

Framework for CAD to Part of Large Scale Additive Manufacturing of Metal (LSAMM) in Arbitrary Directions

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Abstract

The purpose of this research is to provide a framework for Large Scale Additive Metals Manufacturing (LSAMM) in arbitrary directions. Traditionally, slicing and path planning is done along the gravity aligned direction of a part, causing more complex geometrical shapes to have unsupported overhangs. The overhangs can be managed using a part positioner or a powder bed process. A different framework for slicing and building parts out of gravity alignment could improve current capabilities of LSAMM processes. The presented research focuses on segmenting more complex geometrical parts into gravity aligned (GA), non-gravity aligned (NGA), and transition segments to help generate toolpaths. Initial research of segment planning for complex geometrical shapes will be presented, as well as current results from builds completed at the University of Tennessee-Knoxville. The completed builds show that more consistent thermal evolution of a part based on the path sequence and torch angle results in successful builds.

Introduction

Metal additive manufacturing technologies have had significant research advancements in the past 10 years. Additive Manufacturing (AM) is desirable for companies due to the ability to achieve complex geometry with the reduction in waste material. However, issues have persisted with the strength and the production of near net shape parts [1–3]. AM techniques have become specialized to improve upon these issues by changing their material and power sources. If traditional manufacturing techniques can be leveraged for AM, the cost of building parts can be reduced. A summary of additive versus conventional manufacturing can be seen in Figure 1.

Metal additive manufacturing describes a variety of different processes used to build metal parts. In general, two types of AM techniques persist in industry: Directed Energy Deposition (DED) and Powder Bed Fusion (PBF). PBF technologies were developed to give metal parts high resolution, but generally have a lower deposition rate [4]. Highly specialized cabinets are needed to control the layer height, air flow, and heat. DED with powder feed technologies tried to integrate powder with a laser heat source, which allowed for faster deposition. However,

these processes have proved more complex to implement and the production of powder can be expensive. Electron Beam FreeForm Fabrication (EBF3) and Wire and Arc Additive Manufacturing (WAAM) are both DED processes with wire feed. The EBF3 process, while having a large deposition rate, requires a specialized vacuum cabinet. The WAAM

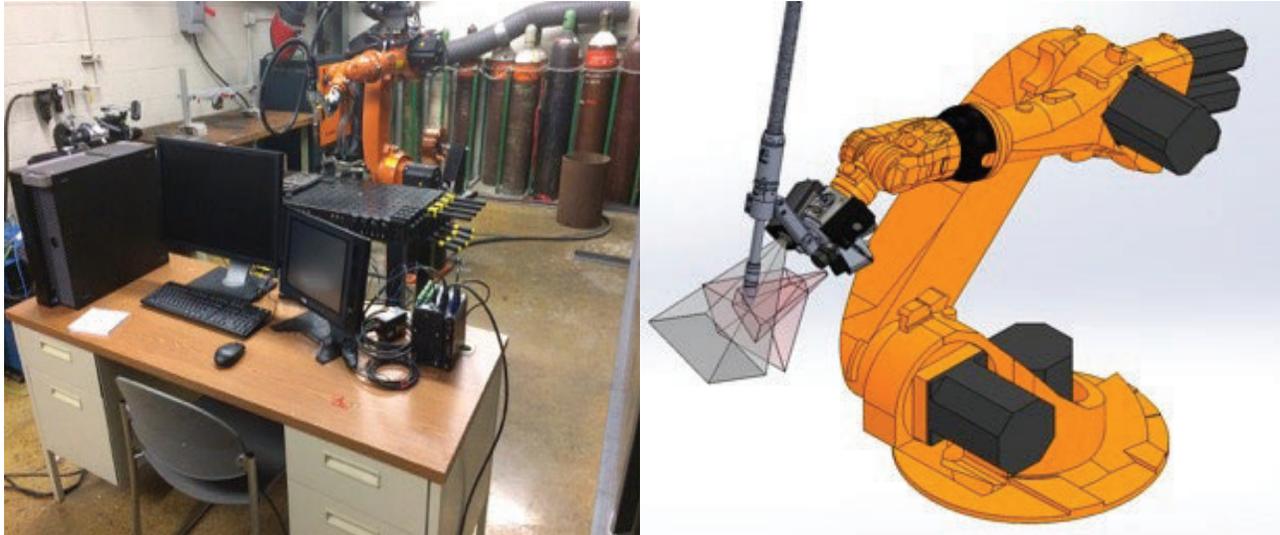
Favor Additive Manufacturing	Favor Conventional Manufacturing
Lower Production Volumes	Large Production Volumes
High Material Cost	Low Material Costs
High Machining Costs	Easily Machined Materials
Capital Investment	Centralized Manufacturing
Logistics Cost	
Transportation Cost	
Prototyping	

Figure 1 - Table from [4] that shows pros and cons of additive manufacturing.

technique describes any arc process similar to welding that is used to deposit material. Current LSAAM focuses on using laser or arc sources to have higher deposition rates [5]. The WAAM process has been demonstrated for large scale structures like excavator arms [5], [6], but the full capabilities of WAAM have yet to be explored.

Wire and Arc Additive Manufacturing (WAAM)

WAAM is a desirable process since traditional manufacturing has relied on robotic WAAM systems to complete simple welding tasks for many years. Most manufacturing centers already have the basic manipulator and welding technology available and the cost for metal wire is relatively inexpensive compared to the powders for laser processes [5]. A setup for a typical WAAM cell can be seen in Figure 2.



(a) Picture of the welding workstation in (b) CAD model of Kuka KR6-2 with sensor Dougherty 110. bracket attached.

Figure 2 - Illustrates the welding cell and setup at the University of Tennessee.

WAAM research has focused on building parts to near net shape [1], [7-10]. As a standard manufacturing technique, there has been significant research on weld pool shape [11], [12], thermal behavior [13], [14], and the microstructure of the resulting welds [6], [15]. Most of the current research on large scale WAAM has been shown in the GA orientation [Typically, this is accomplished by using a welding system and part positioner to move the part to allow the torch to stay in the GA orientation [5], [10]. While demonstrated for large scale parts with large features, more complex geometry will require for the torch to complete deposition in NGA orientations.

