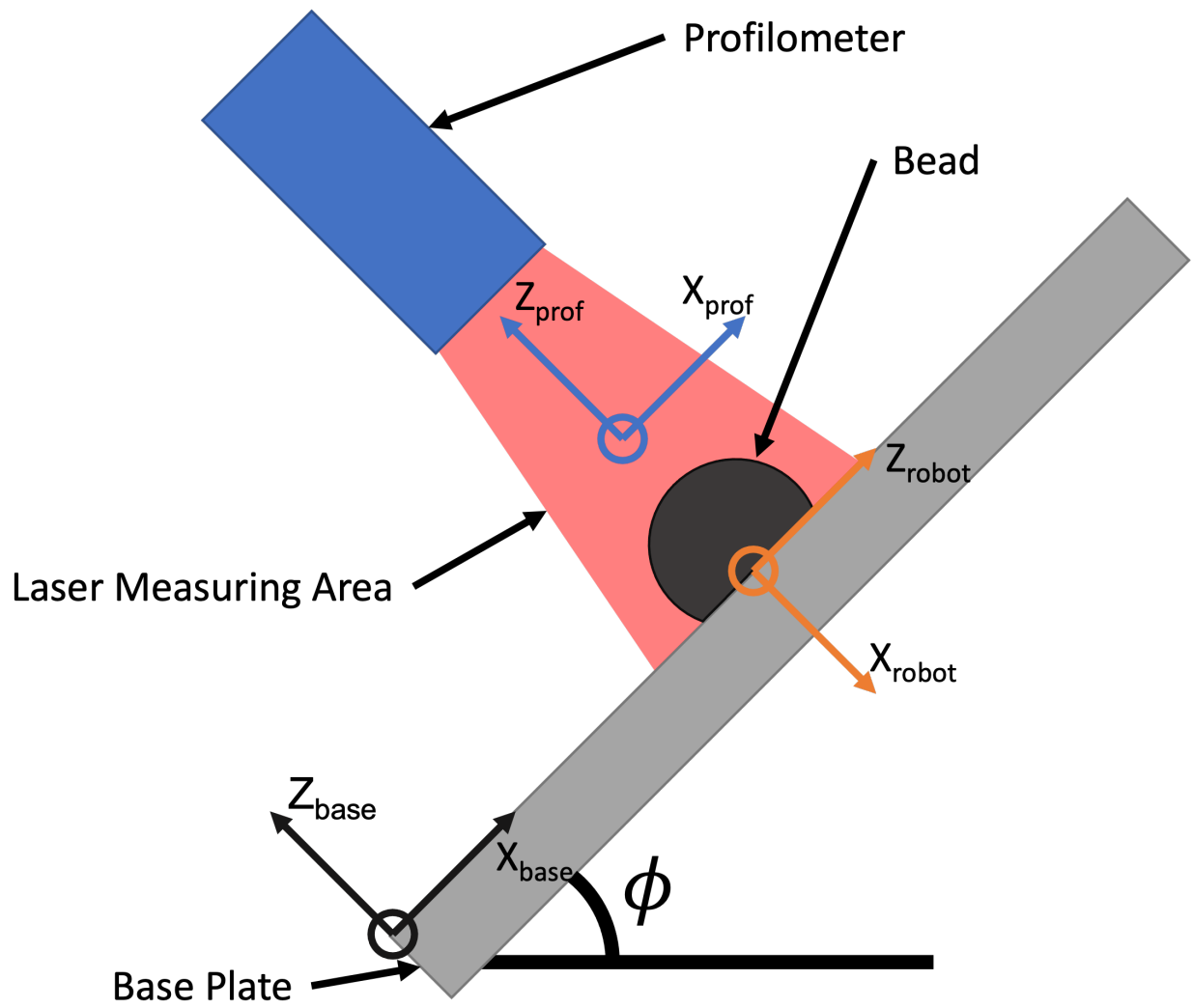


Figure 5.3: Profilometer orientation when the base plate and torch are both incline at an angle ϕ

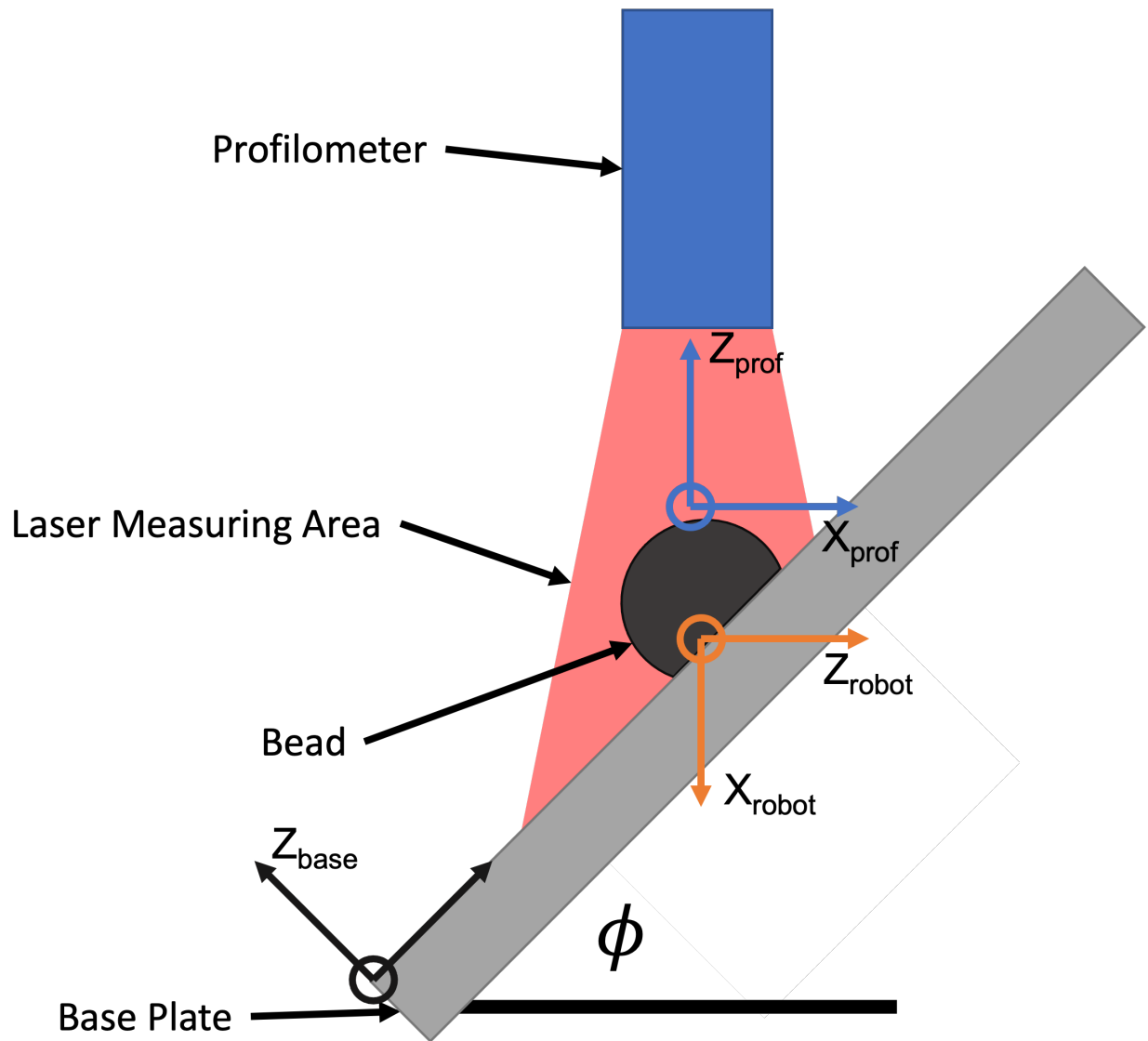


Figure 5.4: Profilometer orientation when the base plate is inclined at an angle ϕ and the torch is left in a gravity aligned orientation

frame using the following:

$$\mathbf{p} = \mathbf{R}_y(\gamma)\mathbf{p}' \quad (5.2)$$

The rotation angle γ is found using the KUKA Robot-Sensor Interface package mentioned in chapter 4. This software package allows for the monitoring of the position of the robot tool coordinate system relative to the currently active robot base coordinate system. The base coordinate system of the robot is calibrated to the base plate to give a base coordinate system orientation as shown in figures 5.2 to 5.4.

By applying equation (5.2) to all data points pulled directly from the profilometer, the profiles are analyzed in the same coordinate frame regardless of torch orientation relative to the base plate. This rotated data will be used to determine if the bead shape is changing due to gravitational effects as the inclination angle changes.

5.3 Experimental Results

A series of experiments were executed to test the validity of using the profilometer in-situ for measuring the shape of the deposited weld bead. The primary metric to used determine deviation the deviation from the desired bead shape is the centroid of the bead profile.

To find the centroid of the bead, several steps are taken. First, the entire profile is rotated using equation (5.2). Then, the first point in the profile is set to zero and all other points in the profile are offset by the original values of the first data point. This ensures a common coordinate system for all of the profiles to more easily compare the location of the found centroids. Next, the gradient of the profile is taken to determine the points at which the the bead begins and ends in the profile. Finally, using only the data between the start and end points of the bead, average x and y values are found between two data points. For the x value, this is a simple average taken over the two points. For the z value, the z values of the two points are averaged and then averaged with the mean height of the plate (the plate being the regions of the profile not between start and end points of the bead). This is done for every profile captured during the deposition of a bead and then the average centroid of the bead is determined by averaging the the centroids of all measured profiles.

Three sets of weld beads were deposited at different inclination angles to observe the profile. First, three control beads were deposited in the fully aligned orientation. These beads serve as the desired weld bead shapes and develop an operating window based on any slight deviations between the three beads. The profiles, centroids, and average centroid as measured by the profilometer can be seen in figures 5.5 to 5.7.

The next beads, seen in figures 5.8 to 5.12, are deposited on a plate inclined at an angle of 45° . For beads one and two (figures 5.8 and 5.9 respectively), the torch was positioned in the full non-gravity aligned orientation with the tool direction of the robot aligned with the z-direction of the base frame. The next two beads (figures 5.10 and 5.11) were deposited with a 15° angle between the robot x-direction and the base z-direction. This orientation tests if the droplet impact force can push the weld bead geometry up the inclined surface of the plate to counteract the gravitational force on the weld pool. The final bead (figure 5.12) is deposited with a gravity aligned torch (i.e. the x-direction of the robot coordinate frame is aligned with the global z-direction, which is also aligned with the gravitational vector).

This same pattern of torch alignments is repeated with the base plate at 65° . The fully non-gravity aligned orientation can be seen in figures 5.13 and 5.14, the 15° offset orientation in figures 5.15 and 5.16, and the gravity aligned torch orientation in figure 5.17.

It can be seen from the presented profiles that the orientation of the profilometer relative to the weld bead has a significant impact on the detected bead shape and the resulting calculated centroid. This is particularly evident in figures 5.12 and 5.17. In both of these cases, with the torch gravity aligned, the underside of the weld bead is obstructed by the weld bead peak. This is illustrated in figure 5.4. This results in almost half of the bead geometry being obstructed from the view of the profilometer, which leads to a skewed calculation of the weld bead centroid. As it has been determined that, when welding on an inclined surface, it is best practice to position the torch perpendicular to the surface, this case should not occur in practice.

After calculating the average centroid for each bead, the average centroids are analyzed to determine what effect plate inclination angle and torch angle have on the shape of the weld bead. First, the fully non-gravity aligned orientation is analyzed (see figure 5.18). The centroids of the beads deposited on a 45° incline have shifted downhill in the x-direction

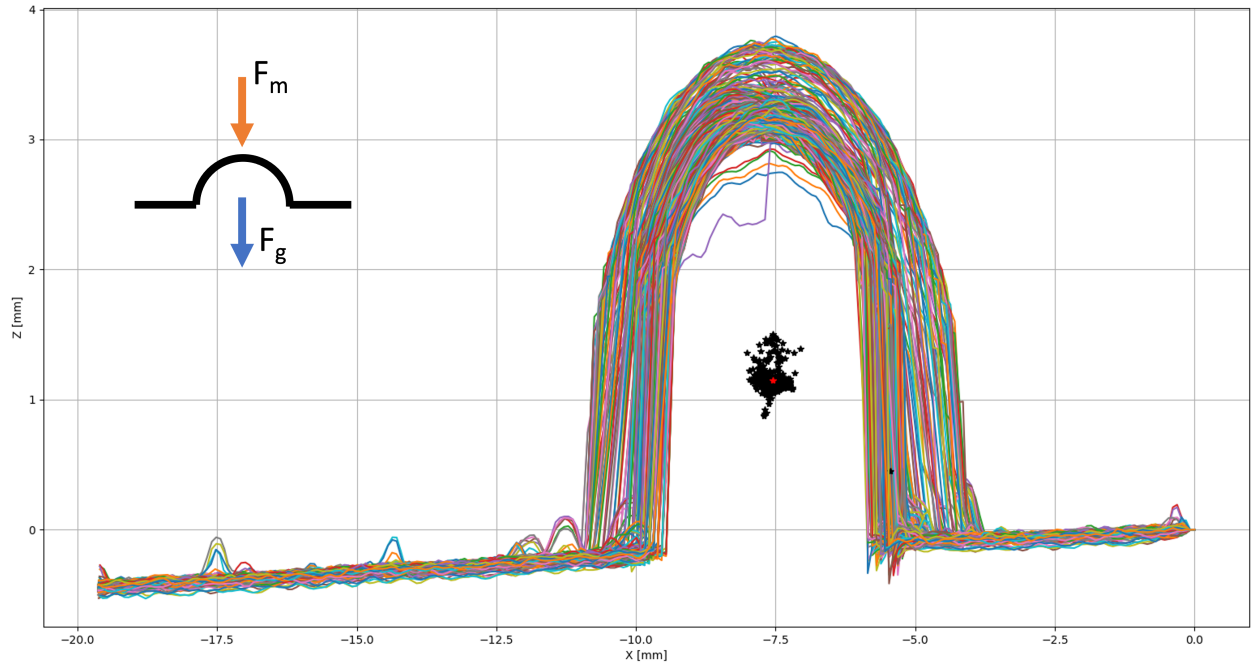


Figure 5.5: Control bead one, deposited in the fully gravity aligned orientation with calculated average centroid of $X = -7.55$ mm and $Z = 1.15$ mm

