CRANFIELD UNIVERSITY

F. MICHEL

INVESTIGATION OF A PATH PLANNING SOLUTION FOR WIRE + ARC ADDITIVE MANUFACTURE

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING
Welding Engineering and Laser Processing Centre

PhD Thesis
Academic Year: 2018–2019

Primary Supervisor: Dr H. Lockett
Secondary Supervisor: Dr J. Ding
December 2018

CRANFIELD UNIVERSITY

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING
Welding Engineering and Laser Processing Centre

PhD Thesis

Academic Year: 2018–2019

F. MICHEL

Investigation of a Path Planning Solution for Wire + Arc Additive Manufacture

Primary Supervisor: Dr H. Lockett
Secondary Supervisor: Dr J. Ding
December 2018

Abstract

Wire + Arc Additive Manufacturing (WAAM) has become a crucial asset for industrial manufacturing in the field of medium to large metallic deposition thanks to its high-rate deposition of various metals, its low-cost equipment and a potentially unlimited build volume. A key element for commercial deployment is to develop an intuitive path planning software, which can determine the optimal deposition strategy, whilst respecting WAAM's constraints inherent to arc welding deposition.

Traditional approaches to additive manufacturing path planning are often derived from CNC machining, but these strategies are incompatible with some fundamental characteristics of WAAM. For this reason, the present work aims to investigate a path planning solution entirely focused on the WAAM requirements. The architecture of a Path Generator Framework for WAAM is, thus, first introduced to offer complete freedom of path planning development all along this study. To validate the developed framework, a feature-based approach is presented: this allows the fast and efficient deployment of the WAAM technology for a limited range of geometric features and sets up the basis of path planning for WAAM. Then, a more flexible solution called Modular Path Planning is introduced to incorporate the modularity of feature-based design into the traditional layer-by-layer build strategy. By assisting the user in dividing each layer into individual deposition sections, this method enables users to adapt the path strategy to the targeted geometry allowing the construction of a wide variety of complex geometries. Finally, a deep learning solution called DeepWAAM is proposed to reach, in the future, a fully automated path planning solution for WAAM by automatically dividing build layers into deposition sections with no need for user intervention.

Keywords

WAAM; Wire and Arc Additive Manufacturing; Path planning; Toolpath generation; Robotics simulation framework; WAAM Platform; Deep Learning; Machine Learning; Neural Network; AI

Contents

List of Figures

List of Tables

List of Abbreviations

AM	Additive Manufacturing
API	Application Programming Interface
APP	Assisted Path Planning
AuPP	Automated Path Planning
BS	Building Strategy
CAD	Computer Aided Design
CMT	Cold Metal Transfer
CNC	Computer Numerical control
CNN	Convolutional Neural Network
DLL	Dynamic-Link Library
FDM	Fused Deposition Modeling
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
GUI	Graphical User Interface
HIP	Hot Isostatic Pressing
IGES	Initial Graphics Exchange Specification
IoU	Intersection over Union
MAT	Medial Axis Transformation
ML	Machine Learning
MPP	Modular Path Planning
NNs	Neural Networks

NN	Neural Network
PPathItem	ProcessedPathItem
PPath	ProcessedPath
SLS	Selective Laser Sintering
STL	STereoLithography
TCP	Tool Center Point
TS	Travel Speed
WAAM	Wire + Arc Additive Manufacture
WFS	Wire Feed Speed
XML	Extensible Markup Language
mIoU	mean Intersection over Union

Acknowledgements

First of all, I would like to express my gratitude to Prof. Stewart Williams and the WAAM-Mat program for giving me the opportunity to make this PhD a reality by supporting financially my research.

I cannot thank my wonderful supervisors enough for being so helpful throughout my PhD. Thank you, Dr Jialuo Ding, for sharing your inexhaustible technical knowledge, and thank you, Dr Helen Lockett, for all your time and support, week after week, I know how lucky I was to have you as a supervisor. Thank you also, Dr Filomeno Martina for your precious comments, your reputation precedes you and I hope we have other opportunities to work together again.

Thank you to all the fantastic colleagues, students and staffs of the Engineering and Laser Processing Centre. Gianrocco, Eloise, Jan, Leo, Kwasi, Xiangfang, Junny, Sergio and so on, you all made me feel part of a big family and transformed this research centre into a fantastic workplace, somehow difficult to leave.

I also thank my parents for always supporting me and my life decisions, even when it means to live far from home.

Finally, I will never be able to thank you enough Marjorie, for all the help, the support and the love you gave me every day throughout this entire journey. I could not have done it without you.

Publications and conferences

Publications

Paper A: *"Path Generator Framework for Wire + Arc Additive Manufacturing", F. Michel, H. Lockett, J. Ding, S. Williams.* This paper presented in **Chapter 3** is ready for submission.

Paper B: *"A feature-based path planning approach for Wire + Arc Additive Manufacturing", F. Michel, H. Lockett, J. Ding, S. Williams.* This paper presented in **Chapter 4** will be submitted to a conference.

Paper C: *"A modular path planning solution for Wire + Arc Additive Manufacturing", F. Michel, H. Lockett, J. Ding, F. Martina, S. Williams.* This paper presented in **Chapter 5** has been published in the Robotics and Computer-Integrated Manufacturing journal.

Paper D: *"DeepWAAM: A deep learning approach for Wire + Arc Additive Manufacturing path planning", F. Michel, H. Lockett, J. Ding, F. Martina, S. Williams.* This paper presented in **Chapter 6** is ready for submission.

Conferences

ICWAM 2017: *"From CAD Models to Parts: Software Development for the Wire+ Arc Additive Manufacture Process", F. Michel, H. Lockett, J. Ding, F. Martina, S. Williams*. Metz Arsenal, France (17 May 2017).

CAMA 2017: *"WAAMSoft: Path Planning Platform for WAAM", F. Michel, H. Lockett, J. Ding, S. Williams*. Bremen Airport, Germany (13 December 2017).

Chapter 1

Introduction

1.1 Research background

Additive Manufacturing (AM) is a production method which fabricates parts by joining material layer-by-layer as opposed to subtractive manufacturing processes such as conventional machining. Once called Rapid Prototyping (RP), this technology has been initially limited to the prototyping application where it quickly revolutionised the field. Eventually, AM naturally evolved to an end-use production as it successfully improved manufacturability by reducing lead-time, tooling, waste and manufacturing constraints. Today, the technology is well established in a wide variety of industrial sectors, from healthcare to aerospace, leading the way to the emergence of numerous specialised AM technologies.

In the field of medium to large metallic deposition, Wire + Arc Additive Manufacture (WAAM) is considered to be a solution with high potential for industrial application. As its name implies, WAAM is an AM process combining wire as feedstock and an electric arc as heat source to produce near-net-shape parts (Fig. 1.1). WAAM uses traditional welding processes like Gas Metal Arc Welding (GMAW) or Gas Tungsten Arc Welding (GTAW) driven by Computer Numerical control (CNC) machines or robotic manipulators (Fig. 1.2). This standard industrial equipment makes WAAM a relatively low-cost technology. Furthermore, the inherent characteristics of welding deposition provide a high-rate deposition of various metals such as steel, aluminium alloy or titanium alloy. As a result, the combination of low-cost equipment and high-rate deposition provides a potentially unlimited build volume, making WAAM a crucial asset for industrial manufacturing.

Figure 1.1: Half machined part built using the WAAM technology

As any AM technologies, WAAM requires a dedicated path planning solution for it to be adopted by a large commercial community; its role is to define the optimum deposition strategy while respecting WAAM's build rules. To reach the widest community, such a solution has to keep a relatively simple and intuitive interface. The complexity of developing this kind of software can vary substantially according to the AM technology. For example, the path generation for Selective Laser Sintering (SLS) is relatively straightforward since, like a traditional printer, it consists of scanning the deposition area and turning on the laser where deposition of parts or supports is required. In Fused Deposition Modeling (FDM), path planning can be relatively more complex, especially when it combines supports and structural reinforcement. However, FDM is quite robust, and its materials can accommodate deposition inaccuracies, especially at intersections. On the other hand, WAAM deposition quality is highly sensitive to the path strategy used, making WAAM path planning software particularly challenging to design.