Traditional CAD to Part for AM

One of the most attractive parts of AM is the CAD to Part methodology. Part designers are able to design a part in their Computer Aided Design (CAD) software of choice, upload the file to a Computer Aided Manufacturing (CAM) software for their machine and finally build the part. A traditional design and build approach for AM can be seen in Figure 3.

The traditional additive manufacturing CAD to Part process can be simplified into: Design, Slicing, Machine Code Generation, and Simulation [16]. The phases are interrelated, but have their own unique effects on the part plan. Some additive techniques use real time control to ensure build success, but they still rely heavily on the pre-part planning done in software programs like Insight or Cura. The goal of the CAD to Part process is to ensure that the part plan for the build maintains geometrical accuracy and strength of the final part. Design focuses on the part shape and the resulting build based on the additive technique. If a certain technique cannot complete the feature type, it must be redesigned keeping the processing parameters in mind [17]. Slicing typically focuses on two types of part representation: boundary or volumetric representation [18]. Slicing the correctly represented

model allows the part planning software to generate the correct robotic moves to improve thermal evolution and shape filling for AM processes. The software then takes the slicing plan and generates the proper machine code to build the part using the specified AM process. The machine code is represented generally by a G-code, but interpretation into machine specific code can be done in-line or by the system controller. Finally, simulation can be done on slicing, machine code, or of other properties to ensure that the part plan can be achieved. Iterating through all of the steps should provide a plan with ideal slicing and machine code to achieve near net shape of the part.

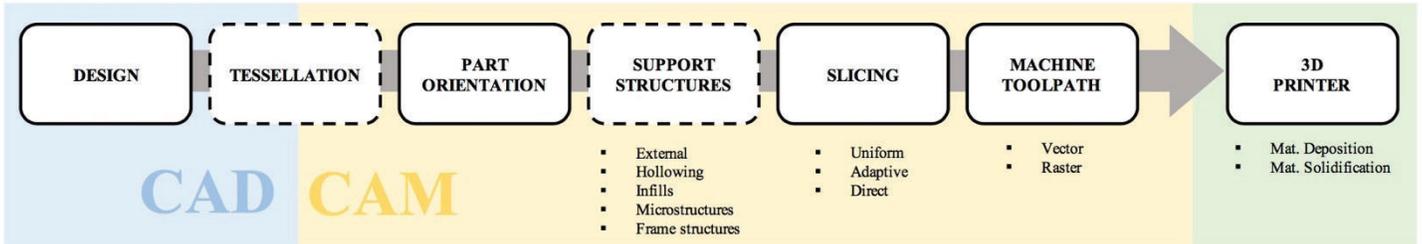


Figure 3 - Traditional CAD to Part Method from [16].

Current Methods

The first goal of this research is to extend the ability of LSAMM in arbitrary directions to make up for the lack of support material and to increase the amount of achievable geometrical complexity. Typically, LSAMM has been accomplished with the deposition being done aligned with gravity. Researchers at the University of Tennessee designed an example complex part that contained the three different types of sections: GA, NGA, and transition segment. The CAD representation can be seen in Figure 4. The designed part will be used as an example to show how different pre planning techniques can be used to help integrate complex geometry.

The current framework for building parts for complex geometry is outlined in Figure 5. Initially the CAD of the part is built in Solidworks. The CAD model will then be sliced and the sequencing of the part plan specified in MasterCam. MasterCam gives the ability within each layer to set travel speed, directions, and start/stop points. After the initial plan is made, the part plan is imported into Octopuz. Octopuz is a robotic

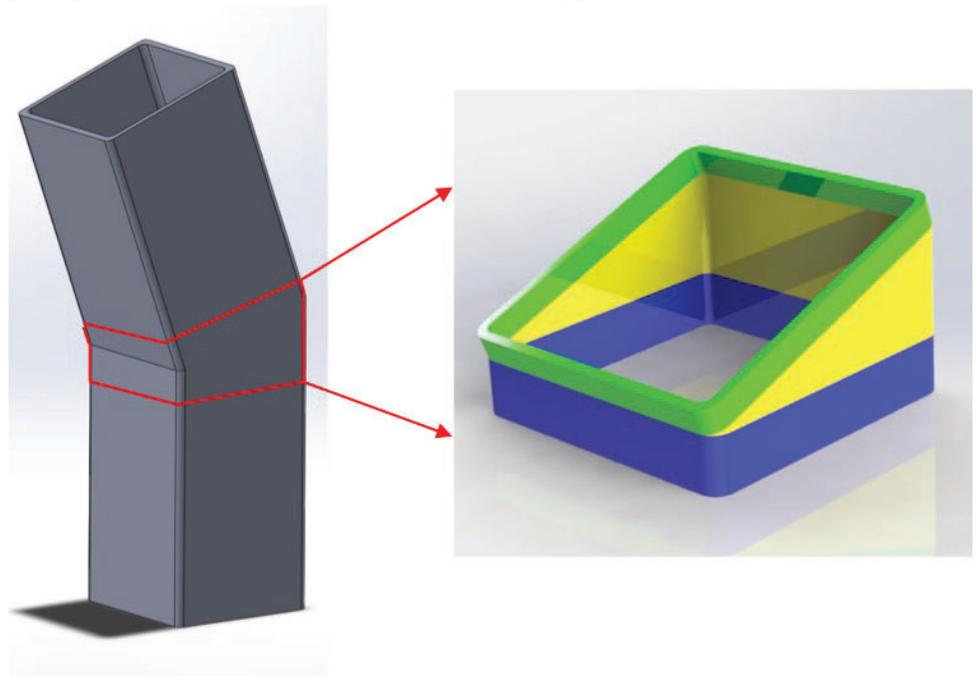
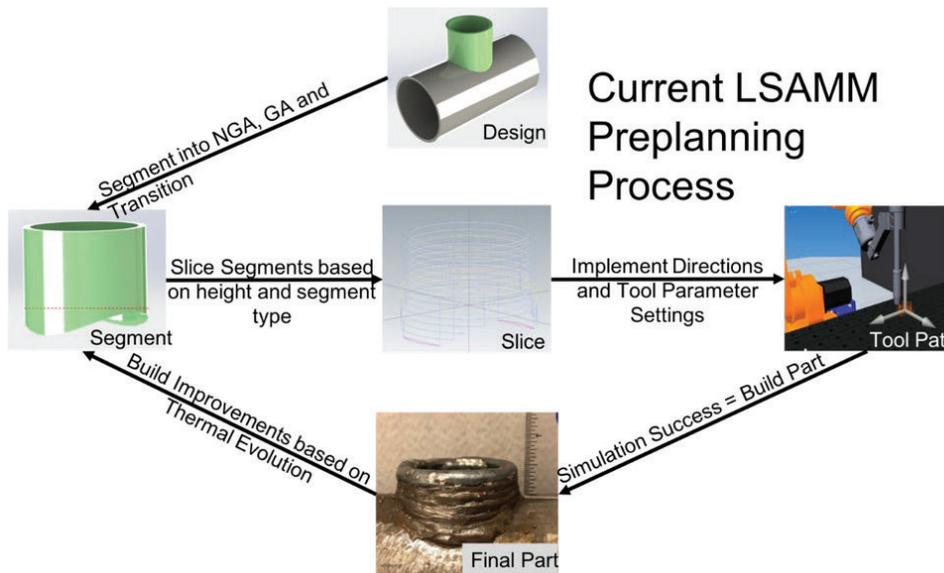