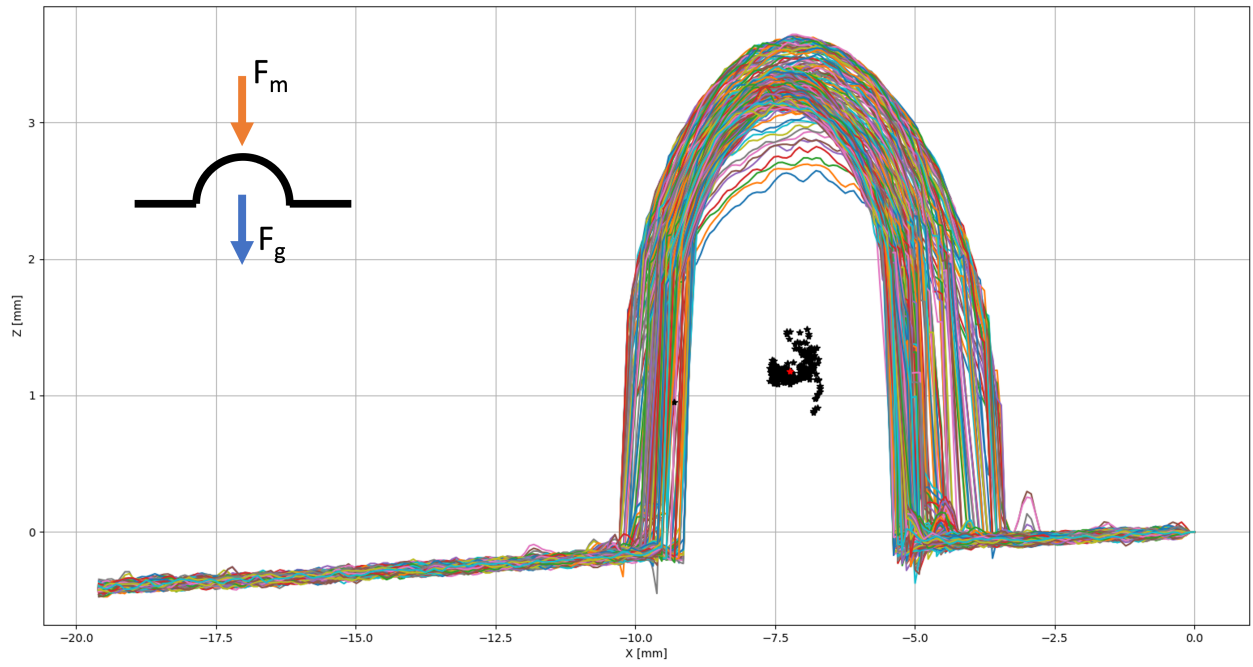


Figure 5.6: Control bead two, deposited in the fully gravity aligned orientation with calculated average centroid of $X = -7.23$ mm and $Z = 1.18$ mm

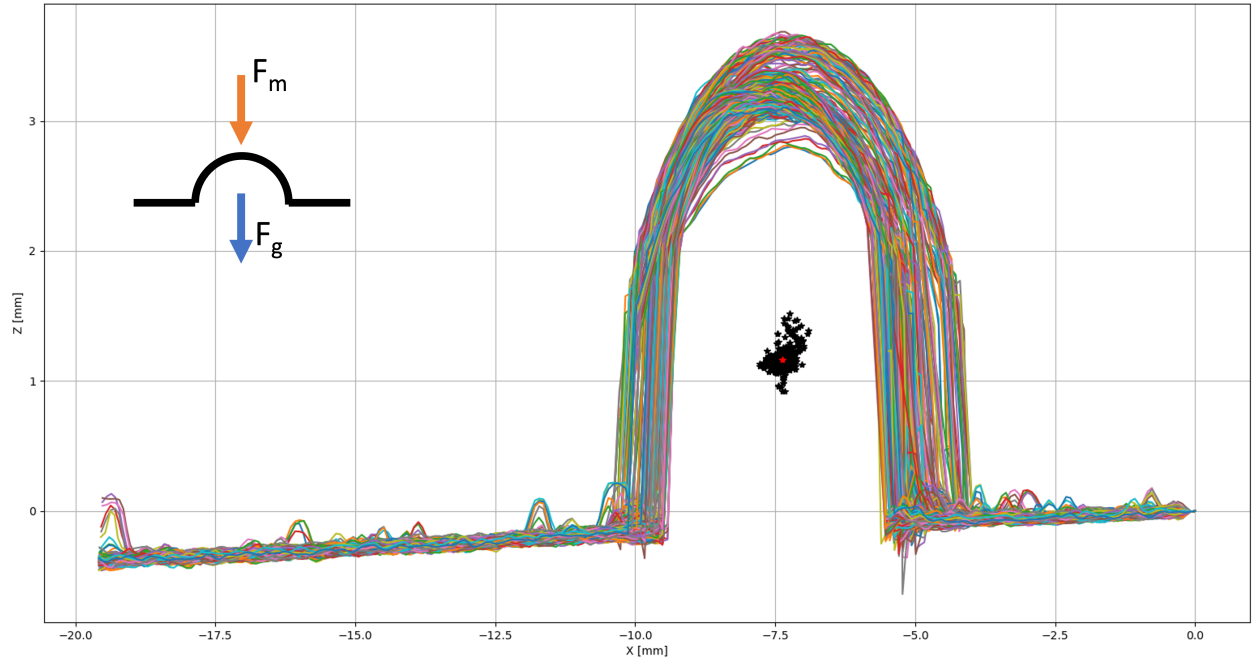


Figure 5.7: Control bead three, deposited in the fully gravity aligned orientation with calculated average centroid of $X = -7.38$ mm and $Z = 1.16$ mm

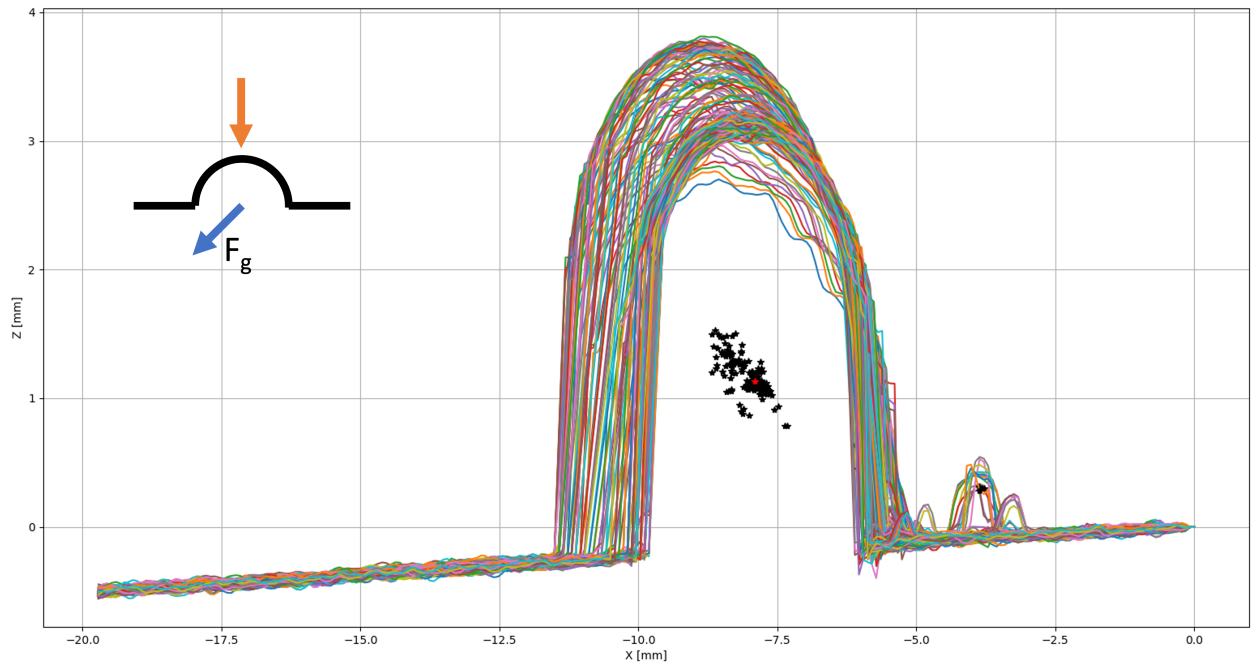


Figure 5.8: 45° bead one, deposited in the fully non-gravity aligned orientation with calculated average centroid of $X = -7.91$ mm and $Z = 1.13$ mm

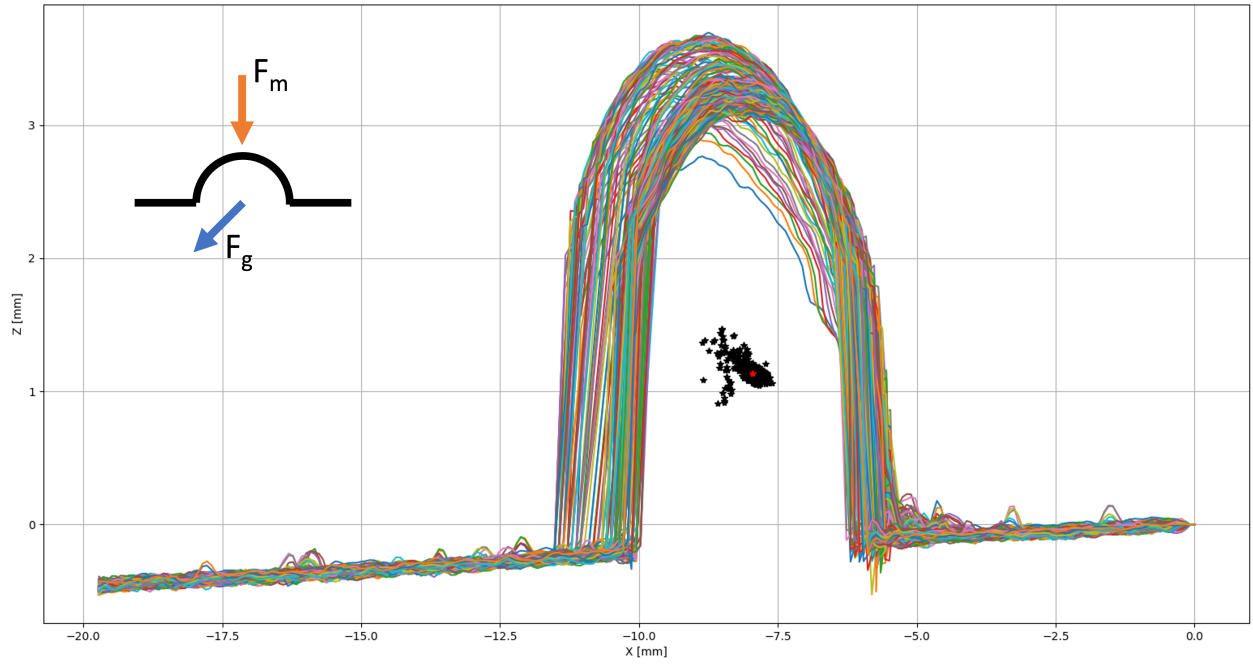


Figure 5.9: 45° bead two, deposited in the fully non-gravity aligned orientation with calculated average centroid of $X = -7.96$ mm and $Z = 1.13$ mm

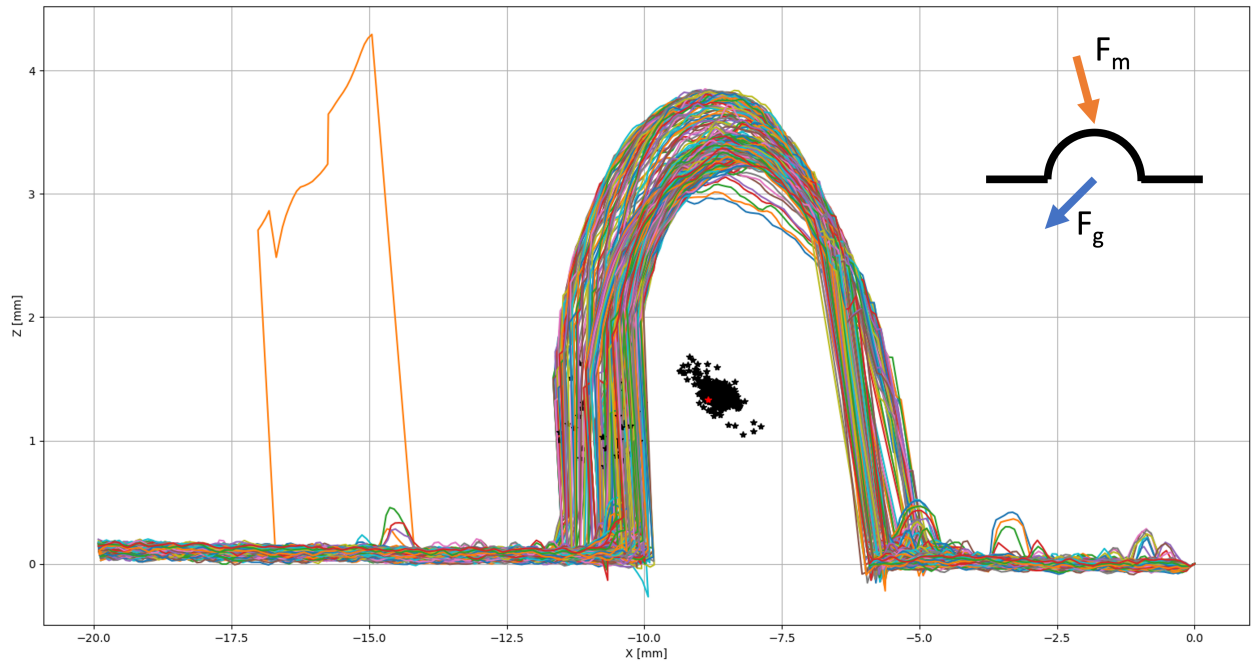


Figure 5.10: 45° bead three, deposited with a torch offset of 15° with calculated average centroid of $X = -8.83$ mm and $Z = 1.33$ mm

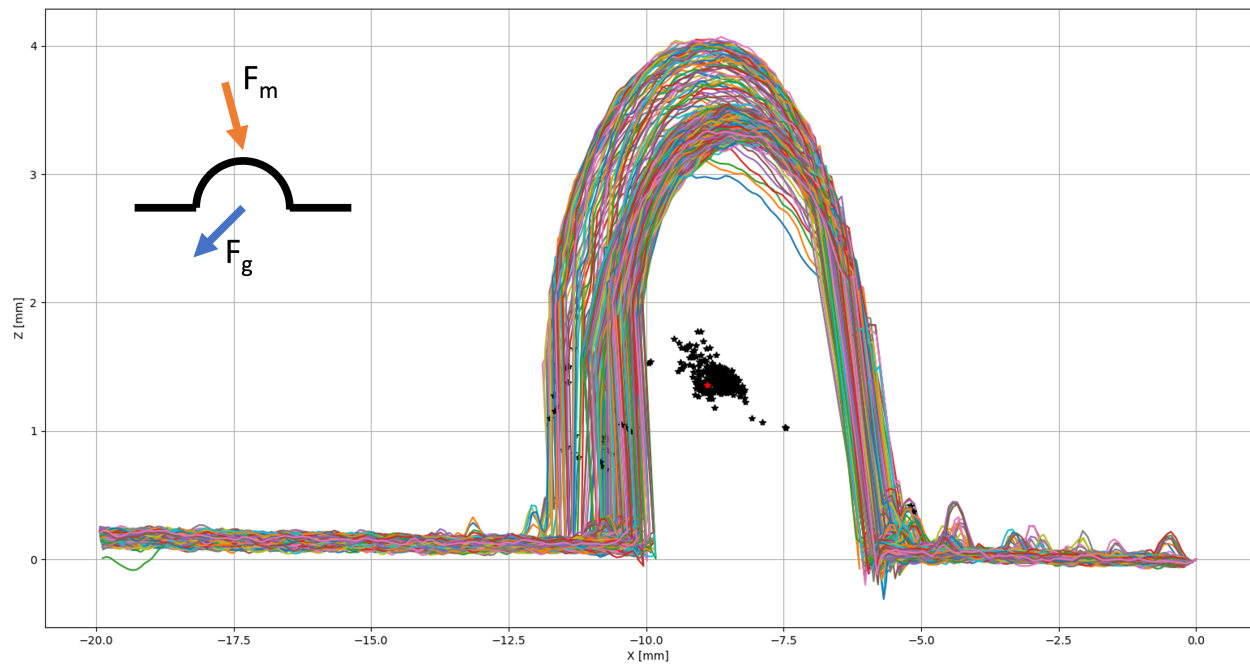


Figure 5.11: 45° bead four, deposited with a torch offset of 15° with calculated average centroid of $X = -8.89$ mm and $Z = 1.36$ mm