Thus, since the development of WAAM, path planning has been an essential research

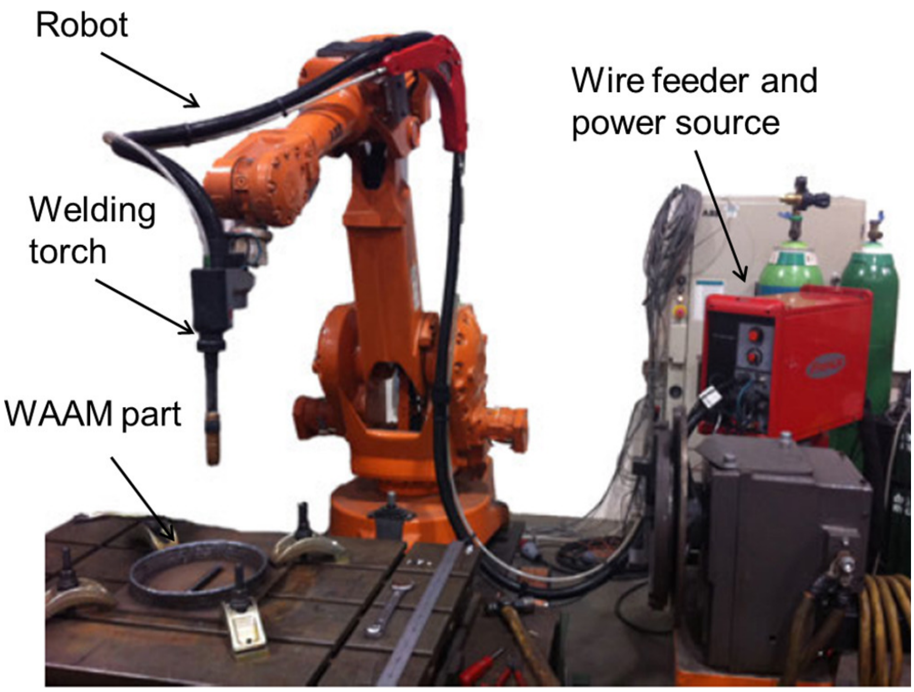


Figure 1.2: Robotic WAAM cell

matter to assure uniform deposition and structural integrity of the manufactured parts. In fact, some path planning solutions for WAAM have been proposed without yet reaching the commercial market. This present PhD study, entirely supported by the WAAMMat programme, aims, therefore, to facilitate the development of a practical path generator for WAAM.

1.2 Research gap

As highlighted in the literature review, a few path planning strategies for WAAM have been elaborated since the creation of this technology. However, at the best of our knowledge, some key research gaps have been identified and are at the foundation of this thesis:

- The WAAM deposition process involves unique requirements inherent to the welding technology. Yet, there is no path generator specifically adapted to WAAM available in the literature. This lack of appropriate research tool is, therefore, a constraint in the development of path strategies for WAAM.

- Path planning solutions for WAAM published in the literature are largely inspired by traditional subtractive technologies. They share, for that reason, a common approach which consists of adapting the path to the geometry shape. This approach results in a substantial variation in building quality. There is, however, no solution allowing users to segment the geometry into more controllable deposition sections.
- Although deep learning technologies have recently impacted many research fields, there is not yet any path planning strategies for WAAM integrating the deep learning efficiency towards an automatic path generation.

1.3 Aim and objectives

1.3.1 Aim

The aim of this project is to investigate and develop a path planning solution for WAAM. Taking into consideration WAAM's constraints, this program will be able to generate an optimised path deposition, from a wide range of 3D Computer Aided Design (CAD) models. This path will then be converted, using robotic plug-ins, into a machine code allowing the use of a wide variety of machines.

The goal of this project is not to develop full commercial software but to investigate a successful global structure for software and prove the feasibility of its key elements by developing a demonstrator software tool. Although some software code will be produced for the purpose of testing, the main outputs of this project will be the algorithms and structures that describe the software. Thus, it will provide a research basis for future commercial tools.

1.3.2 Objectives

To achieve the aim presented above, the following objectives will be targeted:

- Determine the current state-of-the-art of the field.

- Elaborate a path planning development tool adapted to WAAM, compatible with any manipulators, materials and welding technologies.

- Create a library of basic geometries with associated path planning strategies allowing the deposition of these geometries.

- Investigate a path planning solution for WAAM allowing the deposition of any geometries using layer-by-layer strategy.

- Explore the integration of machine learning solutions to achieve a fully automated path generator for WAAM.

- Produce successful algorithms and structures allowing the future development of commercial software.

1.4 Research methodology

The purpose of the study is to investigate a new path planning solution for WAAM that can fulfil the industry requirements and assure quality deposition of a large variety of complex geometries. As this study focuses mainly on software engineering, it was decided to use a constructive research approach and is structured as followed.

First, a literature review will be performed to identify the state-of-the-art of the WAAM path planning field to highlight the main research gaps and the current techniques used in WAAM to build parts.

Exploratory research will also be conducted by performing experiments to develop several simple shapes such as walls and cylinders and using different paths strategies. These path strategies will be manually designed and inspired by the available literature, which will allow us to highlight the essential WAAM requirements and constraints.

Then, based on the knowledge gained through the development of features, a novel path planning solution for WAAM will be developed. The algorithms and structures for the path planning solution will be designed and efficient software implementation of the proposed solution will be detailed.

Finally, to validate the effectiveness of this study, the deposition quality of the proposed solution will be compared to the state-of-the-art. Two factors will be taken into account: the uniformity of the layer height along with the deposition and the presence of defects in the deposition. Furthermore, the new path planning solution will be used to build a real industrial part to validate its ability to produce complex parts within the industry requirements.

Additionally, a proof of concept study will be conducted to overcome some limitations of the proposed path planning solution. Thus, the feasibility of using deep learning solutions to perform path planning segmentation automatically will be investigated and validated through statistical results as well as real-world application.

1.5 Outline of the thesis

The current dissertation is structured as a paper format following the instructions of Cranfield University. This structure has been chosen to facilitate the submission of each paper to peer-reviewed journals. Thus, the present thesis is composed of 8 chapters altogether. Chapters 3 to 6 contain the papers representing the main research work conducted during the PhD and its major outcomes. Additionally, chapters 1, 2, 6 and 7 concern, respectively, the introduction, the literature review, the overall discussion and the conclusion to demonstrate the coherence of the work and ease its readability. Brief descriptions of the chapters are presented below:

- **Chapter 1** contains the Introduction of this dissertation, starting with a brief research background. This chapter also highlights the research gaps as well as the aim and objectives of this research. Finally, the outline of the thesis is also described.

- **Chapter 2** presents the literature review containing a general background of the

AM technologies with particular focus on the metal deposition and the WAAM technology. Then a review of both the AM path planning strategies and the feature-based approach are proposed.

- **Chapter 3** contains **Paper A** titled: *"Path Generator Framework for Wire + Arc Additive Manufacturing"*. This study was motivated by the lack of a robotic path generator entirely focused on the WAAM requirements. Traditionally, path planning solutions are developed using standard CAM software, initially developed for conventional subtractive processes. However, this approach requires modifying the original software to fit the specific properties of WAAM, making path planning research substantially slower and more difficult. Moreover, using tools adapted to other processes, although similar, confines the thinking process into the ability of the tool. Therefore, the presented paper introduces the architecture of a Path Generator Framework entirely focused on the WAAM requirements to facilitate later the investigation of a path planning solution for WAAM.

- **Chapter 4** contains **Paper B** titled: *"A feature-based path planning approach for Wire + Arc Additive Manufacturing*. This study presents the feature-based approach as an alternative solution to path planning strategies for WAAM. In this paper, features, which are defined as geometrical entities associated with one or multiple path strategies, are described through the presentation of the feature library developed at the Cranfield University. Although this study mostly aims to highlight the fundamental rules required to master the complex behaviour of the WAAM deposition, it also shows the advantages of the feature-based approach in a research or a commercial environment.