Figure 4 - Example Part CAD and representation. Blue is GA, yellow is Transition, and green is NGA.

planning software where a model of the work-cell is used to assign welding settings and check the path for errors in the robot orientation. Octopuz then generates the robot code for the machine and is executed from the pendant. Following all of these steps allows the researchers to build up a part plan that has slicing, sequencing,



and settings all specified by researchers. The current LSAMM preplanning process was verified by previous experimentation on simple geometry GA builds developed at the University of Tennessee-Knoxville.

Initial Complex Box Build

The initial complex build was attempted from a part similar to the one seen in Figure 4. The purpose was to test the capability of the planning framework as well as to see the capabilities of the system to complete NGA segments with open loop control. The segments were planned according to the flow diagram seen in Figure 5.

Figure 5 - The preplanning process that includes design, segmentation, slicing, settings, and simulation.

The initial box build part plan will contain three sections of planning: GA, NGA, and transition. These representative sections make up the different types of segments for LSAMM. The blue section in Figure 6 represents the GA section where the deposition occurs with the torch in gravity alignment. The start/stop points are the most concerning sections and these can be mitigated by moving the torch to different parts along the path for the start/stop points. Alternating directions on each layer also allows the part to develop a more consistent thermal evolution between each layer. The sequencing of the GA was taken from previous experimentation on GA structures on this system.

The transition segment planning is also handled in a similar fashion. As a simple plan of the transition zone, the researchers decided to keep the transition segment gravity aligned to ensure build success. The build results in a stair-step effect along the interface between the