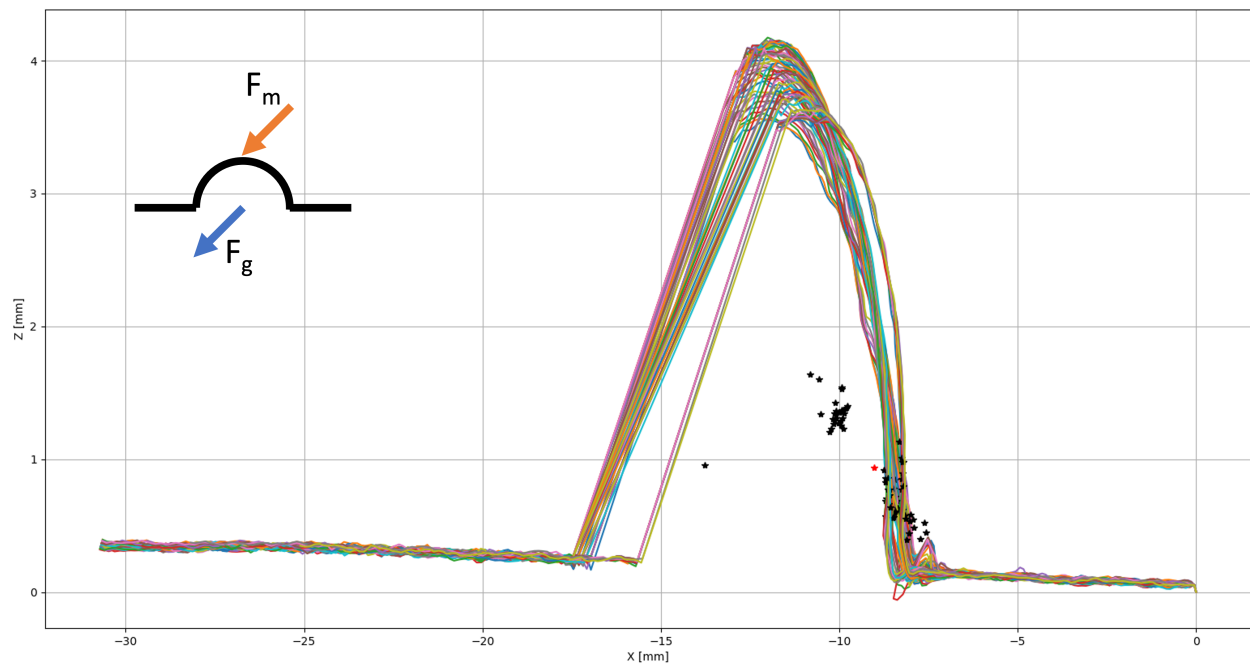


Figure 5.12: 45° bead five, deposited with the torch in a gravity aligned orientation with calculated average centroid of $X = -9.03$ mm and $Z = 0.93$ mm

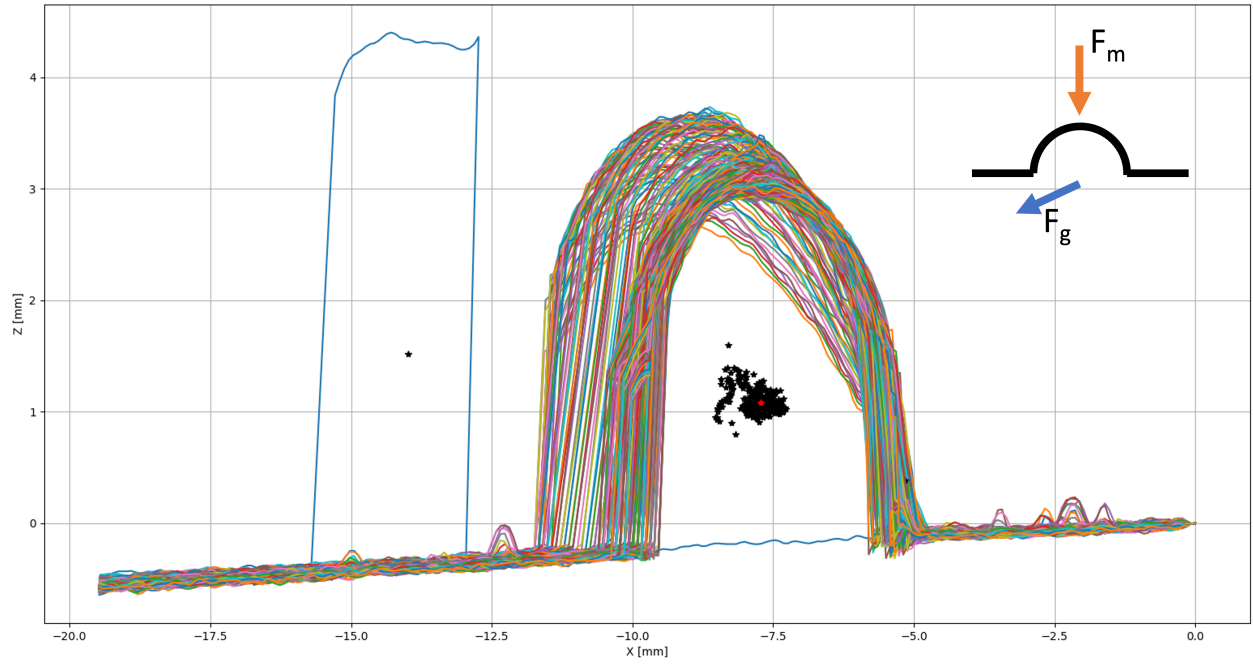


Figure 5.13: 65° bead one, deposited in the fully non-gravity aligned orientation with calculated average centroid of $X = -7.73$ mm and $Z = 1.08$ mm

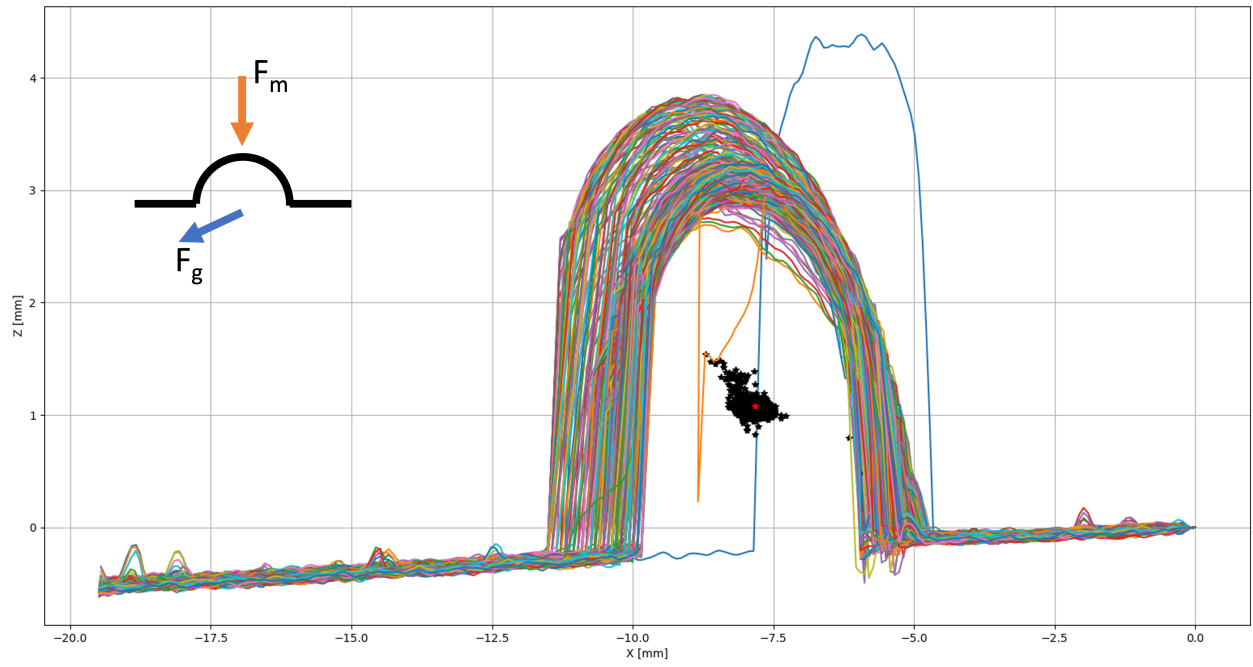


Figure 5.14: 65° bead two, deposited in the fully non-gravity aligned orientation with calculated average centroid of $X = -7.82$ mm and $Z = 1.08$ mm

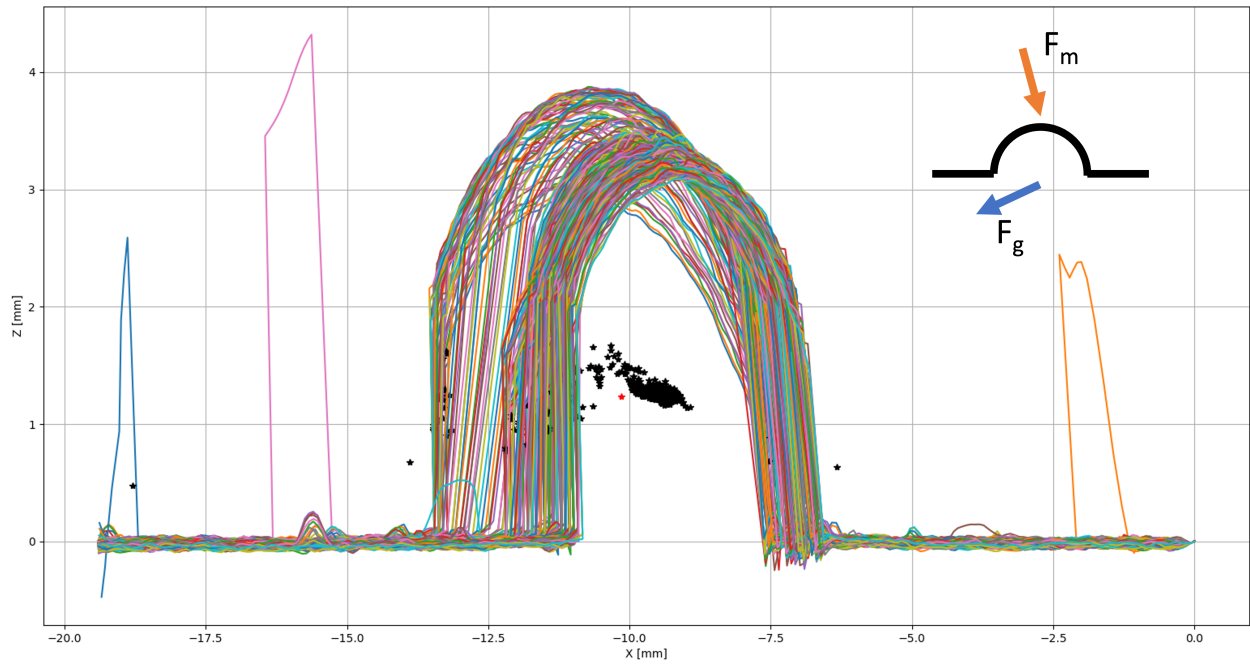


Figure 5.15: 65° bead three, deposited with a torch offset of 15° with calculated average centroid of $X = -10.15$ mm and $Z = 1.24$ mm

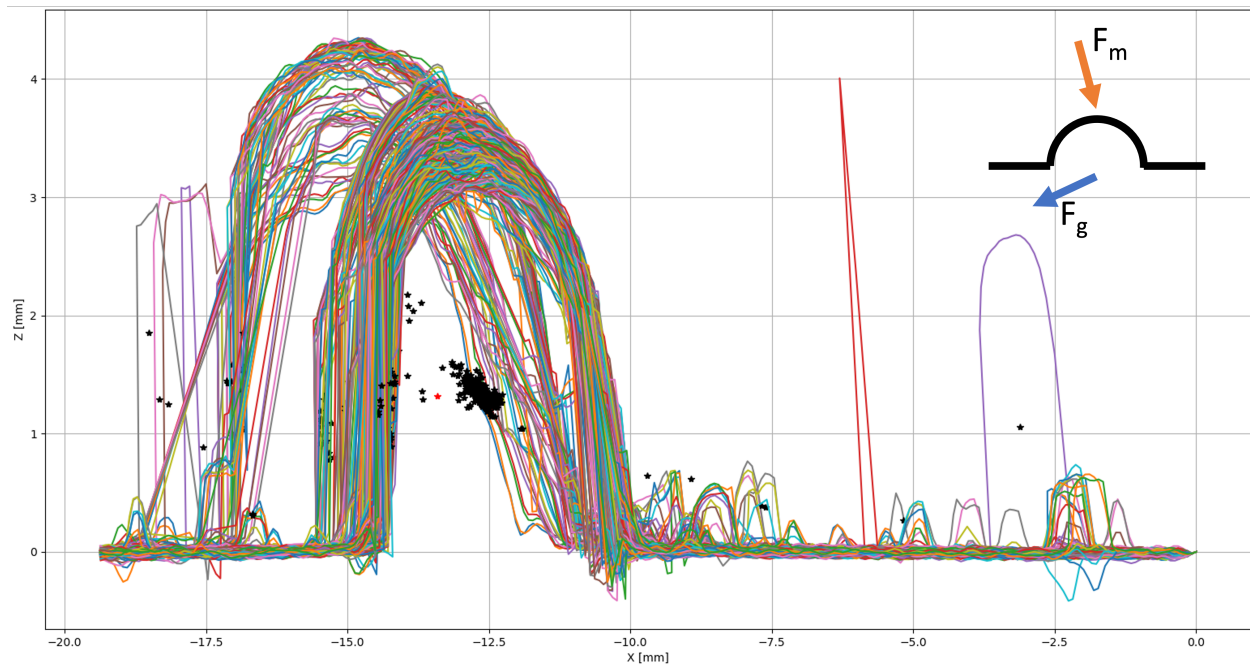


Figure 5.16: 65° bead four, deposited with a torch offset of 15° with calculated average centroid of $X = -13.41$ mm and $Z = 1.32$ mm

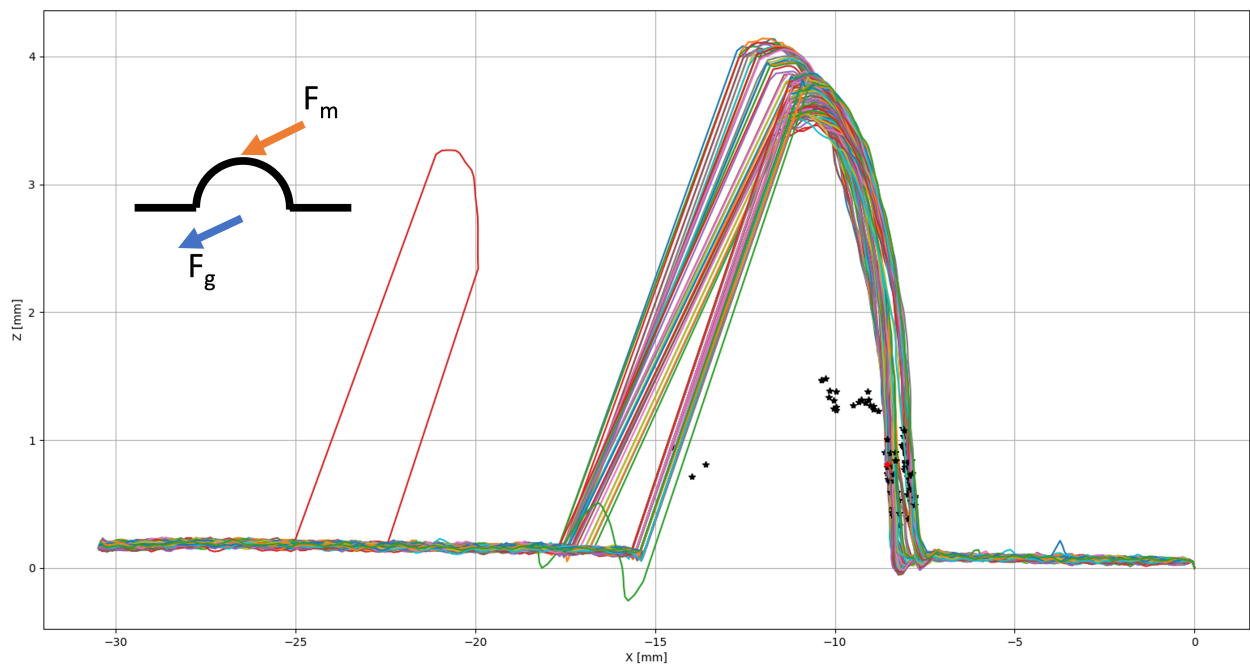


Figure 5.17: 65° bead five, deposited with the torch in a gravity aligned orientation with calculated average centroid of $X = -8.54$ mm and $Z = 0.81$ mm

(towards the direction of gravity) and also shifted down in the z-direction. The same occurs in the case of the 65° incline, but the shift in the z-direction is more significant than that of the 45° inclined plate due to the steeper inclination angle.