- **Chapter 5** contains **Paper C** titled: *"A modular path planning solution for Wire + Arc Additive Manufacturing"*. This study represents the primary outcome of this PhD as it proposes a new approach to path planning for WAAM. Based on the knowledge gained through the development of features, this solution offers users the ability to adapt the path planning strategy to the geometry. Thus, by dividing sliced layers into individual sections, this presented method guarantees better deposition stability and control over interconnections.

- **Chapter 6** contains **Paper D** titled: *"DeepWAAM: A deep learning approach for Wire + Arc Additive Manufacturing path planning"*. In the previous chapter, a new path planning strategy for WAAM was presented. Although this approach improves the building quality by integrating users' expertise into the path generation process, it also increases the processing time and requires experienced users. To overcome these issues, the paper presented in this chapter investigates the feasibility of using deep learning solutions to perform path planning segmentation automatically.

- **Chapter 7** includes the overall discussion of this entire thesis. Thus, a research overview is firstly presented, followed by the contribution to knowledge and finally, the possible impacts on future applications.

- **Chapter 8** finalises this dissertation by formulating the research conclusion and opens an overview of the potential future work following this thesis.

- **Appendix A** contains additional information regarding Chapter 5 to support its research content.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a general background of the AM technologies with particular focus on the metal deposition and the WAAM technology. Then a review of both the AM path planning strategies and the feature-based approach are proposed. Finally, a brief introduction of the image segmentation is given as it can be relevant to automating the path planning process.

2.2 Additive Manufacturing

Additive Manufacturing (AM) is a process that consists in reproducing a model initially designed by a 3D Computer Aided Design (CAD) software (Fig 2.1). To achieve this reproduction, the basic approach is to deposit material layer-by-layer following the 3D CAD model previously sliced. Specific software has been developed to automatically slice geometries and generate code that will be sent to the appropriate machine [1].

However, as the deposited layer has a thickness which depends on the technology and the material used, the result is a near-net-shape product that requires in most cases post-production (sanding, tumbling, etc.).

AM was previously called and is still very often referred as Rapid Prototyping for the

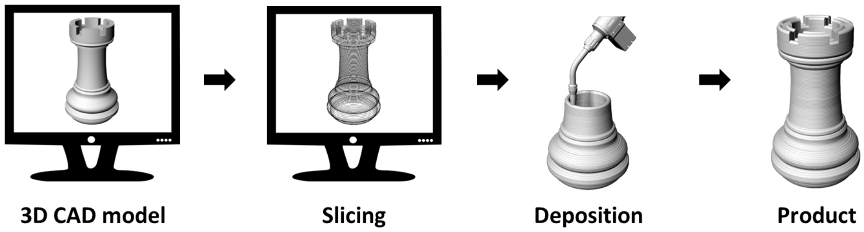


Figure 2.1: Additive Manufacturing process

simple reason that this technology was used to quickly build mock-up, allowing users to appreciate the form of their design or check if it fits in an assembly. However, following the rise of computing power, manipulators and 3D CAD software quickly increased their quality. Therefore, Rapid Prototyping started to output end-use products, forcing the process to be renamed as Additive Manufacturing [1].

AM has numerous benefits that make it popular in industry, such as its ability to reduce the production time significantly, due to the low amount of manufacturing steps. Indeed, whereas in traditional processes each new feature on a product may dramatically increase the number of operations to apply (milling, pocketing, drilling, etc.), AM, regardless of the shape complexity, will count only one deposition stage. Therefore a company will also require fewer skills to develop a multi-feature product. Thus this simplicity will easily enable to change the design without having to redefine the manufacturing process. Otherwise, this technology permits low volume manufacturing and even individual tailor product. Finally, AM can build full assemblies, reducing the number of pieces [1].

Early development of the AM technology was mainly focused on polymer materials limiting its impact on industry. However, metal deposition has more recently become a major field of research, as presented in the following section.

2.3 Metal Additive Manufacturing

AM has proved its efficiency as a new manufacturing process. However, as metal manufacturing is still a major part of industry, metal deposition is a fundamental element for the future of industrial manufacturing [2]. Numerous techniques have been developed and successfully commercialised through many different trade names [3]. The three main concepts are presented in the following sections.

2.3.1 Powder bed fusion

Selective Laser Sintering (SLS) [4], Selective laser melting (SLM) [5] or Direct Metal Laser Sintering (DMLS) [6] are all technologies relying on the same setup. The process, as it can be seen on Fig 2.2, is composed of two main steps: first, a rake spreads some metal powder on the bed, and then a laser melts distinct areas of the spread powder. Once these two steps are completed, a metal layer is obtained. This operation is repeated to build the full geometry.

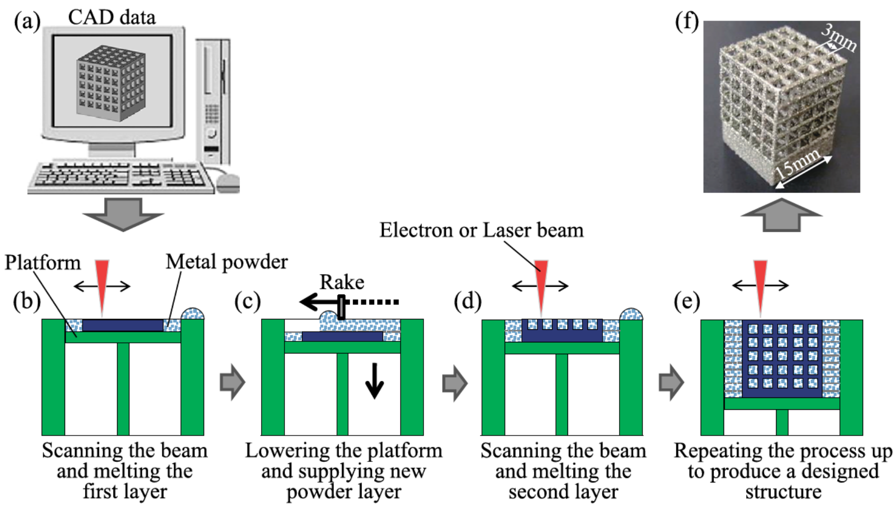


Figure 2.2: Powder bed fusion process overview [7]

This technology is widely used in an industrial situation [8] due to a good finish surface, high precision deposition and the capability of building complex shape without supports [7]. However, this setup can be relatively expensive; it has a slow deposition rate and deposited components are limited to the bed size [8].

Additionally, some technologies like Electron Beam Melting [9] used an alternative heat source that provides better mechanical properties. Nonetheless, using electron beam as a heat source required high vacuum, making it even more expensive [8].

2.3.2 Powder blower

Laser Powder Deposition (LPD), Laser Engineered Net Shaping (LENS) [10] or Laser Forming [11] also melt metal powder to produce metallic components. However, in this case the powder is directly projected into a melted pool which is localised at the focus point of the laser (cf. Fig 2.3). This melted pool is continuously moving and follows a path determined ahead by CAD software [10].

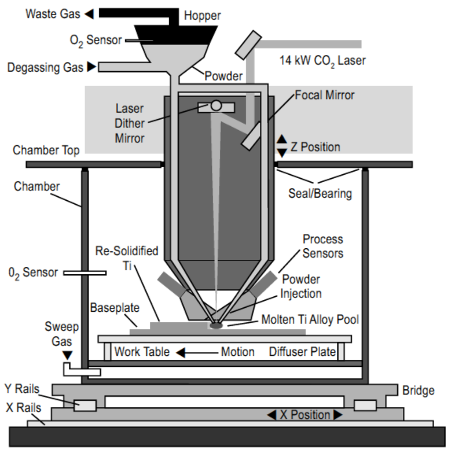


Figure 2.3: Powder blower process overview [11]

This process improves the mechanical properties of the deposited component. However, it produces a poor surface deposition quality [8].