Segment Planning for GA, Transition, and NGA Sections – Initial Planning

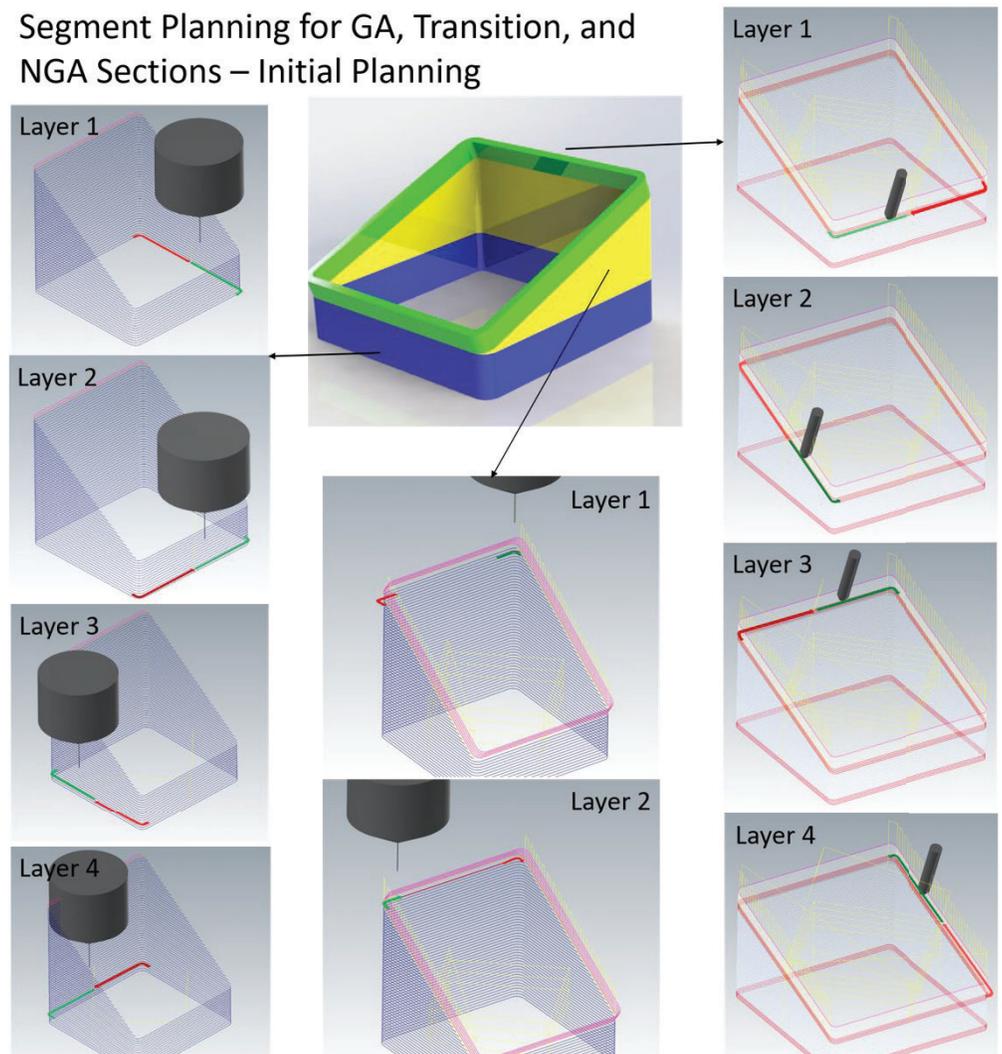


Figure 6 - Path Plan Outlining the GA, Transition, and NGA section. The green arrows indicate starts of layer while red indicates the end of a layer.

NGA and transition segment. Since the segmentation is stair stepped, it allows the torch to remain in the GA position for the entire GA and transition segment. The simplified planning of this transition zone was used for initial feasibility tests, but future research will focus on more complex transition planning techniques.

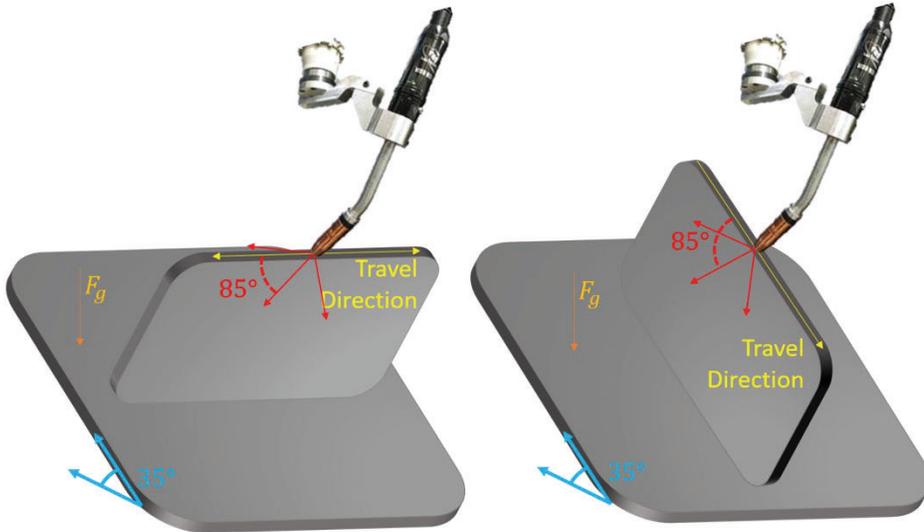


Figure 7 - Torch Angle for Horizontal and Vertical sections for initial complex part build NGA section.

The final section seen on the far right in Figure 6 is the NGA section sequence. The sequencing follows the same order as the GA section, with the only difference being the torch angle. The torch angle for both the horizontal and vertical sections was done perpendicular to the 35-degree NGA orientation. The torch angle was done at this angle for the ease of the path plan program as well as a simple first proof of concept for the NGA sections. A diagram of the torch angles for the NGA can be seen in Figure 7. A layer height of 2mm was chosen for this build

based from previous GA testing on the system. The settings for each of the following builds were not changed only the slicing and sequencing of the part were varied to help reach near net shape. Future research will focus on the effect that welding settings can play in the NGA sections.

The resulting part can be seen in Figure 8. The GA and transition zone sections of this build worked well due to previous work with building other GA parts. The transition zone had a minor issue due to needing to skip a layer. This occurred because the part was growing more rapidly than the part plan had predicted. This occurred around layer 12 of the transition zone. Only three layers of the NGA section were able to be completed due to excessive drooping and issues with layer height. The omission of a layer in the transition zone also altered the total height of the part, thus causing it to deviate from the desired part plan. The decreased height at the top of the transition zone caused long arcing issues with the welding process that also contributed to the ending the build before completion. In general, only the NGA section was unsuccessful, so future builds were designed to focus on improving the NGA sections using variable start/stop points, variable sequencing, and variable torch angles.

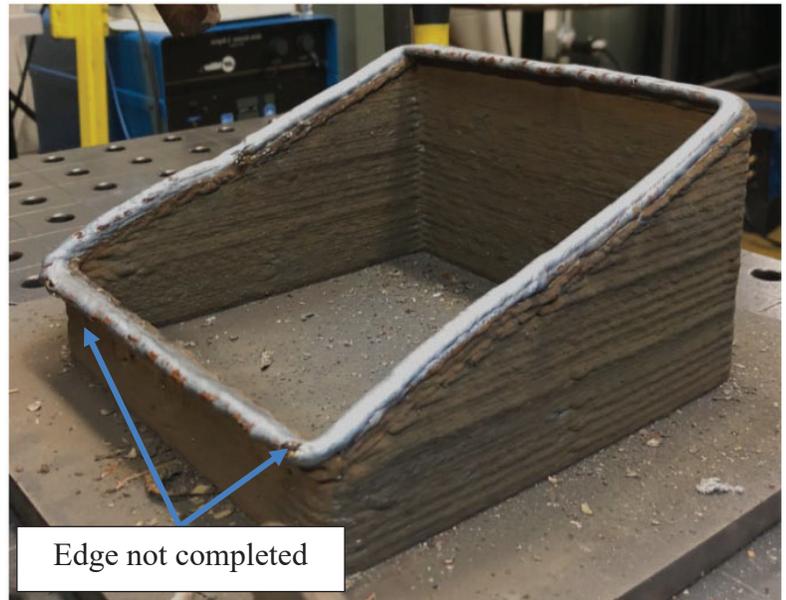


Figure 8 - Results of Initial Complex Part Build. The build was successful up until the NGA sections.