The beads deposited with a 15° offset shift in a different way than those deposited in the fully non-gravity aligned orientation. Here, the centroids of the beads deposited on inclined base plates again shifted downhill in the x-direction from the control beads, but the z-position of the centroids is now higher than those of the control beads. For the 65° walls, the shift in the x-direction is much greater than that of the 45° walls. This is most likely due to curvature in the welding wire (remnant cast as a result of the wire being stored on a spool) and the wire contacting the base plate below the desired path. The different shift in centroid, as compared to the purely NGA orientation, indicates that re-orienting the torch, and thus the direction of the droplet momentum exchange force, the bead shape can be manipulated.

Finally, the centroids for the beads deposited with a gravity aligned torch show the greatest total deviation in the z-direction from the centroids of the control beads. Such a low z-location of the centroid indicates that the weld bead has flowed and become wider while maintaining the same cross-sectional area. This change in layer height is a major issue for WAAM as maintaining a consistent layer height is key to process stability and geometric accuracy. This once again shows that to deposit consistently shaped weld beads on an inclined surface, it is best practice to re-orient the welding torch to manipulate the force balance acting on the weld pool surface.

5.4 Controlling the NGA Weld Bead

The results presented here show that it is possible to control the shape of the weld pool through manipulating the orientation of the welding torch relative to the substrate on which the weld be is deposited. This stems from the force balance that occurs at the surface of the weld pool. The gravitational direction is fixed in space and its effect on the weld pool is directly correlated to the inclination angle of the substrate. By re-orienting the welding torch, the direction of the droplet impact force is changed. If oriented properly, the components of

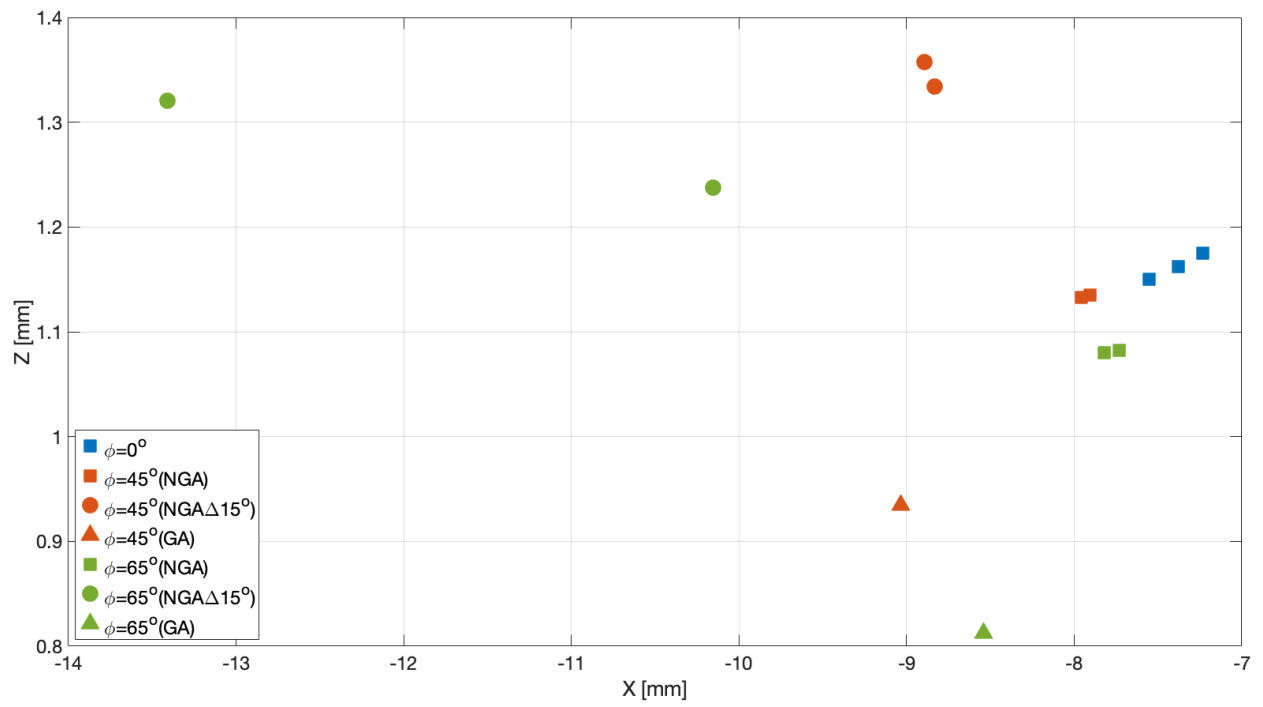


Figure 5.18: Average centroids of all beads.

the droplet impact force can supplement the surface tension of the weld pool to counteract the effect of gravity on the shape of the weld pool.

A possible control structure for this process is shown in figure 5.19. In determining the location of a bead's centroid, it is necessary to first determine if the bead is in the field of view of the profilometer, due to the geometric offset shown in figure 5.1. If the bead is not in the field of view, a process stability model should be implemented to analyze the voltage and current for indications of long arcing or other process instabilities. If no instabilities are detected, this model should instruct the controller to maintain the orientation dictated by the path plan.

Once the bead enters the field of view of the profilometer, the centroid calculation algorithm described above is activated and the calculated centroids are fed into a model relating inclination angle, torch orientation, and centroid location. To determine if correctional action is needed, the centroid locations are compared to a desired centroid location based on a desired bead shape. If the centroid of the current bead is within a prescribed error range of the desired bead shape centroid, then no correctional action is taken. If outside the prescribed range, the model will provide a new torch orientation, which is sent to the robot. Closing the loop in this way extends the current capabilities of WAAM for more complex parts while maintaining geometric accuracy and process stability.

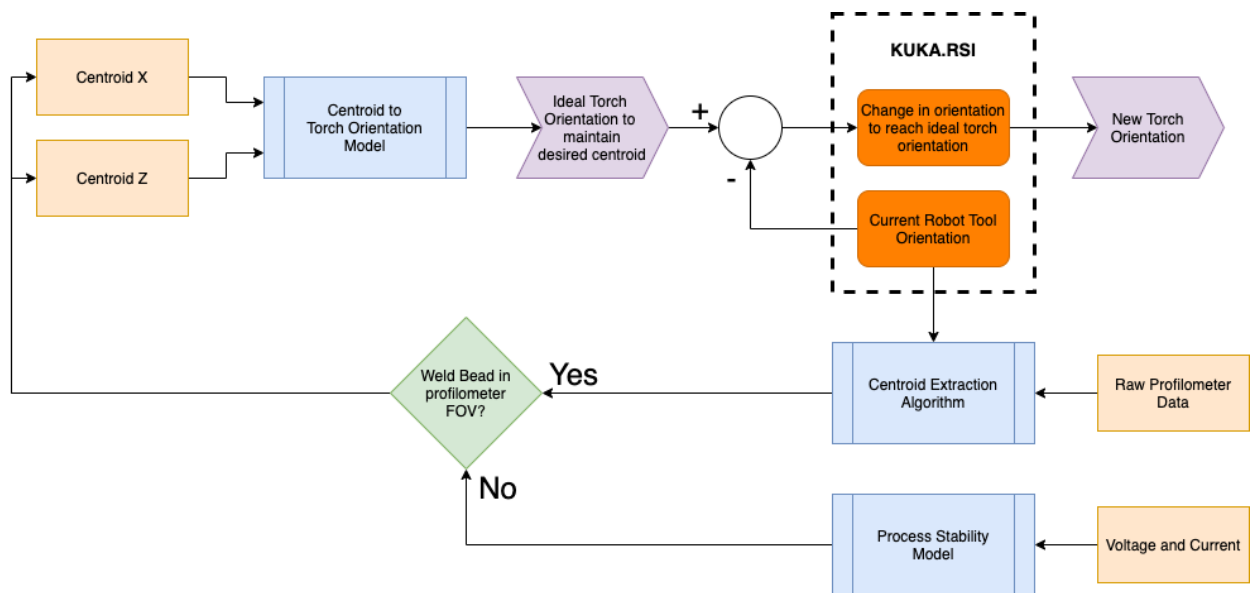


Figure 5.19: Theoretical control structure for bead shape control based on centroid detection

Chapter 6

Open Loop Thermal Evolution Monitoring

Another determining variable in the stability of the WAAM process is interpass temperature. Interpass temperature is the temperature of the previous layer at the start of deposition for the current layer. This temperature plays an important role in dictating how a new layer will be deposited. If the interpass temperature is too high, the new layer may penetrate too deep into the previous layer causing the new layer to be under-built and, in the worst case, causing too much heat to be injected into the part resulting in a part melt down. In WAAM, it is common to wait an arbitrary amount of time for the part to cool between layers, often referred to as the interpass wait time. While implementing an interpass wait time typically results in a stable welding process and avoiding a part meltdown, it is not necessarily the most efficient method. In this chapter, a method of thermal monitoring is explored to inform the WAAM process when a desired interpass temperature has been reached and therefore it is appropriate to begin depositing the next layer.

6.1 Thermal Monitoring

The interpass temperature is monitored using a FLIR A35 Thermal camera [42]. The thermal camera will be used to monitor the overall thermal evolution between welding passes of the part or weld beads being deposited. The camera will be mounted in such a way that the

top surface of the part is visible and images will only be acquired when the arc is off so to avoid interference from the arc light. This data will allow for control over the inter-pass wait time and possibly over the grain structure of the part through controlling the thermal cycles acting on the part. An example of a thermal image captured during the WAAM process can be seen in figure [6.1](#).

To examine the effect of interpass wait temperature on the thermal history of a part as well as on the geometry of the part, several 30-layer walls are built with different amounts of wait time between each layer. The wait times used are 30s, 45s, 60s, and 75s. For each wall, the thermal camera is positioned to look down at the top surface of the build. Then, using FLIR's analysis software, a region of interest is drawn around the wall currently being built. This region of interest is analyzed for the maximum temperature of the area for each frame captured by the camera. This maximum temperature is then extracted from the FLIR software and plotted. The plots for each wall can be seen in figures [6.2](#) to [6.5](#).

Using MATLAB, the thermal history of the parts was analyzed and the interpass temperatures are found. The interpass temperature occurs at the local minima of the thermal history curve. When the welding arc is active, it saturates the range of the thermal camera, as the FLIR A35 has a maximum readable temperature of 1200°F.

Once the interpass wait temperatures are extracted, they are plotted on a per layer basis in figure [6.6](#). As expected, longer interpass wait times result in a lower interpass temperature. The layer-to-layer variation in the interpass temperatures is attributed to the travel direction of the welding torch and the starting point of the current layer relative to the camera position. When the welding torch is traveling towards the the thermal camera, the cup of the welding torch briefly obstructs the cameras view of the welding arc, thus delaying the saturation of the maximum temperature measurement. When this occurs, the the top surface of the previous layer has a slightly longer time to cool, thus appearing a a fluctuation in the interpass temperature.