2.3.3 Wire feeder

Wire feeder technologies are using a very similar process to the powder blower. Indeed, here again, a melted pool is continuously moving following a predetermined path. Nevertheless, instead of using powder, a wire is used to feed the melted pool (cf. Fig 2.4).

Similar heat sources are also used: a laser in the case of Laser Additive Layer Manufacturing (LALM) [3] or Laser Additive Manufacture (LAM) [12] and an electron beam in the case of Wire-based Electron Beam Direct Manufacturing (EBDM) [13] or Electron Beam Freeform Fabrication [14].

This research focusses on Wire + Arc Additive Manufacture (WAAM) which, as opposed to the presented technologies, is using an arc as heat source. This particularity gives

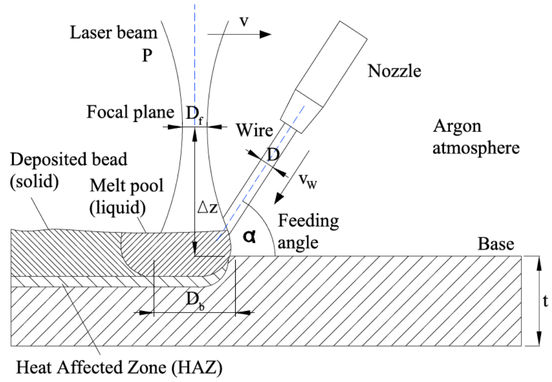


Figure 2.4: Wire feeder process overview [3]

WAAM a high rate of deposition as well as a larger deposition area. This technology will be explained in more details in the next section.

2.4 Wire and Arc Additive Manufacturing

As its name implies, Wire + Arc Additive Manufacture (WAAM) is an AM process. Therefore some characteristics that define AM are also parts of WAAM, such as the deposition layer-by-layer and a near-net-shape product as result.

However, the particularity of WAAM is to deposit weld metal beads to produce 3D metallic components [15]. To do so, WAAM uses traditional welding processes like Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) [15]. These welding technologies are driven by Computer Numerical control (CNC) machines or robots [16] and enable the deposition of various metals such as Steel, Aluminium alloy or Titanium alloy [15](cf. Fig 2.5).

WAAM's main asset is its high deposition-rate allowing the deposition of large components in a reasonable time [16]. Moreover, due to the relatively low cost of material and equipment, the deposition area can be significantly extended without exponentially increasing the system cost, as it can be the case with other technologies. Additionally, WAAM also allows the construction of components with excellent structural integrity [16].

One of the key challenges for industrialising this technology is the transaction between

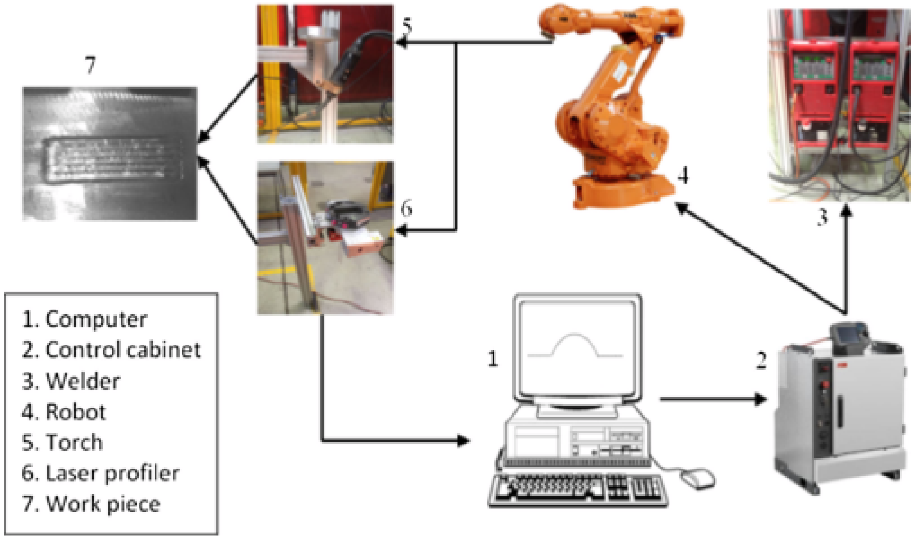


Figure 2.5: Experimental WAAM system [17]

the 3D CAD model and the deposition stage. Indeed, to operate manipulators, a path needs to be generated by analysing the CAD model. This stage is necessary for any Additive Manufacturing process but requires much more constraints in WAAM. Thus, traditional AM path planning approaches cannot be used due to the specific challenges of the welding deposition as introduced in the next section.

2.5 Path strategies

2.5.1 AM path strategies

In AM, the path strategy defines a generation process of the manipulator trajectory to fill the 2D layers representing the cross-sectional geometry of an object. Many path strategies developed for the AM technology have been, in fact, adapted from subtractive manufacturing. Indeed, in both of these technologies the fundamental concept of path planning is to repeat a simple path by offsetting this one at each iteration. Two mains path strategies can be identified as the base of all path strategies: the raster pattern [18], which produces a set of parallel depositions within the cross-section (Fig. 2.6), and the contour method [19], which repetitively offsets the section boundary from outside to inside (Fig. 2.7) using, for both, a constant offset. Other patterns are either evolutions or mix of those two original patterns. Some exceptions can be found, such as the spiral deposition [20] (Fig. 2.8) or the Space-filling strategy [21, 22] (Fig. 2.9) but are rarely used in AM.

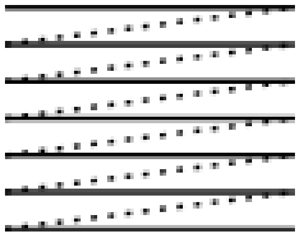


Figure 2.6: Raster pattern [18]

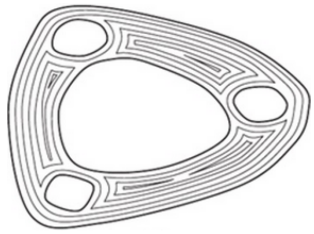


Figure 2.7: Contour deposition [19]

It should be noticed that traditional path planning strategies didn't focus on avoiding voids, overlaps or discontinuities given that technologies such as Fused Deposition Modeling (FDM) or Selective Laser Sintering (SLS) can handle those inaccuracies. Thus, these two primary patterns are poorly adaptable to the WAAM technology. Indeed, the raster deposition requires numerous retractions of the deposition (starting and stopping the deposition) which, as highlighted in the next section, is the cause of irregular deposition [23]. On the other hand, the contour method has the tendency to generate sharp turn, overlapping and gaps, which are all critical issues for the welding deposition [24].

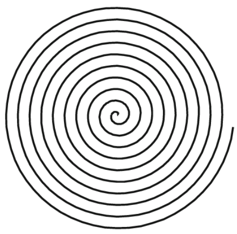


Figure 2.8: Spiral deposition [20]

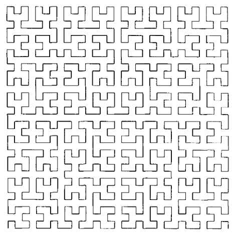


Figure 2.9: Space-filling strategy [21]

The inadequacy of traditional path planning strategies to the welding deposition has been known from the beginning of the WAAM development and are linked to the characteristics highlighted in the next section.

2.5.2 Criteria to avoid for WAAM path generation

Due to the specificity of the WAAM inherent of the welding deposition, some characteristics should be avoided in the path planning strategy to assure the uniform deposition of each layer. Thus, a list of criteria to avoid has been extracted from the literature so that it can be used to analyse the different path strategies available in the literature. This list of criteria is presented as followed:

- **Retraction:** The starting and stopping stages of the WAAM deposition are highly inconsistent and introduce some irregularities in the deposition. As these stages cannot be completely removed from the process, they should be limited or controlled to guarantee the deposition quality [23, 25].
- **Discontinuity:** A sudden direction variation of the path, called discontinuity or sharp-turn, induces disruptions on the deposition rate. These perturbations also create irregularities in the deposition of a layer and should, therefore, be limited if not completely avoided [23, 24].
- **Gap:** Gaps or voids consist of areas that have not been covered with material and are more likely to appear around discontinuities. These imperfections may not induce visible irregularities but will certainly lead to a structural failure. Gaps cannot be fixed in post-production and should, therefore, be absolutely avoided [17, 24].
- **Overlap:** When compared to other AM processes, WAAM is very sensible to overlaps. Indeed when the weld bead is deposited and solidified, it does not allow any flexibility. Overlaps are also more likely to appear around discontinuities and lead to irregular layer deposition [24].