NGA Experimentation

After the initial complex part was unsuccessful, researchers decided to try and isolate the NGA section for further experimentation. The goal was to determine what best techniques could be used to help counteract the effect that gravity plays on the weld pool in NGA orientations. Initial work from [2] helped guide initial ideas on varying torch angle to help counteract gravity effects. Researchers also focused on defining a sequencing

technique for the NGA section to help improve the ability of welding in NGA sections. Researchers decided to weld only the NGA sections at 45-degrees to test different ideas on improving NGA sections.

Initial 45-Degree Test

The first test was to see if rotating the torch would help counteract the gravity effects seen in the NGA sections. Initially, researchers modified the torch angle just slightly from parallel and attempted to build with a similar sequence to the NGA section seen in Figure 6. The torch angle plan can be seen in Figure 9. The torch angles

were just slightly modified and the layers alternated direction and started and ended on the midpoint of the four sections.

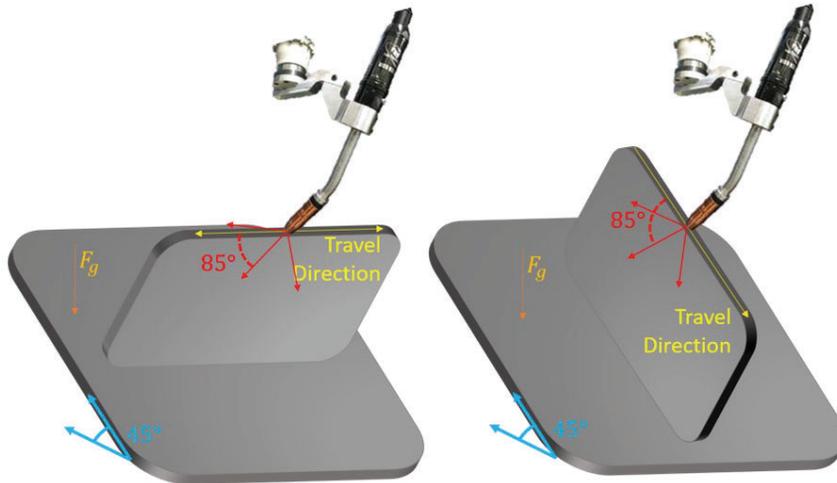


Figure 9 - Initial 45 Degree Torch Angles with similar layer sequence. The horizontal(left) and vertical(right) sections have the same torch angle variability.

sections had a much cleaner top geometry since they were held up by the torch angle during deposition. The bumpiness and variability of layer height contributed greatly to the part plan not predicting the exact height during the build. However, in general the initial NGA section welded at 45 degrees was much more successful than the initial complex part NGA

Therefore, it was decided from this result that a different layer sequence must be attempted that could eliminate uphill welding. Since the sequence was changed, there would have to be more stop/start points on the top layer to only weld downhill. Varying the torch angle also helped the vertical and horizontal sections hold the weld pool against gravity and provided more stability for the arc in the NGA orientations.

Downhill Welding Sequences

After determining that varying only torch angle was not sufficient for producing consistent layers for NGA sections, researchers decided to modify the sequence to only have downhill welding sections in the vertical sections. The horizontal sections would have multiple start/stop points, and the effects of welding downhill to produce consistent layers could be identified. By combining a variable torch angle and a unique sequencing for NGA sections a consistent layer growth could be achieved for both the vertical and horizontal sections.



Figure 10 - Initial 45-degree part results. Note the bumpiness in the vertical sections while the horizontal sections had a much smoother surface.

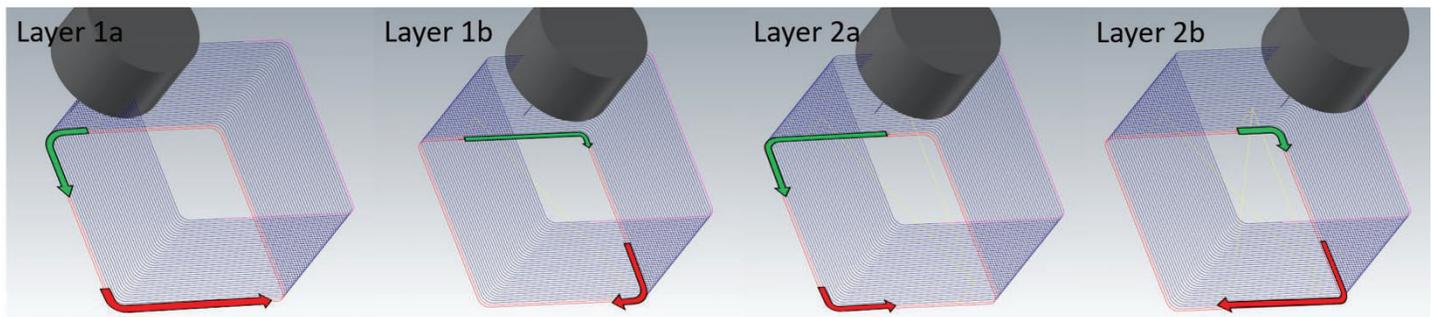


Figure 11 - New two-start sequence. Green indicates the starting layer with red indicating the end of that layer. The layers are alternated for the entire build.

The initial new sequencing is outlined within Figure 11. The sequencing required two start/stop points along the top layer so that both vertical sections could be welded downhill. Initially, only minimal layer heights were achieved due to the effects of the welding angle along with the new sequencing. Researchers decided to isolate the effects of the sequencing from the angle to help ensure that the new sequencing was effective in producing a closer near net shape than the old sequence. If more layers could be built than the previous NGA segment using a different sequence, it can be considered an improvement on the stability of the process to grow layer to layer. The result of the new sequence perpendicular to the 45-degree plate in both the horizontal and vertical section can be seen in Figure 12.