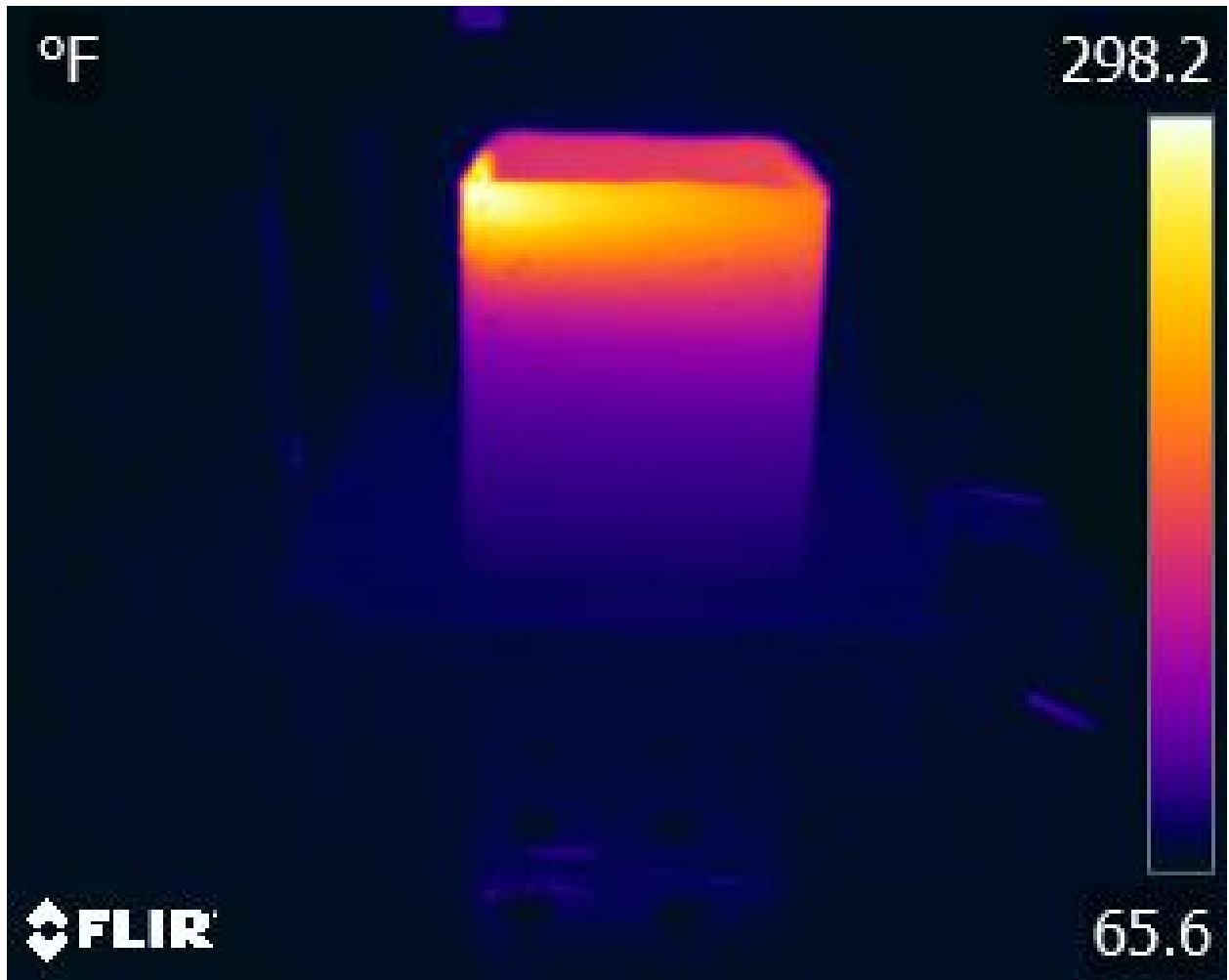


Figure 6.1: Example of thermal layering in Wire Arc Additive Manufacturing

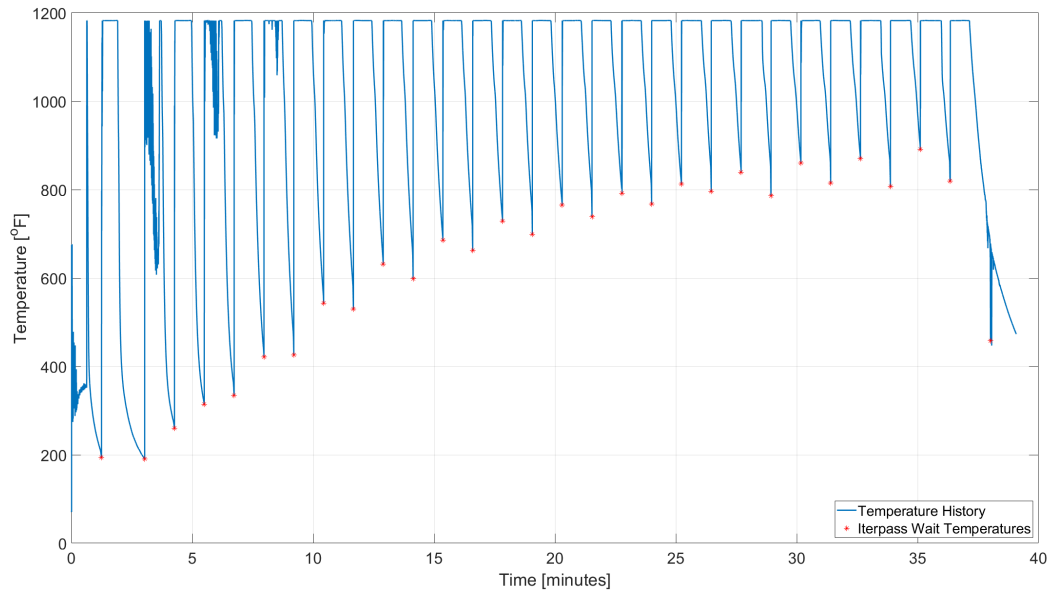


Figure 6.2: Thermal history of a wall with a 30 s interpass wait time

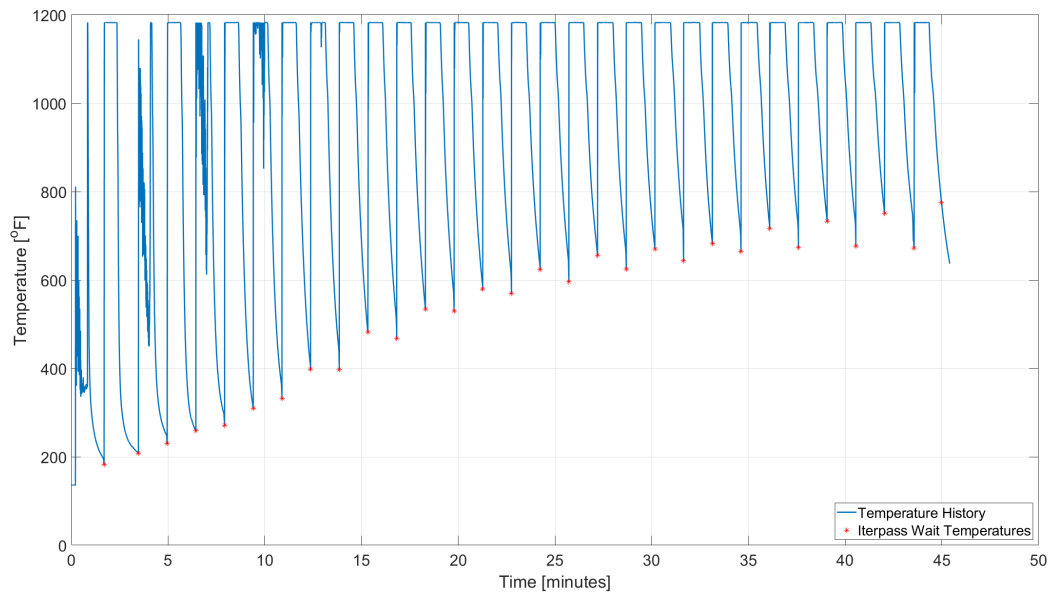


Figure 6.3: Thermal history of a wall with a 45 s interpass wait time

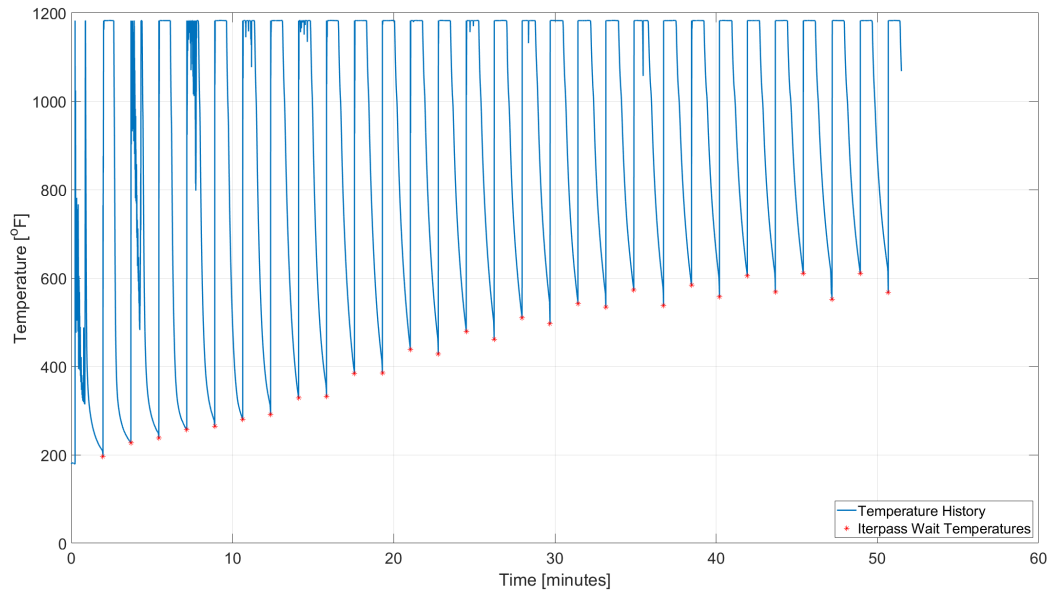


Figure 6.4: Thermal history of a wall with a 60s interpass wait time

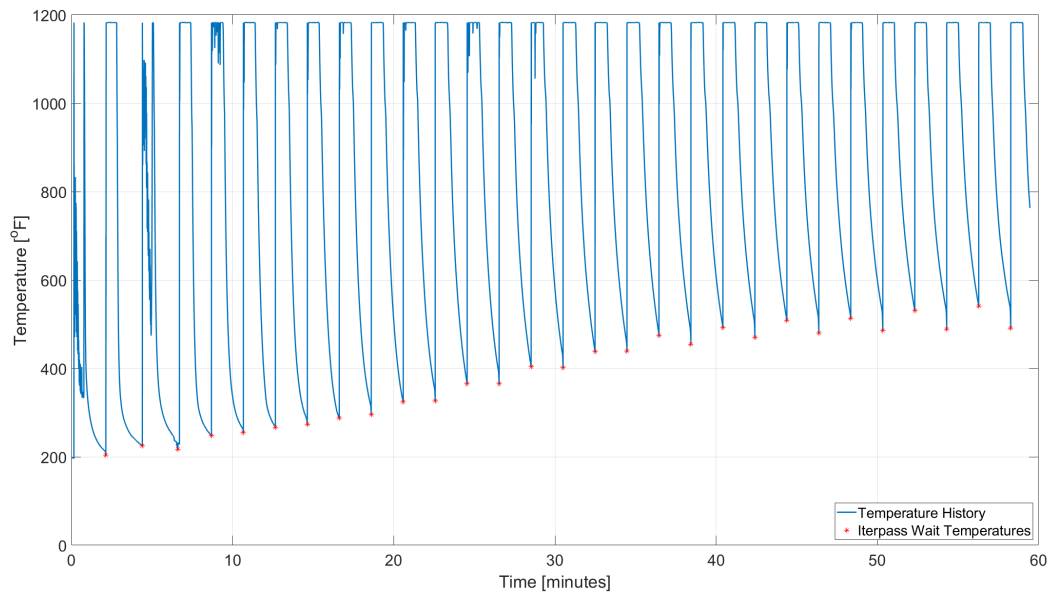


Figure 6.5: Thermal history of a wall with a 75s interpass wait time

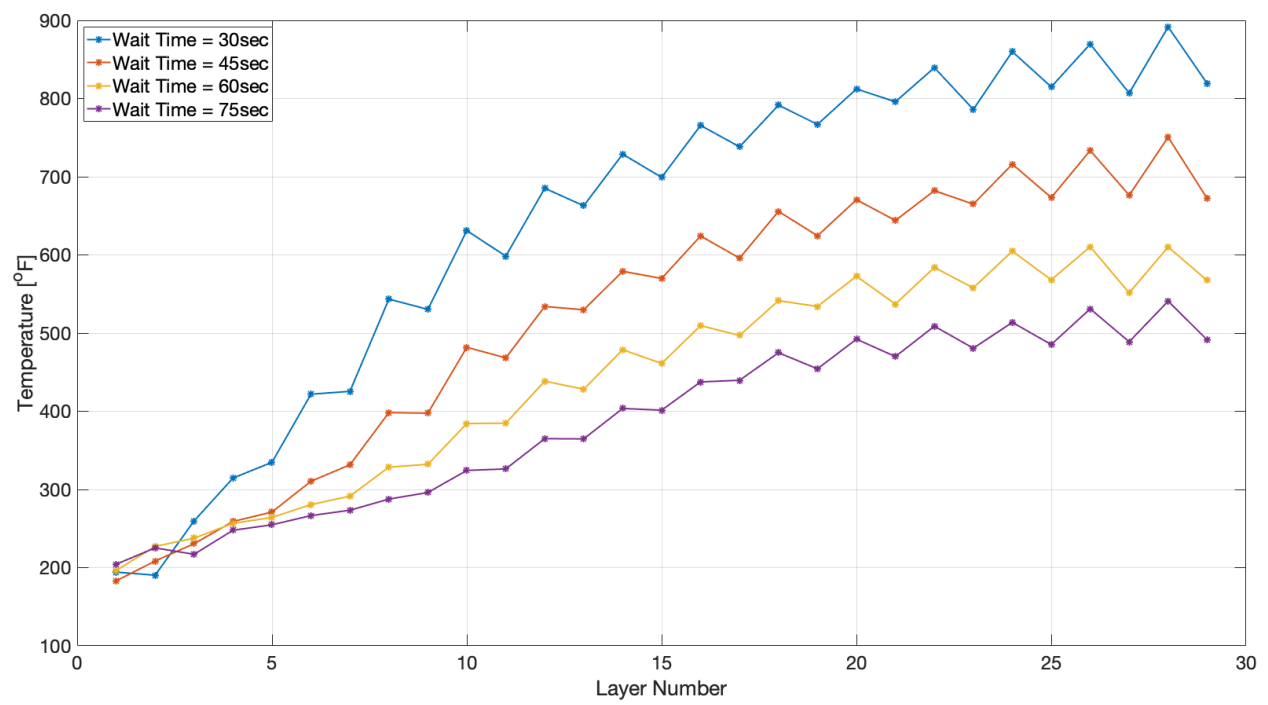


Figure 6.6: Trends in the interpass wait temperatures for all four walls

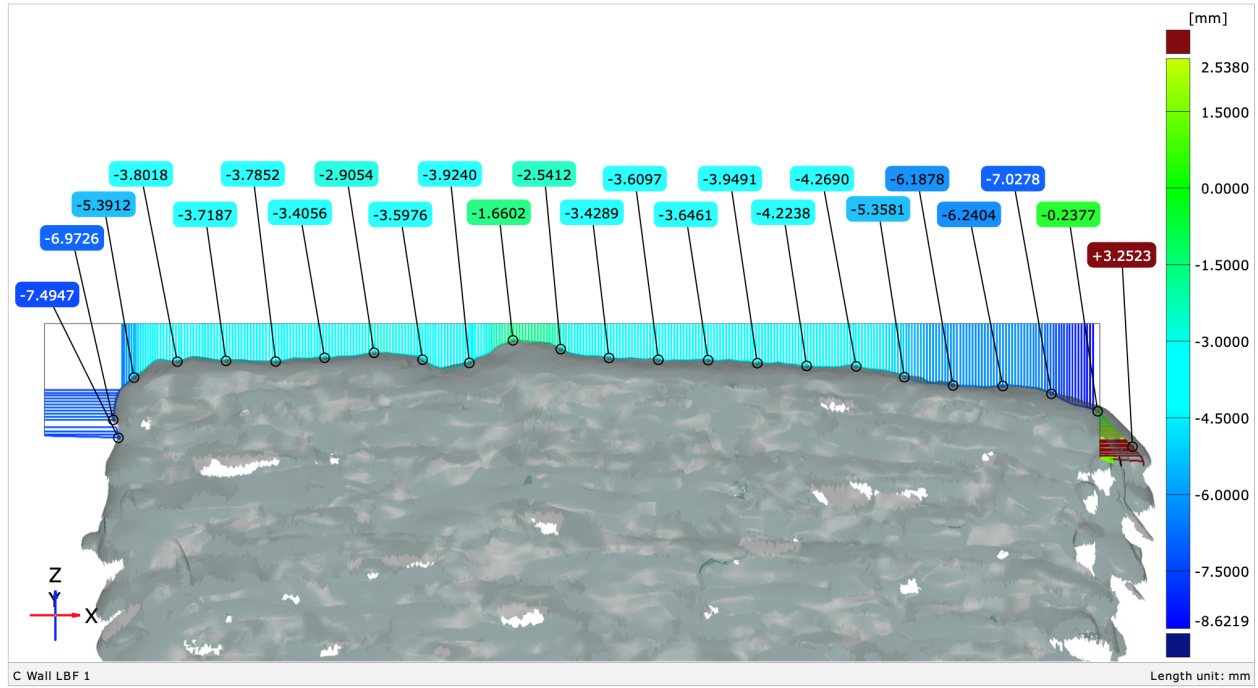
6.2 Effect of Interpass Temperature on Geometry

The deposited walls are scanned using a GOM ATOS Q 3-dimensional scanner. The scans are then compared to the desired CAD design used to create the path plans for the walls. The primary feature of the deposited walls examined in this analysis is the height of the top surface of the printed walls. If the previous layer temperature is too high, the penetration of the next deposited layer can be too great, resulting in a decreased layer height.