2.5.3 WAAM path strategies

The first known study on WAAM path planning can be attributed to Zhang et al. [25] in 2003. Their approach was to mix two common path strategies: Zigzag and contour (Fig. 2.10). The idea was to counter-effect the poor deposition created at each sharp turn of the zigzag deposition by depositing a contour path on the boundary of the cross-section. However, this approach has a high chance to create gaps between the inside and outside paths, which is critical for the structural integrity of the finish part.

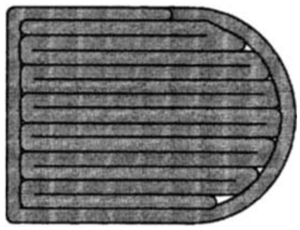


Figure 2.10: Hybrid path strategy [25]

Figure 2.11: Continuous path strategy [24]

Quickly after, in 2004, Dwivedi et al. [24] proposed a new pattern for WAAM. In their study, they acknowledged the retraction to be the main contribution of deposition irregularity. Thus, they proposed a new path strategy that generates a single and continuous deposition path for each layer (Fig. 2.11). This is achieved by subdividing a cross-section into a set of monotone polygons, generating a raster path on each polygon and connecting each path into a continuous path. The result of this approach has indeed for advantage to remove retractions completely, but it creates numerous sharp turns close to each other that can lead to overlapping or voids which are not preferable to the irregularity of the deposition.

More recently, in 2014 Ding et al. [23] proposed an updated version on the previous approach. In this study, they adapted the path generation so that the direction of the raster pattern is optimised in each sub-polygon (Fig. 2.12). This solution limits the number of discontinuities on some particular shapes, like hollow geometries, increasing the variety of buildable shape compare to the Dwivedi solution. However, discontinuities are still numerous, and if in the case of Dwivedi discontinuity were mostly happening on the boundary of the part (where defects can be removed in post-production), those discontinuities are frequently present inside the part that is very likely to end-up with voids.

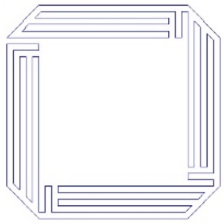


Figure 2.12: Mix path strategy [23]

Then, Ding et al. introduced an innovative solution using Medial Axis Transformation (MAT) that generates the geometry skeleton [17]. Starting from the skeleton, Ding et al. fill the geometry from the inside towards the boundary (Fig. 2.13). This strategy has considerable advantages over the previous ones as it can be applied to any shape, with or without holes and more importantly, it removes discontinuities, gaps and overlaps. However, this solution generates numerous retractions inside the cross-section and increases substantially wasted material that will need to be removed in post-production.

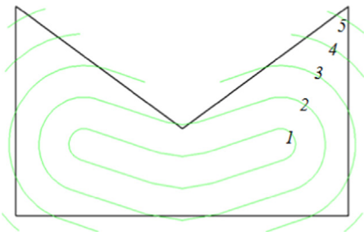


Figure 2.13: MAT path strategy [17]

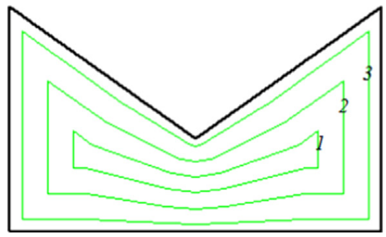


Figure 2.14: Adaptive MAT [26]

Finally, Ding et al. updated their previous strategy to create the adaptive path planning solution [26]. Like their previous work, the path generation starts from the skeleton of the part obtained by the MAT but in this case the layer is filled with a variable offset (Fig. 2.14). This solution can be seen as the state-of-the-art in the field of path generation for WAAM. However, compared to the previous method, this strategy decreases the waste of material, it re-integrates discontinuity inside the section similarly to the contour method which, as discussed previously, can disturb the uniformity of deposition.

2.6 Feature-based approach

In this study, we define features like Shah et al. [27] as a generic shape with which engineers can associate specific attributes like in our case some path strategies. Thus, in contrast with the path strategies research, the feature-based studies do not attempt to provide a path strategy that could be used to build any geometrical shapes but instead focus on providing solutions to build targeted geometries. Nevertheless, those studies, presented in the following sections, provide fundamental knowledge regarding the path generation for WAAM.

2.6.1 Inclined and horizontal walls

In their paper, Kazanas et al. [28] proposed a method to build inclined walls using a pyramidal shape at the base of the wall as it can be seen in Fig 2.15. This strategy enables a more flexible deposition strategy as it does not need support or rotation of the substrate. Additionally, an experiment has been conducted on building a horizontal wall using different torch angles and has shown the feasibility of building overhang parts with some flexibility of the torch position (cf. Fig 2.16).

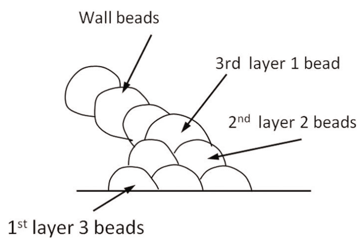


Figure 2.15: Inclined wall pyramidal solution [28]

Figure 2.16: Horizontal wall building with torch angle [28].

2.6.2 Closed and curved shapes

Following the successful deposition of inclined walls, Kazanas et al. [28] have proved the feasibility of building closed shapes. The strategy consisted of building two vertical walls and depositing an overhanging wall as previously. Results can be seen on Fig 2.17. Finally, a curved shape has been produced by building two carter circles and joining them in the middle (cf. Fig 2.18). However, in this case, a standard GMAW process has been preferred to Cold Metal Transfer (CMT) to achieve a better junction of both walls using a higher heat input.

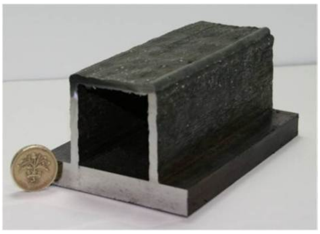


Figure 2.17: Enclosed structure with a section of 50 mm square [15]

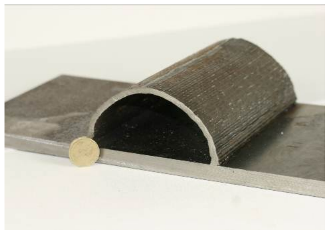


Figure 2.18: 50 mm radius semicircle [15]

2.6.3 Cross structure

Junctions are a key element to develop complex and variable geometries. In this purpose, Mehnen et al. [15, 29] have studied wall crossing and shown that the use of standard deposition strategy leads to a peak formation, followed by a deposition failure during the layers deposition (cf. Fig 2.19). Therefore, after experimenting with multiple build strategies, Mehnen et al. demonstrate that defects could be eliminated (cf. Fig 2.20) by using an appropriate building strategy illustrated in their paper.

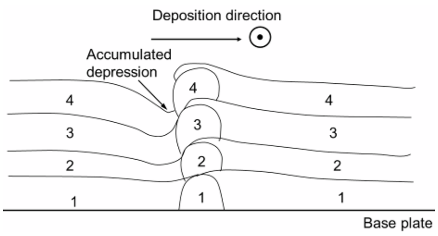


Figure 2.19: Schematic diagram of the development of deposition failure [15]

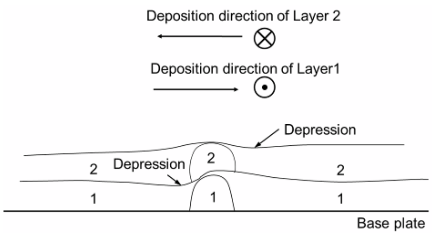


Figure 2.20: Elimination of deposition failure [15]

Similarly, Venturini et al. [30] studied the deposition of T-crossing and developed a building strategy to increase the deposition quality (cf. Fig 2.21). Unfortunately, such a strategy would significantly complicate the automatization of large geometries.