While more layers were achieved than the initial 45-degree part in Figure 10, the results of the layer growth are vastly different. The upper surface is much smoother to the eye in the two-start sequencing, but the layer growth was more consistent when the welding sequence included uphill and downhill welding in the vertical sections. The layers also seemed to build up on the bottom of the part, since the weld pool was always traveling downhill. On the horizontal sections, the start/stop points could easily be identified due to a variation of heat and mass input from the arc ramp up and down for beginning and ending layers.



Figure 12 - Side and Top View for new sequence 45-degree build.

While the results were a mixed success, researchers considered that a combination of proper torch angles in the vertical and horizontal sections alongside a new sequencing should improve the ability to build new NGA sections. Note for all of these builds the process parameters were not changed; only sequencing and torch angle were improved. All of these builds were completed open loop, without any real time control to keep layer height consistent. Ideally a robust LSAMM system would have a combination of pre planning and real time control strategies to help maintain a consistent layer height and resultant layer geometry.

New Complex Part Build

Researchers were encouraged from the results of the 45-degree builds to attempt the complex part again with a new torch angle and sequencing. The same process was followed from the first complex build by building the path plan through MasterCam and Octopuz to allow modification and simulation of the machine code for the

robot. The design of the new sequencing can be seen in Figure 13. The sequencing of the NGA section was modified to have 5 start/stop points along the horizontal sections to help mitigate the effects of the humps seen in Figure 12. All vertical sections were welded downhill to help improve top surface quality and to have a more consistent layer height for the build. The sequencing of the GA and Transition segments were not changed from the initial complex part build.

Segment Planning for GA, Transition, and NGA Sections

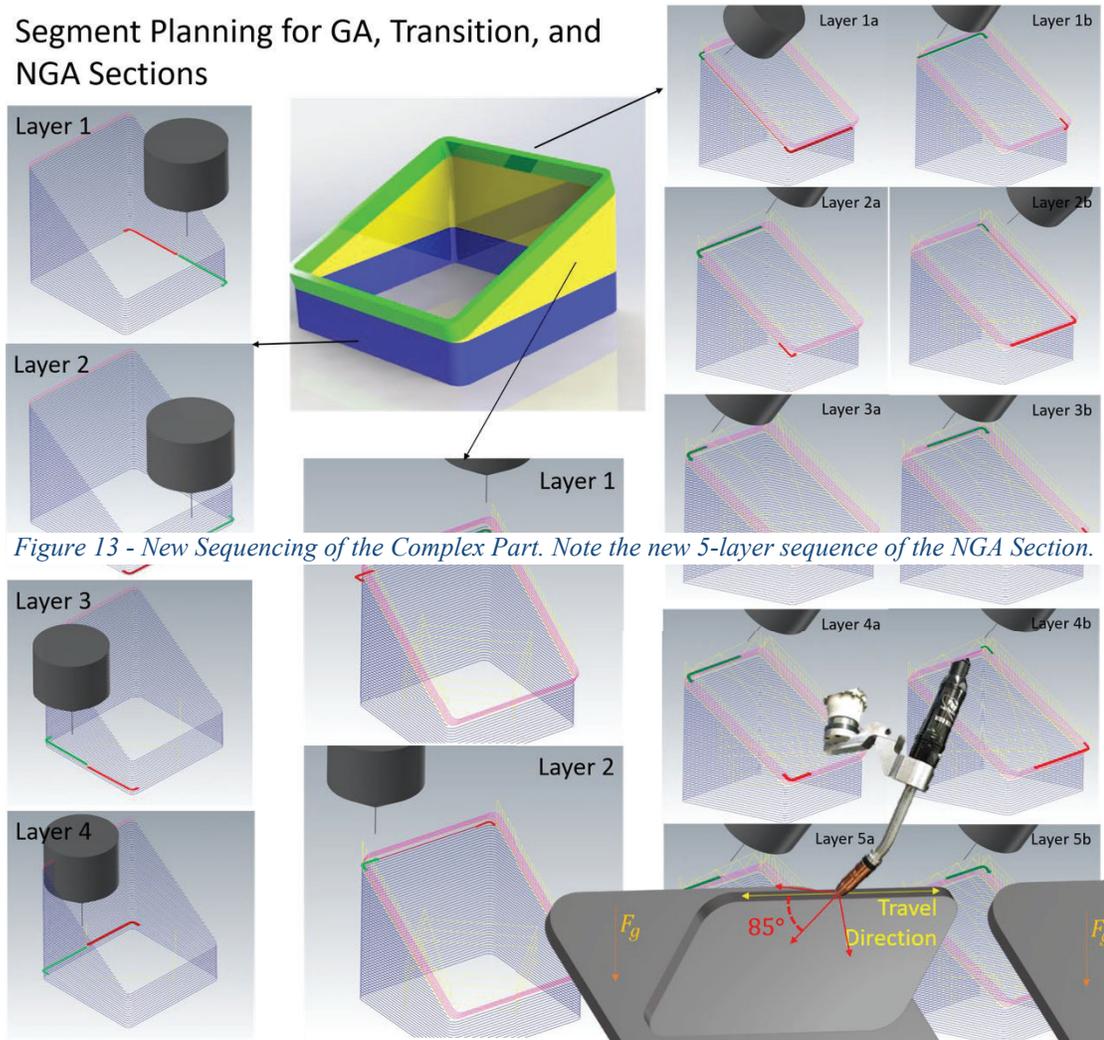


Figure 13 - New Sequencing of the Complex Part. Note the new 5-layer sequence of the NGA Section.

The torch angles for the new complex part can be seen in Figure 14. The torch angles were slightly different in both the vertical and horizontal sections. Since the horizontal sections worked relatively well at any

angle, they were only put 5 degrees off the 45-degree plate. The vertical sections had a steeper torch angle to help mitigate the downhill welding pooling effect at the bottom of the section, in an effort to get similar growth in the vertical and horizontal sections. The welding settings were the same for this part as were on the initial complex part build, as to keep consistent results.