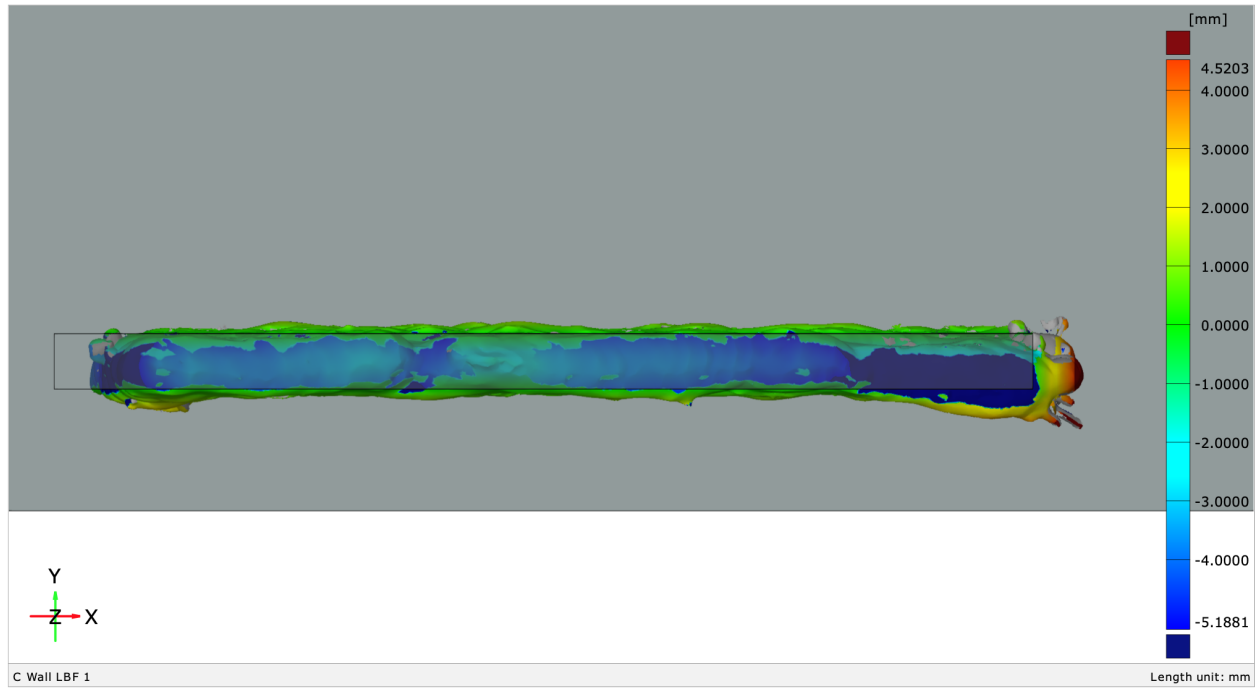
The scan of the first wall (with an interpass wait time of 30 s) is shown in figure 6.7. It can be seen that the entire top surface is under-built, with a maximum deviation of -7.028 mm and an average deviation of 3.74 mm. Next (in figure 6.8), the wall built with an interpass wait time of 45 s is also under-built, but the maximum deviation is only -5.99 mm with an average deviation of 2.15 mm. The third wall, with an interpass wait time of 60 s, has a maximum vertical deviation of -5.58 mm and an average deviation of 2.79 mm (see figure 6.9). And finally, the fourth wall, with an interpass wait time of 75 s (shown in figure 6.10), has a maximum vertical deviation of -7.71 mm and an average deviation of 3.45 mm.

With wall 2 having the lowest average deviation from the desired CAD, this suggests that waiting approximately 45 s between layers is the ideal interpass wait time. But, as shown in figure 6.6, the interpass temperature is not constant and increases to a roughly steady state point over the first 25 layers. This shows that there is a transient period in the thermal evolution of the part where the conduction pathways, as well as sufficient surface for free convection, are built to reach an equilibrium state.

Taking the interpass temperature curve for wall 2 as the baseline, the ideal steady state interpass temperature is approximately 700°F . But, for the first 25 layers it is more appropriate to use a function based on layer number to determine the ideal interpass temperature.

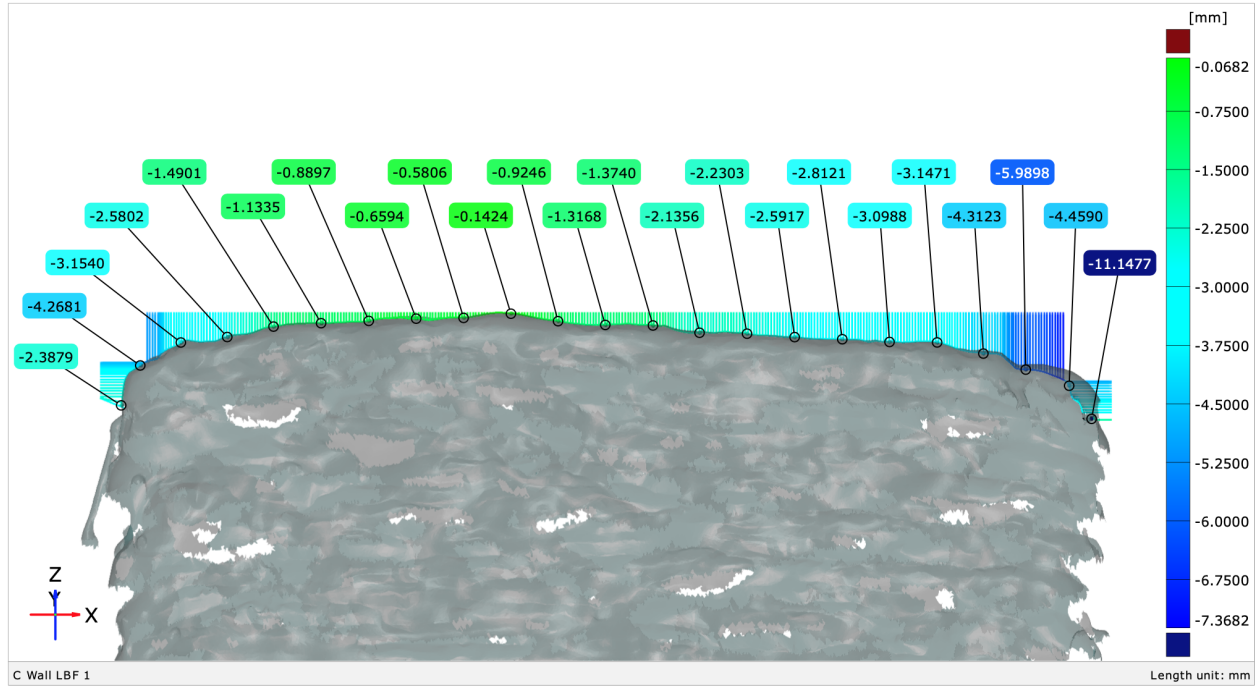


(a) Top surface deviation at the centerline of the desired CAD

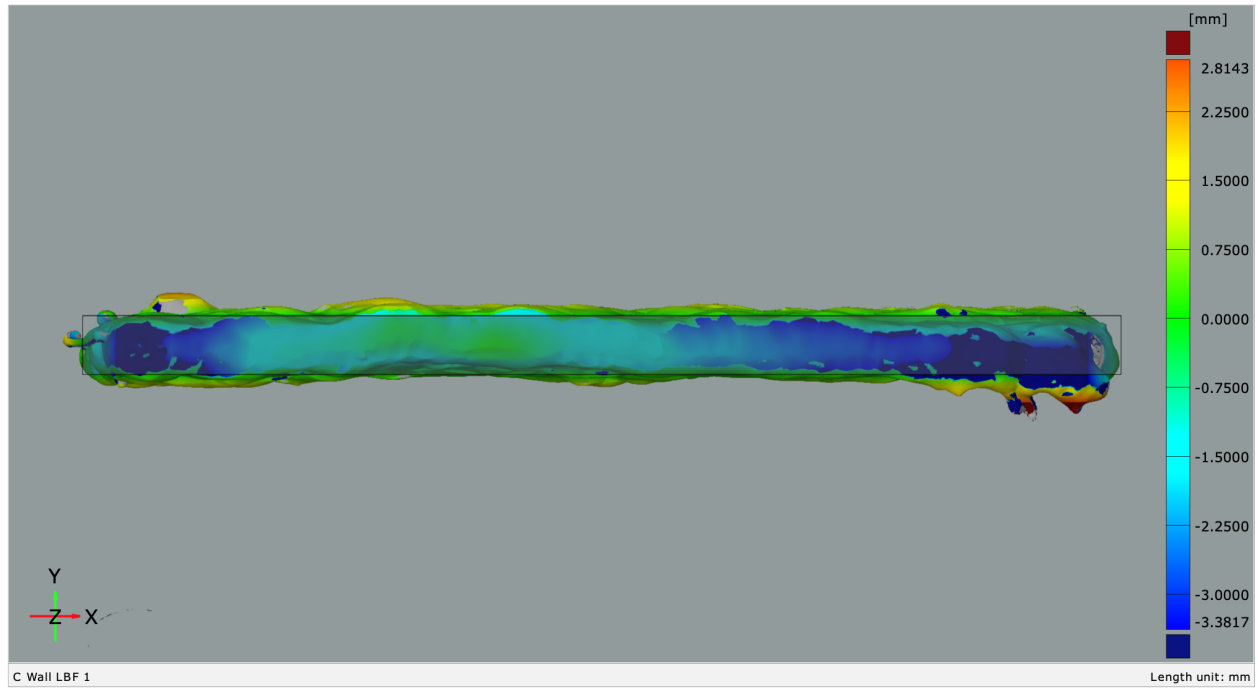


(b) Surface comparison of the top plane between the as-built wall and the desired CAD

Figure 6.7: Geometry comparisons between the desired CAD and the wall built with a 30 s interpass wait time.

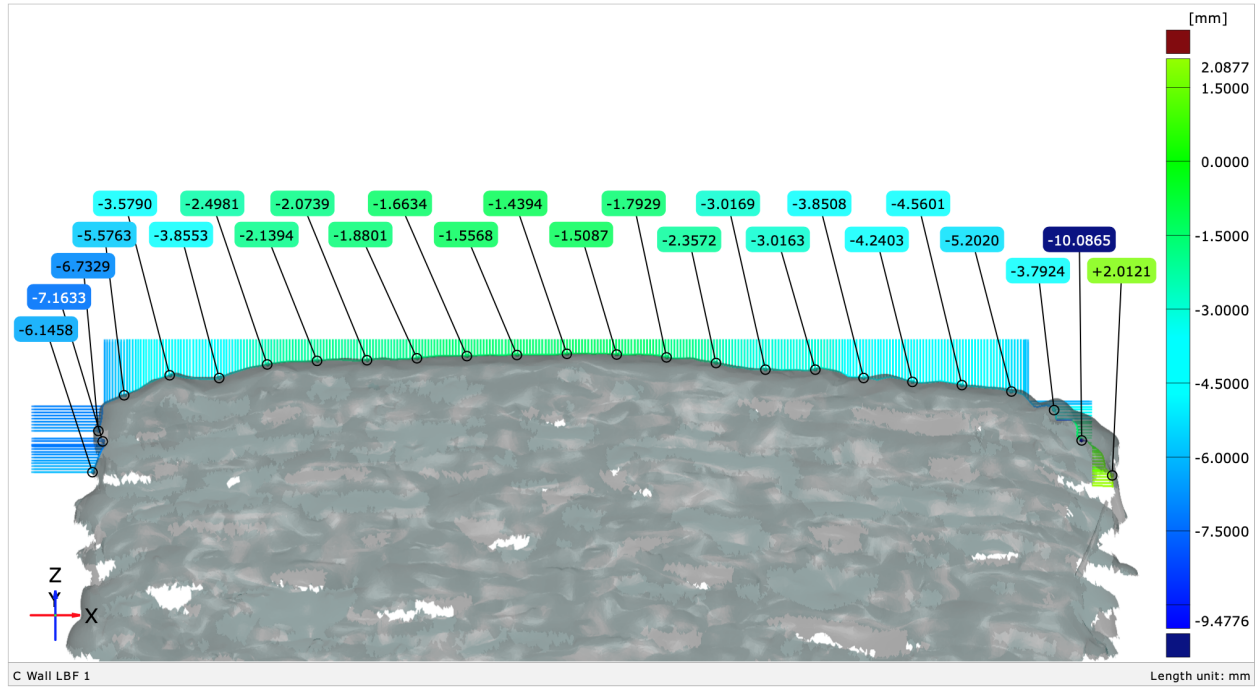


(a) Top surface deviation at the centerline of the desired CAD

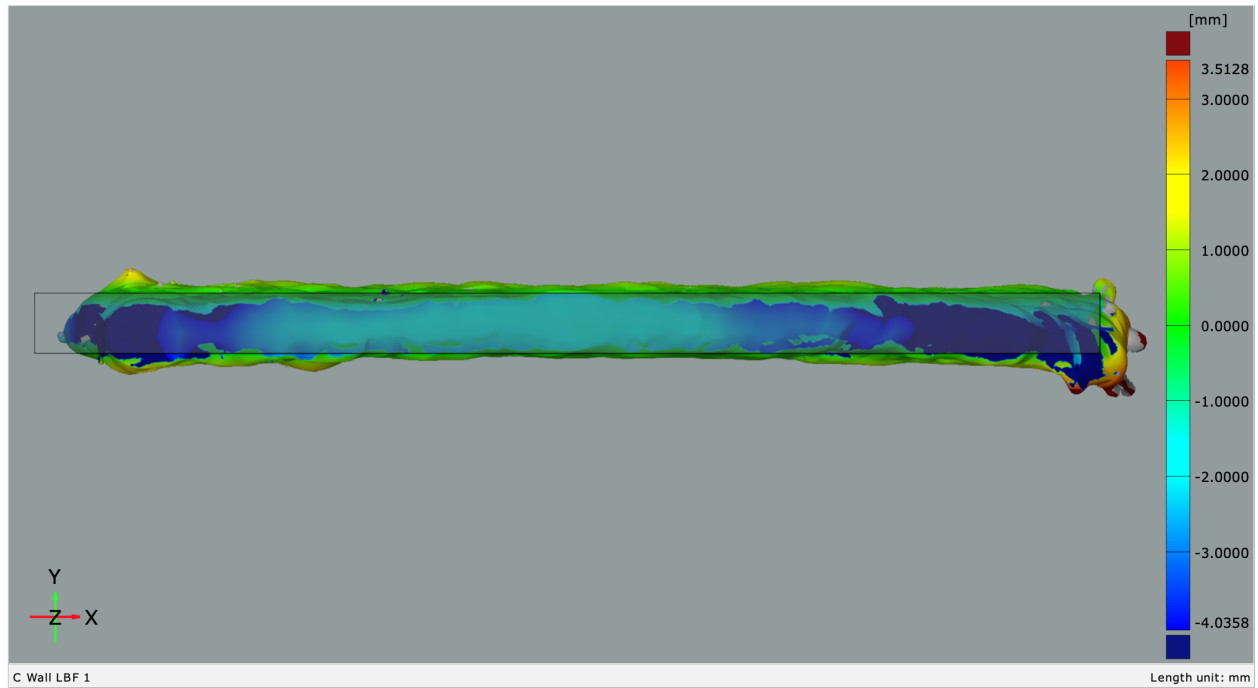


(b) Surface comparison of the top plane between the as-built wall and the desired CAD

Figure 6.8: Geometry comparisons between the desired CAD and the wall built with a 45 s interpass wait time.