The feature-based approach has shown its ability to produce quality deposition of complex geometries and is today a solid solution for industries that produce a limited range of part geometries. This approach is also a good practice to learn the fundamental rules of WAAM technology and develop more complex solutions. However, the path planning strategies developed with this approach are not generalisable to any shape, making it

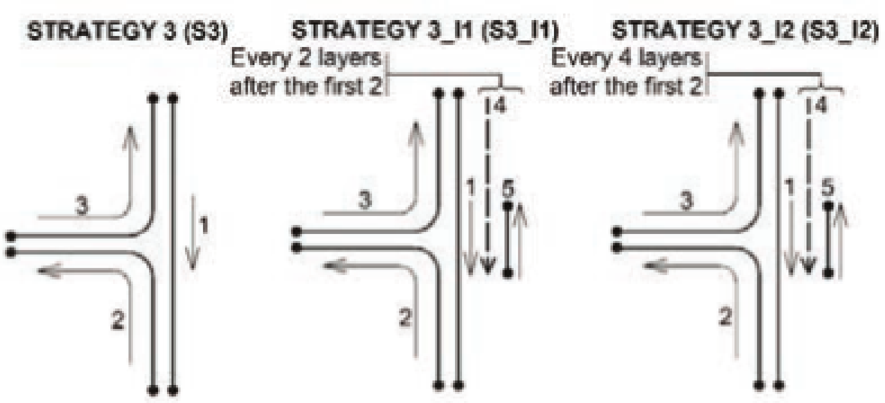


Figure 2.21: T-crossing building strategies [30]

not suitable as a general solution.

2.7 Semantic segmentation

Automated path planning relies on being able to subdivide a layer of an AM part into simpler regions for path planning. This can be viewed as an image segmentation problem, and a brief review of image segmentation literature has been performed.

The image segmentation process consists of dividing the content of an image into multiple segments according to their classification. In other words, image segmentation is the task of assigning a class, or label, to every pixel in a given image. This operation results in a set of segments covering the entire image. Usually, those segments are recoloured to easily distinguish the different contents of the image (cf. Fig 2.22).

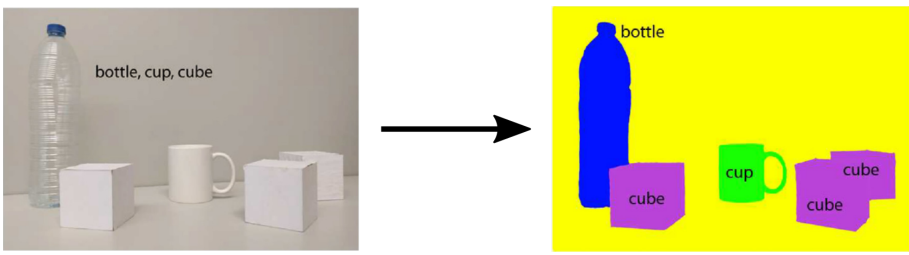


Figure 2.22: Semantic segmentation [31]

Image segmentation has been studied for many years, leading to the development of numerous methods such as Thresholding [32], Edge detection [33] or Graph partitioning [34]. However, most of these methods are using the variation of colour, intensity and texture to define the different fragments of a picture. In the case of AM layer segmentation, images are bicolour (black and white) and require therefore methods capable of understanding distinct geometries.

In recent years, the deep learning technology has become very popular in the field of computer vision since it can intuitively extract complex information from pictures and achieve high-level tasks such as global scene understanding. In this field, image segmentation is known as semantic segmentation [31, 35] and is used across a variety of applications, such as autonomous driving [36]; medical imagery analysis [37] or human-computer interaction [38]. Because of this recent popularity, many Neural Network (NN) architectures have been developed and compared to each other using common datasets [39].

To the best of our knowledge, there is no previous attempt to use this technology in the path generation for WAAM, which could be explained by the fact that it only became popular recently. Nevertheless, semantic segmentation has proved its efficiency in many fields and could, potentially, be applied to path planning segmentation for WAAM.

2.8 Summary of the literature review

In this literature review, a general background of the AM technologies and the specificities of the WAAM technology have been presented. Additionally, a list of criteria to avoid in the path generation for WAAM has been extracted from the literature to review proposed WAAM path strategies and to highlight the current state-of-the-art. Finally, an alternative solution called the feature-based approach, and the image segmentation have been presented as they can be relevant to create a fully automated path planning process.

References

[1] I. Gibson, D. W. Rosen, and B. Stucker. *Additive Manufacturing Technologies*. Springer US, 2010.

[2] L. E. Murr, S. M. Gaytan, D. A. Ramirez, E. Martinez, J. Hernandez, K. N. Amato, P. W. Shindo, F. R. Medina, and R. B. Wicker. Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies. *Journal of Materials Science and Technology*, 28(1):1–14, 2012.

[3] E. Brandl, B. Baufeld, C. Leyens, and R. Gault. Additive manufactured Ti-6A1-4V using welding wire: Comparison of laser and arc beam deposition and evaluation with respect to aerospace material specifications. *Physics Procedia*, 5(PART 2): 595–606, 2010.

[4] W. Carter and M. Jones. Direct laser sintering of metals. *Proceedings of the SFF Symposium*, pages 51–59, 1993.

[5] J. P. Kruth, L. Froyen, J. Van Vaerenbergh, P. Mercelis, M. Rombouts, and B. Lauwers. Selective laser melting of iron-based powder. *Journal of Materials Processing Technology*, 149(1-3):616–622, 2004.

[6] M. W. Khaing, J. Y. H. Fuh, and L. Lu. Direct metal laser sintering for rapid tooling: Processing and characterisation of EOS parts. *Journal of Materials Processing Technology*, 113(1-3):269–272, 2001.

[7] T. Nakano and T. Ishimoto. Powder-based additive manufacturing for development of tailor-made implants for orthopedic applications. *KONA Powder and Particle Journal*, 32(32):75–84, 2015.

[8] B. Baufeld, O. V. D. Biest, and R. Gault. Additive manufacturing of Ti6Al4V components by shaped metal deposition: Microstructure and mechanical properties. *Materials & Design*, 31:S106–S111, jun 2010.

[9] L. E. Murr, S. M. Gaytan, A. Ceylan, E. Martinez, J. L. Martinez, D. H. Hernandez, B. I. Machado, D. A. Ramirez, F. Medina, S. Collins, and R. B. Wicker. Characterization of titanium aluminide alloy components fabricated by additive manufacturing using electron beam melting. *Acta Materialia*, 58(5):1887–1894, 2010.

[10] F. Wang, J. Mei, H. Jiang, and X. Wu. Laser fabrication of Ti6Al4V/TiC composites using simultaneous powder and wire feed. *Materials Science and Engineering A*, 445-446:461–466, 2007.

[11] F. G. Arcella and F. H. Froes. Producing titanium aerospace components from powder using laser forming. *Jom*, 52(5):28–30, 2000.

[12] R. Miranda, G. Lopes, L. Quintino, J. Rodrigues, and S. Williams. Rapid prototyping with high power fiber lasers. *Materials & Design*, 29(10):2072–2075, 2008.

[13] D. Tomus, M. Qian, C. A. Brice, and B. C. Muddle. Electron beam processing of Al-2Sc alloy for enhanced precipitation hardening. *Scripta Materialia*, 63(2):151–154, 2010.

[14] P. Joshi, S. B. Mulani, S. P. Gurav, and R. K. Kapania. Design Optimization for Minimum Sound Radiation from Point-Excited Curvilinearly Stiffened Panel. *Journal of Aircraft*, 47(4):1100–1110, 2010.

[15] J. Mehnen, J. Ding, H. Lockett, and P. Kazanas. Design study for wire and arc additive manufacture. *International Journal of Product Development*, 19(1/2/3):2, 2014.