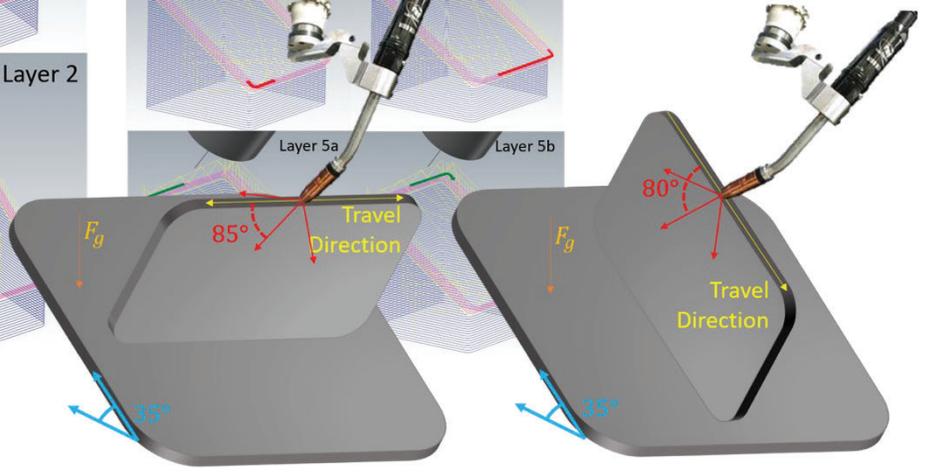
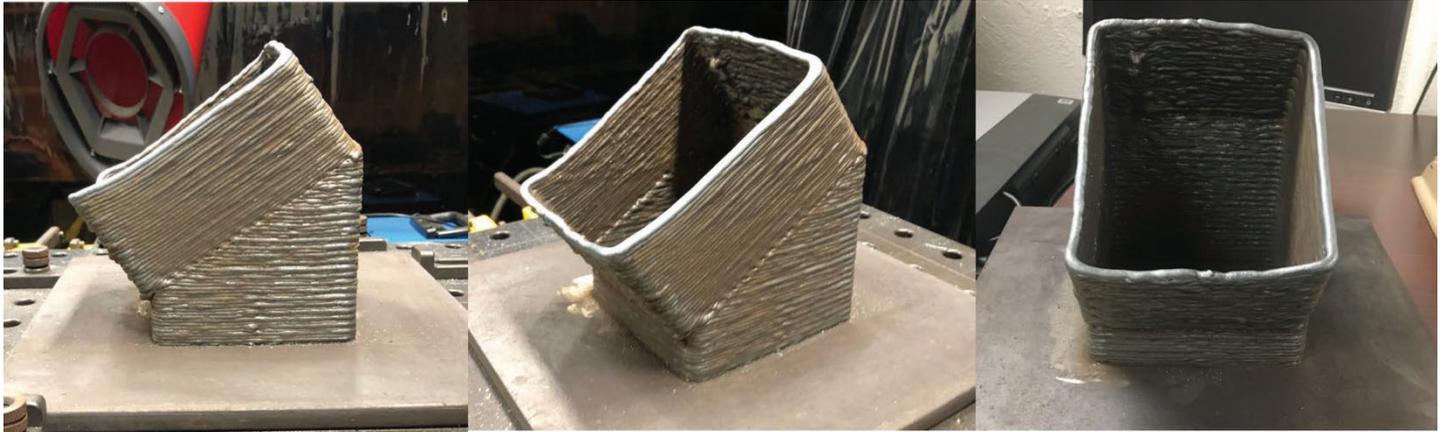


Figure 14 - Torch angles for the horizontal and vertical sections of the new complex geometry sequence.

The results of the build can be seen in Figure 15. The build was successful and completed all 30 programmed layers of the NGA section. The new sequencing and torch angles proved successful to build the NGA sections. It is determined now that it is more than feasible that through a combination of new sequencing, angles, and power settings that NGA segments can be implemented into LSAMM for more complex geometries. The success of

Figure 15 - Results of the new complex geometry with a new sequencing for the NGA sections.

these builds and experimentations can be used to help modify the existing framework for LSAMM planning which should help part planners reach a better near net shape.



Conclusions and Future Work

From the current research results, researchers have proved that by modifying just the sequencing and torch angle in the path planning section will help improve near net shape of complex geometries with NGA sections. The effects of variable bead height, more robust real time weld pool control, and new types of sequencing and slicing strategies need to be considered for future work. Future research will focus on extending the ability of LSAMM systems to build complex parts with integrated NGA sections. Commercially available slicers do not typically have this type of capability so tools to build integrated complex geometries need to be developed to improve research in this area. If these tools can be developed and integrated with experimental results from NGA welding segments, novel approaches to planning and programming LSAMM parts using WAAM can be considered. A deeper dive into horizontal versus vertical sections during LSAMM using WAAM has begun, with initial results that can be seen in Figure 16. The walls in Figure 16 were produced with a simple sequence and perpendicular torch angle; but the real effect of colder welding settings can be seen to produce overhangs up to 105 degrees – if not further. A combination of sequencing, torch angle, and process parameters can be used to produce a high degree of overhang in the horizontal orientation, but integrating vertical and horizontal overhang sections into an automatically planned framework will be the main focus of future research.