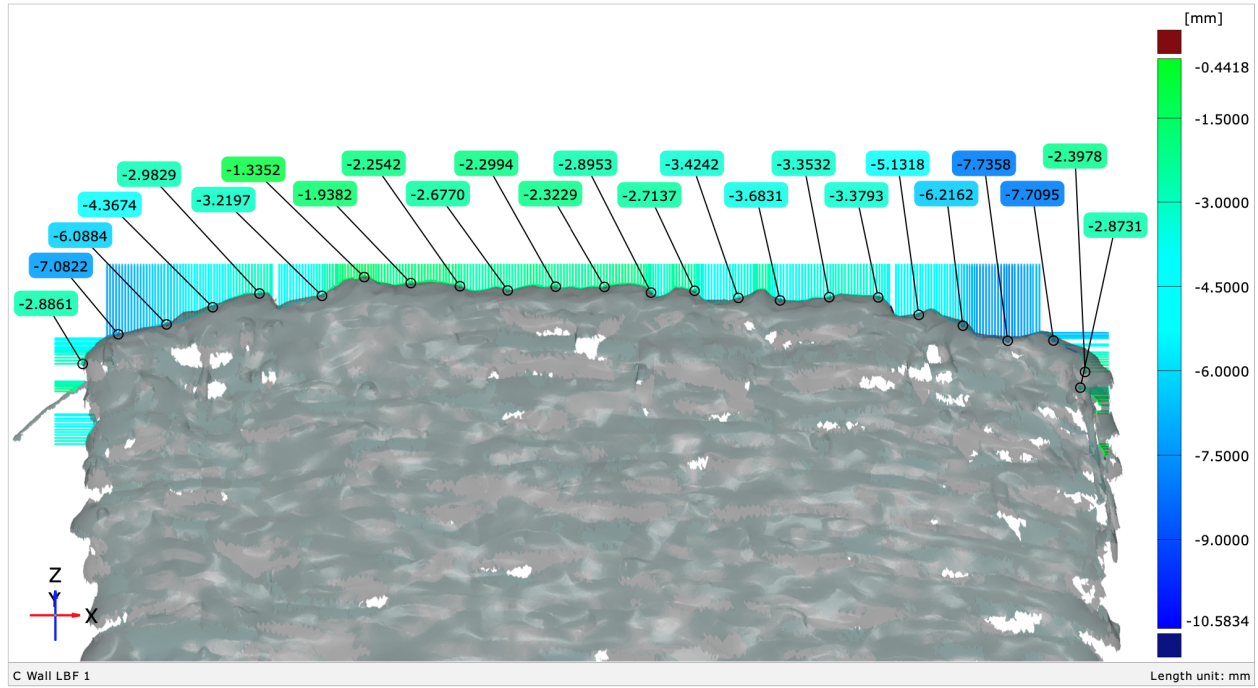


(a) Top surface deviation at the centerline of the desired CAD

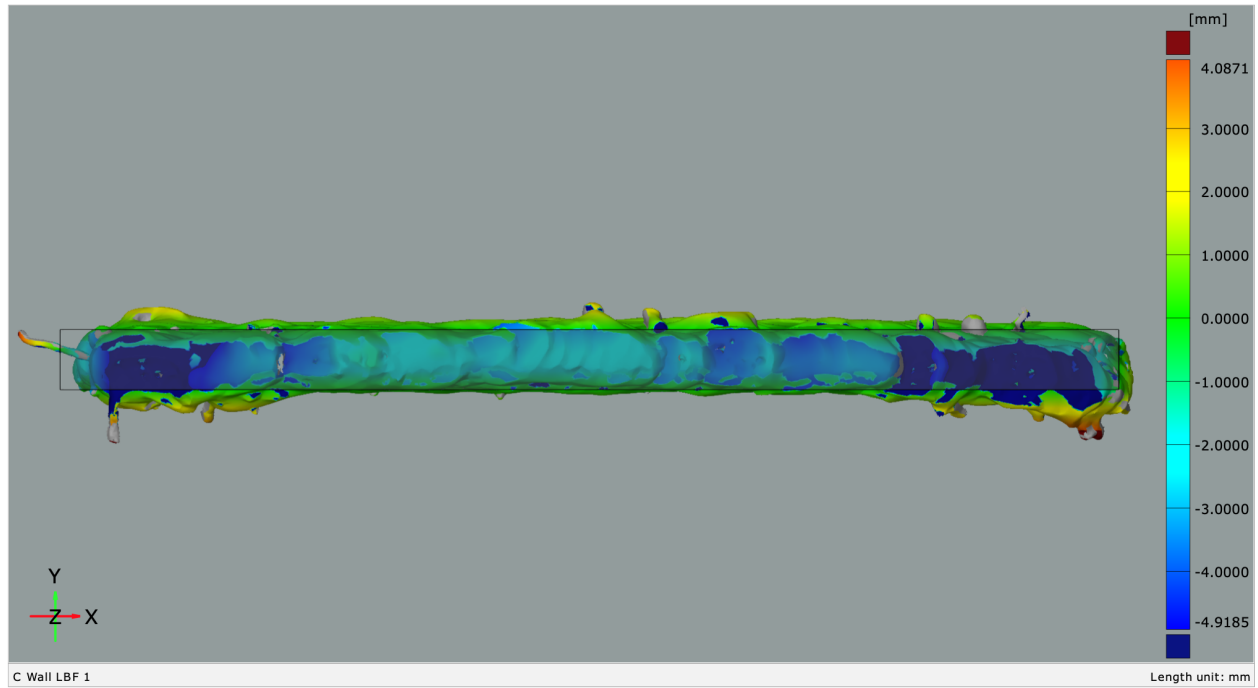


(b) Surface comparison of the top plane between the as-built wall and the desired CAD

Figure 6.9: Geometry comparisons between the desired CAD and the wall built with a 60 s interpass wait time.



(a) Top surface deviation at the centerline of the desired CAD



(b) Surface comparison of the top plane between the as-built wall and the desired CAD

Figure 6.10: Geometry comparisons between the desired CAD and the wall built with a 75s interpass wait time.

Chapter 7

Fundamental Contributions

7.1 Non-Gravity Aligned Weld Pool Mechanics

Through studying the first principles force balance at the weld pool mass and surface, a better understanding of how base plate inclination and relative weld torch orientation effect the shape of a deposited weld bead is developed. The analysis of the force system, as well as experimental results, showed that it is possible to manipulate the shape of the deposited weld bead through control of the direction of the droplet impact force vector during the wire arc metal deposition process. This leads to the ability to build more complex parts using non-gravity aligned WAAM techniques

7.2 Sensor Data Fusion for Gas Metal Arc Welding

Several sensors are deployed simultaneously to gain a holistic understanding of the active GMAW process, particularly for WAAM. Voltage and current sensors are used to monitor the CTWD and the stability of the arc welding process. A profilometer is used to monitor the shape of the weld bead as it is deposited. This is important particularly in the non-gravity aligned WAAM application to ensure that the deposited weld bead maintained in the desired shape in spite of gravity disturbances. The voltage and current sensor data, along with the profilometer data, are spatially synchronized through the robot position and orientation. This facilitates spatial and temporal analysis of the WAAM process and post

analysis of the part if flaws occurred during the part build. Finally, a thermal camera is used to monitor the top surface temperature of the part. This data informs the robot when the part is at an optimal temperature to begin the next layer, thus ensuring the part will not melt down during deposition due to overheating and that the part will have improved geometric conformity to the desired geometry.

7.3 Real-Time Control of Gas Metal Arc Welding for Wire Arc Additive Manufacturing

The first layer of real-time control implemented is a layer height control algorithm which maintains a desired CTWD based on the sensed voltage and current values of the GMAW process. By maintaining a desired CTWD, a smoother, more even surface is deposited and a desired layer height is maintained. Next is the framework for a bead shape control based on an in-situ captured profile of the deposited weld bead. By implementing this framework, a more consistent weld bead can be deposited regardless of base plate inclination angle. Finally, a framework for thermal management of a part by measuring and dictating a desired interpass temperature is developed. In implementing this framework, the thermal evolution of the part can be more carefully curated thus improving the geometric conformity of the final part and maintaining a structurally stable part throughout the build.

Chapter 8

Future Work

8.1 Layer Height Control in NGA Orientations

Extending from chapter 4, the layer height control algorithm should be tested and evaluated in the non-gravity aligned torch orientation. To implement the layer height control algorithm in a non-gravity aligned orientation, first the corrections to the robot position must be made relative to the robot tool coordinate frame. With corrections made relative to the torch coordinate system rather than the base coordinate system, then the orientation of the torch will not need to be considered to calculate the CTWD offset.

Ideally, the model developed for the gravity aligned orientation will apply in the non-gravity aligned orientation. But, data should be collected for a range of inclination angles to update the SVR model with this third input parameter. Also, the PID gains may need to be re-tuned for a better response in the non-gravity aligned orientation. By implementing the layer height control algorithm for both gravity aligned and non-gravity aligned orientations, geometric conformity can be better ensured regardless of part complexity.

8.2 Implementing Bead Shape Control

As shown in chapter 5, changing the orientation of the weld torch relative to the base plate changes the shape of the weld bead. This knowledge can be applied in a real-time control scheme to maintain a desired weld bead shape during non-gravity aligned welding. To

implement this control, several tools must be developed. First, a mathematical relationship between the torch orientation and the shape of the deposited weld bead. As discussed in chapter 3, the analytical solution for calculating the shape of the weld bead is complex and not suited for a real-time control application. Thus, a more heuristic approach should be used based on experimental data to analyze this relationship.

This relationship will build upon the shape extraction algorithm developed in chapter 5 and use the calculated centroid position as a starting input to the control system. To build a more accurate model, more experiments should be run to widen the scope of data available. To properly capture the relationship between inclination angle, torch orientation, and centroid location, smaller increments of inclination angle should be tested with more torch orientations. As has been shown, the using a gravity aligned torch orientation on an inclined surface causes a greater deviation in the centroid location, so this case can be eliminated in further testing.

The developed control structure will follow the Vernier approach of supplementing the primary control (the closed loop motion controller of the robot following the desired path) with an additional control mechanism to fine tune the robot orientation subject to maintaining the desired bead shape. The output of the controller is a small angle change to the torch orientation around the travel direction of the torch. Limits should be applied to this angle change to account for the geometry of the welding torch. If too much of an orientation change is made, the cup of the welding torch could contact the base plate or other deposited material.

By controlling the bead shape, rather than solely relying upon the open-loop part plan, a greater level of near-net shape conformity can be achieved for more complex parts. By reducing the overbuild on the underside of large overhangs due to drooping of the weld bead, the amount of final machining necessary to reach the final geometry is also reduced.

8.3 Implementing Thermal History Control

The experiments performed in chapter 6 showed, what is well known in WAAM part building, that maintaining a prescribed interpass temperature between layers improves the geometric

conformity of the final part. Thus a simple boolean control structure can be developed to trigger the execution of the next layer based on the maximum temperature of the part in the time between layers. In addition to improving the geometric conformity of the part, implementing this control system can shorten the amount of time for a full part build by not requiring the part to cool for an arbitrary amount of time, but rather cool to only the highest allowable or desirable temperature to assure good layer fusion and metallurgical results.

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Appendices

A Python Code

A.1 Support Vector Regression Model Generation

```
1 from nptdms import TdmsFile
2 from matplotlib import pyplot as plt
3 from matplotlib import cm
4 import numpy as np
5 import time
6 from sklearn.svm import SVR
7 from sklearn.model_selection import train_test_split
8 import welding_lib as wl
9 from joblib import dump
10 import os
11 from pathlib import Path
12
13 file_path = r'21-05-27 Model Testing'
14 file_ext = r'.tdms'
15 file_names = [_ for _ in os.listdir(file_path) if _.endswith(file_ext)]
16
17 number_of_beads = 18
18 current_vals = []
19 voltage_vals = []
20 va_vals = []
21 height_vals = []
22 tdms_files = []
23 plt.rcParams.update({'font.size':22})
24
25 window = 200
26
27 # Importing the TDMS Files -----
28 print('Starting file import...')
29 t0 = time.time()
30 for bead in file_names:
31     file_name = bead+'.tdms'
32     print('Opening file -> '+bead)
```

```

33     tdms_files.append(TdmsFile.open(file_path / Path(bead)))
34 open_time = time.time() - t0
35 print(str(number_of_beads)+' TDMS files opened in %.3fs' % (open_time))
36
37 # Calculating the moving window averages -----
38 for bead in tdms_files:
39     print('Processing '+bead.properties['name'])
40     [weld_start,weld_end] = wl.findArcStartEnd(bead['Layer 1'])
41     voltage = bead['Layer 1']['voltFFT'][weld_start:weld_end]
42     current = bead['Layer 1']['ampFFT'][weld_start:weld_end]
43     height = bead['Layer 1']['Robot Z'][weld_start:weld_end]
44     for i in range(len(voltage)-window+1):
45         voltage_vals.append([np.average(voltage[i:i+window])])
46         current_vals.append([np.average(current[i:i+window])])
47         va_vals.append([np.average(voltage[i:i+window]),np.average(current
            [i:i+window])])
48         height_vals.append([np.average(height[i:i+window])])
49
50 volt_val = [voltage_vals]
51 curr_val = [current_vals]
52
53 voltage_vals = np.asarray(volt_val)
54 current_vals = np.asarray(curr_val)
55 height_vals = np.asarray(height_vals)
56
57 voltage_vals = np.ravel(voltage_vals)
58 current_vals = np.ravel(current_vals)
59
60 # Splitting the data in training and testing sets -----
61 volt_train, volt_test, zv_train, zv_test = train_test_split(voltage_vals,
        height_vals,train_size=0.8,test_size=0.2,random_state=3)
62 amp_train, amp_test, zc_train, zc_test = train_test_split(current_vals,
        height_vals,train_size=0.8,test_size=0.2,random_state=3)
63 va_train, va_test, zva_train, zva_test = train_test_split(va_vals,
        height_vals,train_size=0.8,test_size=0.2,random_state=3)
64

```



```

65 # volt_train = np.asarray([volt_train])
66 volt_train = [[val] for val in volt_train]
67 volt_train = np.asarray(volt_train)
68 volt_train.reshape(-1,1)
69 zv_train = [val[0] for val in zv_train]
70 zv_train = np.asarray(zv_train)
71 zv_train.ravel()
72 volt_test = [[val] for val in volt_test]
73 volt_test = np.asarray(volt_test)
74 volt_test.reshape(-1,1)
75 zv_test = [val[0] for val in zv_test]
76 zv_test = np.asarray(zv_test)
77 zv_test.ravel()
78
79 amp_train = [[val] for val in amp_train]
80 amp_train = np.asarray(amp_train)
81 amp_train.reshape(-1,1)
82 zc_train = [val[0] for val in zc_train]
83 zc_train = np.asarray(zc_train)
84 zc_train.ravel()
85 amp_test = [[val] for val in amp_test]
86 amp_test = np.asarray(amp_test)
87 amp_test.reshape(-1,1)
88 zc_test = [val[0] for val in zc_test]
89 zc_test = np.asarray(zc_test)
90 zc_test.ravel()
91
92 zva_train = [val[0] for val in zva_train]
93 zva_train = np.asarray(zva_train)
94 zva_train.ravel()
95 zva_test = [val[0] for val in zva_test]
96 zva_test = np.asarray(zva_test)
97 zva_test.ravel()
98
99 # Regression over voltage data -----
100 print('-- Performing Voltage regression')