[16] S. W. Williams, F. Martina, a. C. Addison, J. Ding, G. Pardal, and P. Colegrove. Wire + Arc Additive Manufacturing. *Materials Science and Technology*, 32(7):641–647, may 2016.

[17] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A practical path planning methodology

for wire and arc additive manufacturing of thin-walled structures. *Robotics and Computer-Integrated Manufacturing*, 34:8–19, aug 2015.

[18] M. R. Dunlavey. Efficient polygon-filling algorithms for raster displays. *ACM Transactions on Graphics*, 2(4):264–273, 1983.

[19] R. Farouki, T. Koenig, K. Tarabanis, J. Korein, and J. Batchelder. Path planning with offset curves for layered fabrication processes. *Journal of Manufacturing Systems*, 14(5):355–368, jan 1995.

[20] F. Ren, Y. Sun, and D. Guo. Combined reparameterization-based spiral toolpath generation for five-axis sculptured surface machining. *International Journal of Advanced Manufacturing Technology*, 40(7-8):760–768, 2009.

[21] J. Griffiths. Toolpath based on Hilbert's curve. *Computer-Aided Design*, 26(11): 839–844, 1994.

[22] J. J. Cox, Y. Takezaki, H. R. Ferguson, K. E. Kohkonen, and E. L. Mulkay. Space-filling curves in tool-path applications. *Computer-Aided Design*, 26(3):215–224, 1994.

[23] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A tool-path generation strategy for wire and arc additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 73(1-4):173–183, jul 2014.

[24] R. Dwivedi and R. Kovacevic. Automated torch path planning using polygon subdivision for solid freeform fabrication based on welding. *Journal of Manufacturing Systems*, 23(4):278–291, jan 2004.

[25] Y. Zhang, Y. Chen, P. Li, and A. T. Male. Weld deposition-based rapid prototyping: a preliminary study. *Journal of Materials Processing Technology*, 135(2-3):347–357, apr 2003.

[26] D. Ding, Z. Pan, D. Cuiuri, H. Li, and N. Larkin. Adaptive path planning for wire-feed additive manufacturing using medial axis transformation. *Journal of Cleaner Production*, 133:942–952, oct 2016.

[27] J. Shah and M. Mäntylä. *Parametric and Feature-Based CAD/CAM: Concepts, Techniques, and Applications*. A Wiley-Interscience publication. Wiley, 1995.

[28] P. Kazanas, P. Deherkar, P. Almeida, H. Lockett, and S. Williams. Fabrication of geometrical features using wire and arc additive manufacture. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 226(6):1042–1051, jun 2012.

[29] J. Mehnen, J. Ding, H. Lockett, and P. Kazanas. Design forwire and arc additive layer manufacture. In *Global Product Development - Proceedings of the 20th CIRP Design Conference*, pages 721–727. springer berlin, 2011.

[30] G. Venturini, F. Montevecchi, A. Scippa, and G. Campatelli. Optimization of WAAM Deposition Patterns for T-crossing Features. *Procedia CIRP*, 55:95–100, 2016.

[31] A. Garcia-Garcia, S. Orts-Escolano, S. Oprea, V. Villena-Martinez, P. Martinez-Gonzalez, and J. Garcia-Rodriguez. A survey on deep learning techniques for image and video semantic segmentation. *Applied Soft Computing Journal*, 70:41–65, 2018.

[32] M. Sezgin and B. Sankur. Survey over image thresholding techniques and quantitative performance evaluation. *Journal of Electronic Imaging*, 13(1):146 – 165 – 20, 2004.

[33] T. Lindeberg and M.-X. Li. Segmentation and classification of edges using minimum description length approximation and complementary junction cues. *Computer Vision and Image Understanding*, 67(1):88 – 98, 1997.

[34] J. Shi and J. Malik. Normalized cuts and image segmentation. *IEEE Trans. Pattern Anal. Mach. Intell.*, 22(8):888–905, Aug. 2000.

[35] Y. Guo, Y. Liu, T. Georgiou, and M. S. Lew. A review of semantic segmentation using deep neural networks. *International Journal of Multimedia Information Retrieval*, 7(2):87–93, 2018.

[36] A. Ess, T. Mueller, H. Grabner, and L. van Gool. Segmentation-Based Urban Traffic Scene Understanding. *Procedings of the British Machine Vision Conference 2009*, pages 84.1–84.11, 2009.

[37] D. D. Patil, S. G. Deore, and S. Bhusawal. Medical Image Segmentation: A Review. *Ijcsmc*, 2(1):22–27, 2013.

[38] M. Oberweger, P. Wohlhart, and V. Lepetit. Hands Deep in Deep Learning for Hand Pose Estimation. *CoRR*, abs/1502.0, 2015.

[39] M. Everingham, S. M. Eslami, L. Van Gool, C. K. Williams, J. Winn, and A. Zisserman. The Pascal Visual Object Classes Challenge: A Retrospective. *International Journal of Computer Vision*, 111(1):98–136, 2014.

Chapter 3

Paper A

“Path Generator Framework for Wire + Arc Additive Manufacturing”

Florent Michel[a], Helen Lockett[b], Jialuo Ding[a], Stewart Williams[a]

[a] *Welding Engineering and Laser Processing Centre, Cranfield University, Cranfield MK43 0AL, UK*
[b] *Open University, Walton Hall, Kents Hill, Milton Keynes MK7 6AA, UK*

Abstract Wire + Arc Additive Manufacturing (WAAM) has become very popular in the field of medium to large metallic deposition thanks to its high-rate deposition, low-cost equipment and ability to deposit different metals. A crucial issue to solve, for a commercial WAAM system, is the generation of an optimised path to guarantee a uniform deposition. Existing path generator software is, indeed, not compatible with the specific requirements inherent to arc welding deposition, which requires continuous control of welding process parameters and adapted building sequences. However, to investigate automated path planning for WAAM, an appropriate development tool is required. In this paper, the architecture of a Path Generator Framework for WAAM (PGFW) is introduced. This framework can extend the capabilities of any 3D modelling software to visualise and manipulate paths as well as simulate manipulators behaviour and generate appropriate machine codes. To provide a basis for WAAM development, the described software structure guarantees the integration of any manipulators and welding equipment. Additionally, the PGFW offers a path structure which can be used as an API, allowing researchers to develop and experiment new path planning solutions quickly. This paper also details the implementation of the PGFW into the Rhinoceros and Grasshopper 3D environment to create a flexible and intuitive WAAM platform. Finally, the PGFW capabilities are exposed through the development of a single deposition wall.

Keywords WAAM; Wire and Arc Additive Manufacturing; Path planning; Toolpath generation; Robotics simulation framework; WAAM Platform

3.1 Introduction

Thanks to its simple concept of layer-by-layer deposition, Additive Manufacturing (AM) recently evolved from a prototype application to an end-use production as it successfully improved manufacturability and reduced lead time compared to conventional manufacturing processes [1, 2].

In the field of medium to large metallic deposition, Wire + Arc Additive Manufacturing (WAAM) is considered to be a solution with high potential for industrial application [3]. Indeed, WAAM enables the deposition of different metals, such as steel, aluminium alloy or titanium alloy [4]. Additionally, the wire-based welding solution used in WAAM provides high-rate deposition [5] using low-cost equipment [4]. Nevertheless, one crucial issue to solve, for a practical and commercial WAAM system, is the generation of an optimised path to drive manipulators [6] and guarantee a uniform deposition.

In fact, even though path planning for WAAM has been studied for many years [7, 8], it has emerged following the trend of AM, starting with innovative research in Cranfield University [5, 9] and more recently the substantial work of Ding et al. [10–17].

However, most of these investigations were made using traditional machining CAM software which can constrain the development into a machining-like solution. The alternative is to develop a bespoke path manager tool using a coding platform such as MATLAB or to manually edit manipulator instructions. Nevertheless, these solutions potentially limit interoperability and can lead to a critical workload for researchers. Indeed, such a tool requires not only the ability to create, visualise and manipulate paths but also the ability to drive actual manipulators which involve simulation and post-processing.