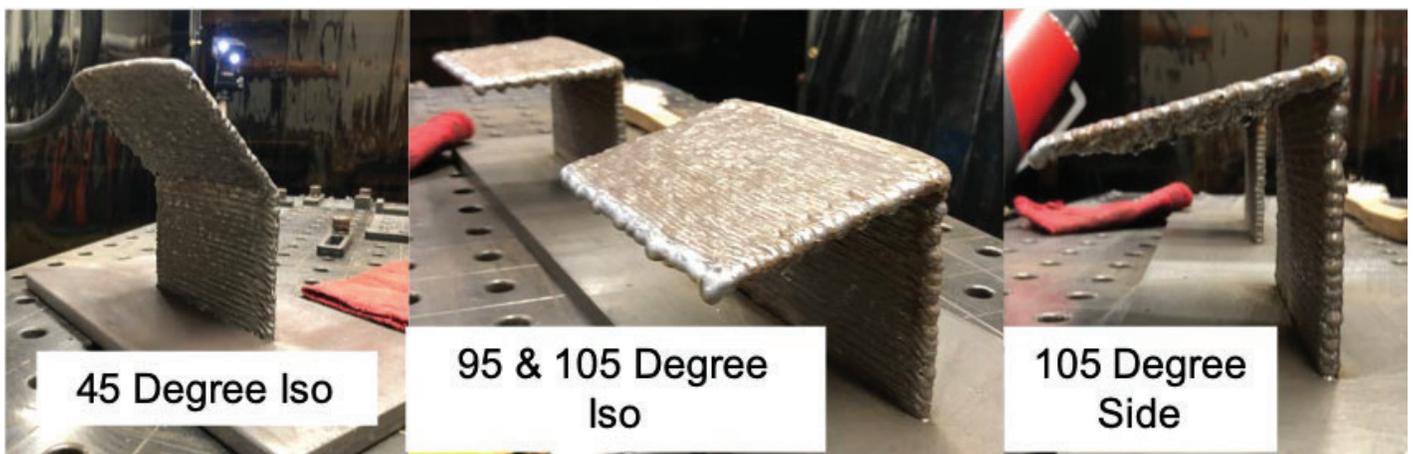


Figure 16 - Recent Experimental results of horizontal oriented overhang sections. The sequencing was alternating directions and keeping torch angle perpendicular to the build.

Bibliography

- [1] Donghong Ding, Chen Shen, Zengxi Pan, et al. “Towards an automated robotic arc- welding based additive manufacturing system from CAD to finished part”. In: *Computer Aided Design* 73 (2016), pp. 66–75. issn: 0010-4485.
- [2] S. W. Williams, F. Martina, A. C. Addison, et al. “Wire + Arc Additive Manufacturing”. In: *Materials Science and Technology* 32.7 (2016), pp. 641–647. issn: 0267-0836.
- [3] William J Sames, FA List, Sreekanth Pannala, et al. “The metallurgy and processing science of metal additive manufacturing”. In: *International Materials Reviews* 61.5 (2016), pp. 315–360. issn: 0950-6608.
- [4] William E Frazier. “Metal additive manufacturing: a review”. In: *Journal of Materials Engineering and Performance* 23.6 (2014), pp. 1917–1928. issn: 1059-9495.
- [5] Andrzej Nycz, Adeola I Adediran, Mark W Noakes, et al. “Large scale metal additive techniques review”. In: *Proceedings of the 27th Annual International Solid Freeform Fabrication Symposium*.
- [6] Benjamin Shassere, Andrzej Nycz, Mark W Noakes, et al. “Correlation of Microstructure and Mechanical Properties of Metal Big Area Additive Manufacturing”. In: *Applied Sciences* 9.4 (2019), p. 787.
- [7] Jayaprakash Sharma Panchagnula and Suryakumar Simhambhatla. “Manufacture of complex thin-walled metallic objects using weld-deposition based additive manufacturing”. In: *Robotics and Computer-Integrated Manufacturing* 49 (2018), pp. 194–203. issn: 0736-5845.
- [8] Rajeev Dwivedi and Radovan Kovacevic. “Automated torch path planning using polygon subdivision for solid freeform fabrication based on welding”. In: *Journal of Manufacturing Systems* 23.4 (2004), pp. 278–291. issn: 0278-6125.
- [9] GQ Jin, WD Li, CF Tsai, et al. “Adaptive tool-path generation of rapid prototyping for complex product models”. In: *Journal of manufacturing systems* 30.3 (2011), pp. 154– 164. issn: 0278-6125.
- [10] Andrzej Nycz, Mark Noakes, and Maciej Cader. “Additive Manufacturing—A New Challenge for Automation and Robotics”. In: *Conference on Automation*. Springer, pp. 3– 13.
- [11] Donghong Ding, Zengxi Pan, Dominic Cuiuri, et al. “A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM)”. In: *Robotics and Computer- Integrated Manufacturing* 31.Supplement C (2015), pp. 101–110. issn: 0736-5845. Page 33 PhD Proposal 2019
- [12] Alexandre Dolgui and A Pashkevich. “Cluster-level operations planning for the out-of- position robotic arc-welding”. In: *International Journal of Production Research* 44.4 (2006), pp. 675–702. issn: 0020-7543.
- [13] J Ding, P Colegrove, J Mehnen, et al. “A computationally efficient finite element model of wire and arc additive manufacture”. In: *The International Journal of Advanced Manufacturing Technology* 70.1-4 (2014), pp. 227–236. issn: 0268-3768.
- [14] YuMing Zhang, Yiwei Chen, Pengjiu Li, et al. “Weld deposition-based rapid prototyping: a preliminary study”. In: *Journal of Materials Processing Technology* 135.2 (2003), pp. 347–357. issn: 0924-0136.
- [15] John J Lewandowski and Mohsen Seifi. “Metal additive manufacturing: a review of mechanical properties”. In: *Annual Review of Materials Research* 46 (2016), pp. 151– 186. issn: 1531-7331.
- [16] Marco Livesu, Stefano Ellero, Jona`s Martínez, et al. “From 3D models to 3D prints: an overview of the processing pipeline”. In: *Computer Graphics Forum*. Vol. 36. Wiley Online Library, pp. 537–564. isbn: 1467-8659.
- [17] Donghong Ding, Zengxi Pan, Dominic Cuiuri, et al. “Wire-feed additive manufacturing of metal components: technologies, developments and future interests”. In: *The International Journal of Advanced Manufacturing Technology* 81.1 (2015), pp. 465– 481. issn: 1433-3015.
- [18] Wei Gao, Yunbo Zhang, Devarajan Ramanujan, et al. “The status, challenges, and future of additive manufacturing in engineering”. In: *Computer-Aided Design* 69 (2015), pp. 65–89. issn: 0010-4485.