```

```

101 svr_volt = SVR(kernel='rbf',gamma='scale',C=250,epsilon=0.01)
102 t0 = time.time()
103 svr_volt.fit(volt_train,zv_train)
104 svr_fit = time.time() - t0
105 print("---- SVR Voltage model fit in %.3f s" % svr_fit)
106 dump(svr_volt, 'svr_volt_model.joblib')
107
108 # Regression over current data -----
109 print('-- Performing Current regression')
110 svr_amp = SVR(kernel='rbf',gamma='scale',C=250,epsilon=0.01)
111 t0 = time.time()
112 svr_amp.fit(amp_train,zc_train)
113 svr_fit = time.time() - t0
114 print("---- SVR Current model fit in %.3f s" % svr_fit)
115 dump(svr_amp, 'svr_amp_model.joblib')
116
117 # Regression over voltage and current data -----
118 print('-- Performing Voltage/Current regression')
119 svr_va = SVR(kernel='rbf',gamma='scale',C=250,epsilon=0.01)
120 t0 = time.time()
121 svr_va.fit(va_train,zva_train)
122 svr_fit = time.time() - t0
123 print('-- SVR Voltage/Current model fit in %.3f s' % svr_fit)
124 dump(svr_va, 'svr_voltamp_model.joblib')
125
126 # Test models -----
127 print('Testing models...')
128 svr_volt_score = svr_volt.score(volt_test,zv_test)
129 print('-- Voltage complete...')
130 svr_amp_score = svr_amp.score(amp_test,zc_test)
131 print('-- Current complete...')
132 svr_va_score = svr_va.score(va_test,zva_test)
133 print('-- Voltage+Current complete...')
134
135 # # Generate continuous curve model representation
    -----

```

```

136 volt_max = np.max(voltage_vals)
137 volt_min = np.min(voltage_vals)
138 amp_max = np.max(current_vals)
139 amp_min = np.min(current_vals)
140 va_size = 250
141 volt_step = (volt_max-volt_min)/va_size
142 amp_step = (amp_max-amp_min)/va_size
143 volt_pred = np.arange(volt_min,volt_max,volt_step)
144 volt_pred_2 = np.linspace(np.min(voltage_vals),np.max(voltage_vals),
    va_size)[: ,None]
145 amp_pred = np.arange(amp_min,amp_max,amp_step)
146 amp_pred_2 = np.linspace(np.min(current_vals),np.max(current_vals),va_size
    )[: ,None]
147 X = [[val] for val in volt_pred]
148 X = np.asarray(X)
149 Y = [[val] for val in amp_pred]
150 Y = np.asarray(Y)
151 va_pred_x,va_pred_y = np.asarray(np.meshgrid(X, Y))
152
153 print('Generating curves/surfaces...')
154 z_pred_volt = svr_volt.predict(volt_pred_2)
155 print('-- Voltage complete...')
156 z_pred_amp = svr_amp.predict(amp_pred_2)
157 print('-- Current complete...')
158
159 z_pred_va = []
160 for v in X:
161     row = []
162     for a in Y:
163         temp = np.asarray([v,a])
164         row.append(svr_va.predict(temp.T))
165     z_pred_va.append(row)
166
167 zva_pred_final = np.empty([va_size,va_size])
168 for i in range(0,va_size):
169     for j in range(0,va_size):

```

```

170         zva_pred_final[j][i] = z_pred_va[i][j][0]
171
172 print('z_pred_va: ' + str(np.shape(z_pred_va)))
173 print('zva_pred_final: ' + str(np.shape(zva_pred_final)))
174 print('-- Voltage+Current complete')
175
176 print('Voltage model scored a %.3f' % svr_volt_score)
177 print('Current model scored a %.3f' % svr_amp_score)
178 print('Voltage/Current model scored a %.3f' % svr_va_score)
179
180 # Plot voltage model -----
181 plt.figure()
182 plt.plot(volt_train, zv_train, 'o', color='darkorange', label='Training Data')
183 plt.plot(volt_test, zv_test, 'o', color='darkgreen', label='Testing Data')
184 plt.plot(volt_pred, z_pred_volt, '-', color='navy', label='Model')
185 plt.grid()
186 plt.xlabel('Voltage [V]')
187 plt.ylabel('CTWD Offset [mm]')
188 plt.legend()
189 plt.title('Regression over Voltage (score = %.3f)' % (svr_volt_score))
190
191 # Plot Current model -----
192 plt.figure()
193 plt.plot(amp_train, zc_train, 'o', color='darkorange', label='Training Data')
194 plt.plot(amp_test, zc_test, 'o', color='darkgreen', label='Testing Data')
195 plt.plot(amp_pred, z_pred_amp, '-', color='navy', label='Model')
196 plt.grid()
197 plt.xlabel('Current [A]')
198 plt.ylabel('CTWD Offset [mm]')
199 plt.legend()
200 plt.title('Regression over Current (score = %.3f)' % (svr_amp_score))
201
202 # Plot Voltage/Current model -----
203 fig = plt.figure()
204 ax = fig.add_subplot(projection='3d')
205 va_train_array = np.array(va_train)

```

```

206 va_test_array = np.array(va_test)
207 ax.scatter(va_train_array[:,0],va_train_array[:,1],zva_train,color='
    darkorange',label='Training Data')
208 ax.scatter(va_test_array[:,0],va_test_array[:,1],zva_test,color='navy',
    label='Testing Data')
209 ax.plot_surface(va_pred_x,va_pred_y,zva_pred_final,cmap=cm.coolwarm,
    linewidth=0,alpha=0.75,antialiased=False)
210 ax.legend()
211 ax.set_xlabel('Voltage [V]',labelpad=20)
212 ax.set_ylabel('Current [A]',labelpad=20)
213 ax.set_zlabel('CTWD Offset [mm]',labelpad=20)
214
215 plt.show()

```

B LabVIEW Control Application

B.1 Main Front Panel

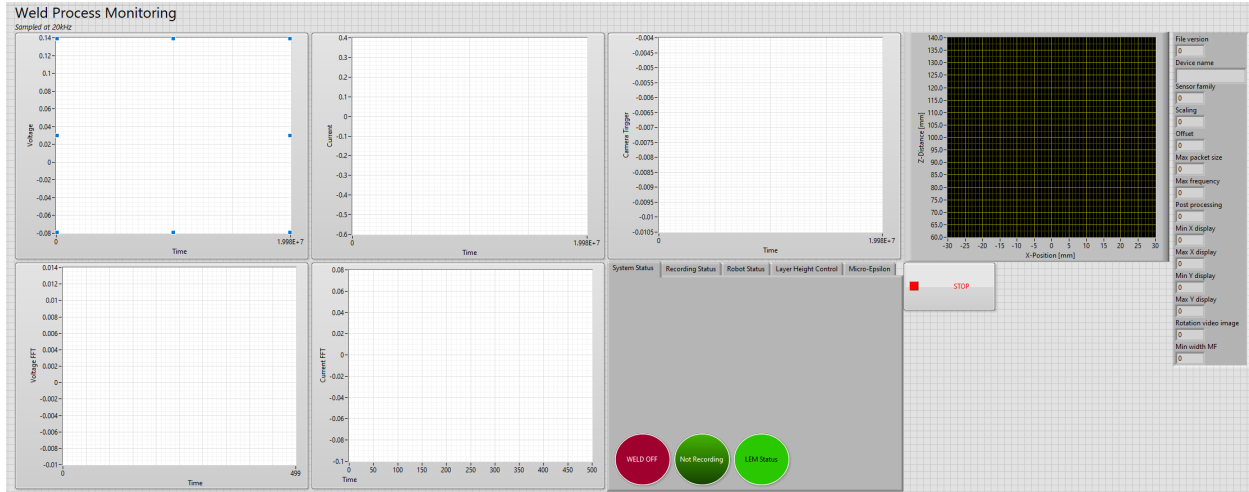


Figure 1: Front panel of main LabVIEW code for implementing the sensing and control of the WAAM process

B.2 KUKA Communications

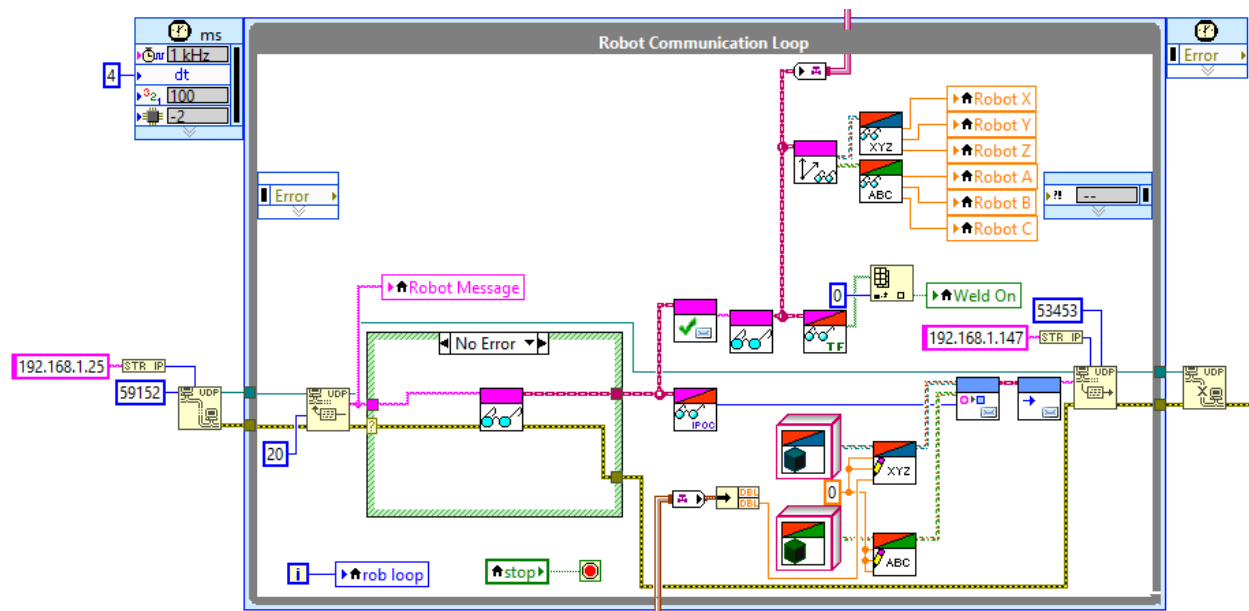


Figure 2: Loop responsible for sending and receiving data from the KUKA controller

B.3 LEM Box Interface

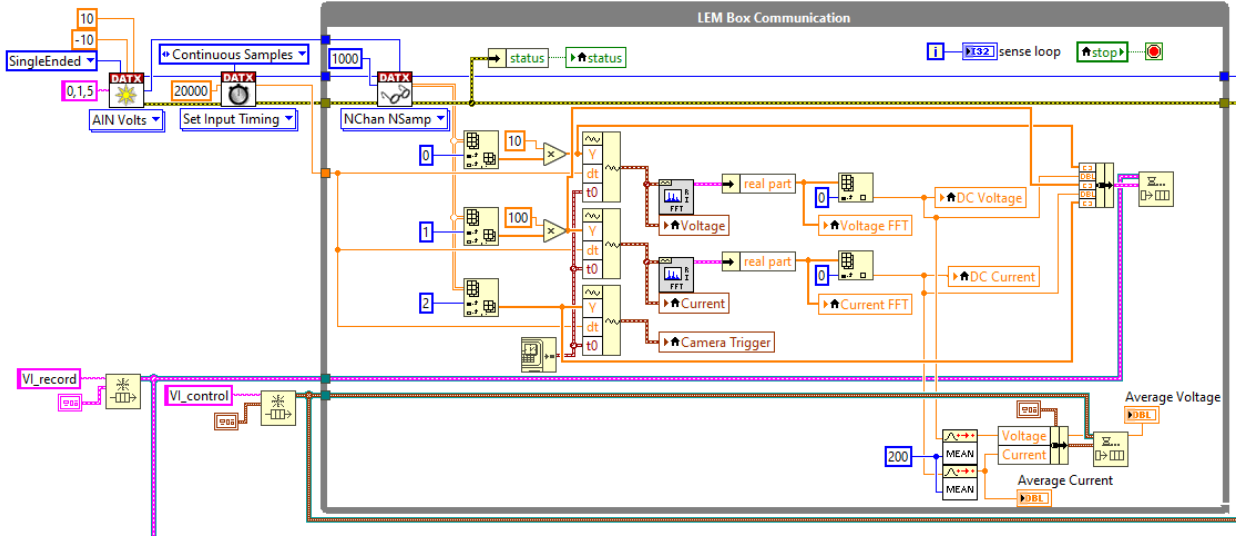


Figure 3: Loop responsible for capturing the voltage and current data generated by LEM Box

B.4 Controls Loop

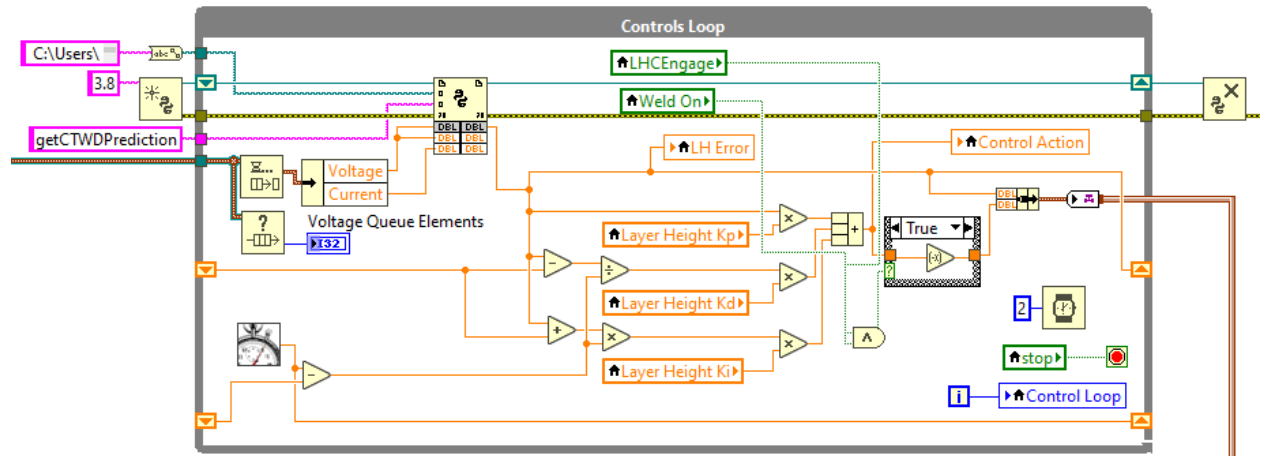


Figure 4: Loop responsible for implementing the developed controls algorithms and generating the necessary control signals for the robot

Vita

Joshua Penney received a BS in Mechanical Engineering with an Honors Concentration in 2016 from the University of Tennessee - Knoxville. During his undergraduate career, he worked in the BioRobotics Lab under Dr. William Hamel; assisting with research activities on the Tracking Fluoroscope System. Upon graduation, Mr. Penney transitioned to a graduate research position to pursue a PhD at the University of Tennessee again under Dr. William Hamel. In 2019, Mr. Penney received his MS in Mechanical Engineering with a concentration in Systems and Controls. During his graduate career, Mr. Penney researched Large Scale Additive Metals Manufacturing, served as a Graduate Teaching Assistant for manufacturing and design classes, and taught an undergraduate class in Computer Aided Design as a Graduate Teaching Associate. He plans to continue researching the development and application of Large-Scale Additive Metals Manufacturing.