Therefore, to support any path planning research in the future, this paper introduces the architecture of a Path Generator Framework for WAAM (PGFW). This presented framework can extend the capabilities of any 3D modelling software to visualise and manipulate paths as well as simulate manipulator behaviour and generate appropriate machine codes. Moreover, because WAAM technology is not limited to any specific hardware [4], the PGFW is structured to facilitate the integration of new manipulators or new deposition devices. Additionally, to avoid using multiple platforms, the PGFW can integrate additional processes such as rolling [18, 19], peening [20] and also traditional machining. Finally, following the architecture presented in this paper, the PGFW can be implemented with all programming languages into any 3D platforms and operating systems.

Given that this paper subject is inherently connected to robotics, it is fundamental to clarify technical terms that can lead to confusion. Thus, in this paper, as shown in Fig. 3.1, a **Manipulator** defines any devices capable of moving tools according to a predefined order. This definition contains, therefore, industrial robots and Computer Numerical control (CNC) machines. Following the Craig [21] definition, a **Position** defines a single point in space where a **Location** combines position and orientation which can be represented by a **Frame**. It is essential to highlight that these spatial representations are necessarily described relative to a **Reference** frame [22]. Additionally, in this paper, a **Posture**, defined by a multi-dimensional vector, represents the axes rotations of a manipulator at a given time. Finally, following Brady et al. [23], a **Trajectory**, which characterises a time sequence of intermediate postures, is distinct from the **Toolpath**, which represents the space curve traced by the Tool Center Point (TCP) [22]. However, both of these terms only describe spatial behaviour where the **Path**, in this paper, represents the desired behaviour of the manipulator. Therefore, this path can contain motions but also non-spatial actions like starting deposition order.

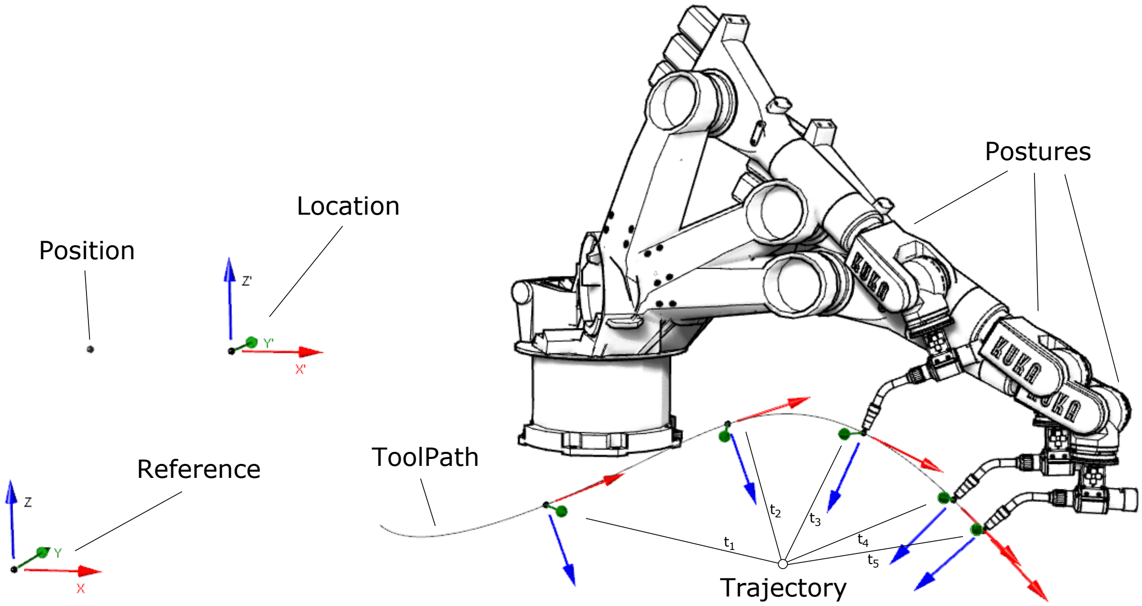


Figure 3.1: Definition of the technical terms

Thus, in the following section, the complete methodology details the PGFW architecture, its main elements and their interactions. To demonstrate its feasibility, in Section 3.3, the PGFW is implemented using C# into the Rhinoceros 3D environment and its plugin Grasshopper to create a WAAM platform. This section describes the overall framework integration as well as a potential user interface solution. Then, Section 3.4 demonstrates the platform efficiency by using it to develop path planning scripts called features. Finally, conclusion and future works are discussed in Section 3.5.

3.2 Methodology

3.2.1 Path: Visualisation and manipulation

The most critical aspect of the PGFW is to offer the ability to generate, visualise and manipulate paths in a 3D environment. All those proprieties are provided by the Path object (Fig. 3.2a).

As presented above, the Path represents all the manipulator behaviours for a given period. Technically, this simply means that the Path object (Fig. 3.2a) contains a list of PathItem where a PathItem can define any motions (Fig. 3.2b) but also static actions such as activating a digital output or displaying a message to the operator at a given moment (Fig. 3.2c). Thus, any Path can be created by aggregating PathItems in the correct order.

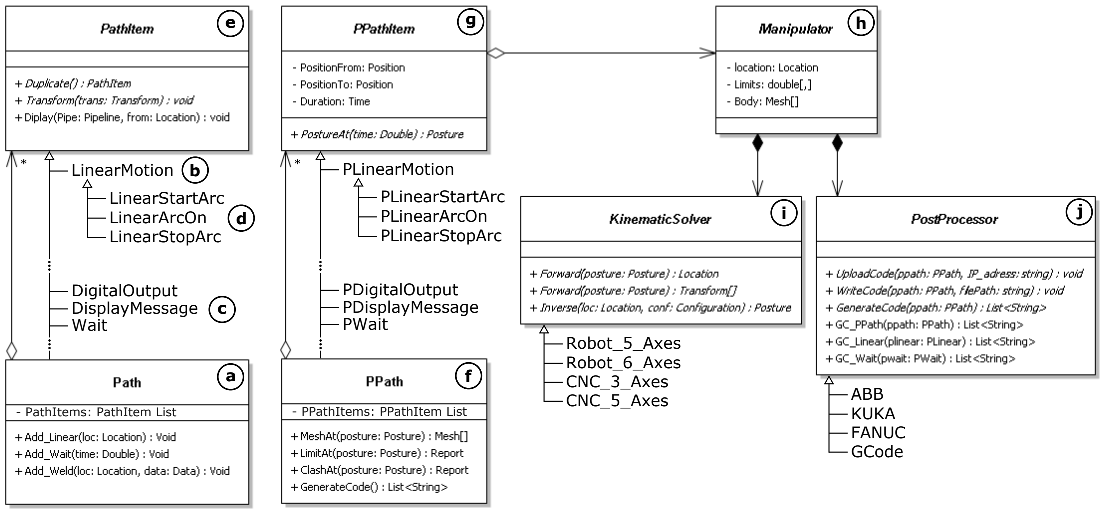


Figure 3.2: Class diagram of the Path Generator Framework for WAAM

It can be seen on Fig. 3.2 that the Path class is itself a PathItem. With this recursivity, users can organise their path into a sub-paths structure, meaning that a Path can contain other Path instances in its PathItem list. This structure facilitates the Path creation process, but given that the path structure is conserved through the simulation and the code generation, it also helps operators to localise events in a path that can contain millions of actions.

The PGFW's key feature is to visualise paths into a 3D environment. To achieve this, each PathItem has to override a function called Display and uses the given pipeline to draw its own representation on the screen. However, as can be seen on Fig. 3.3(b), PathItems representing motions like LinearMotion contain only the targeted location (*Loc1*) and not the starting location. Thus, a PathItem cannot draw its own 3D representation by itself. The solution here is to use the final location of the previous PathItem as the starting location of the current one. For this reason, the Display function (Fig. 3.2e) contains, as a second input, the starting location which is, in fact, the final location of the previous

PathItem and outputs the targeted location to be used as starting location of the following PathItem. This solution requires, however, to define a home position which represents the location of the manipulator before any motions.

Finally, to fill all the PGFW's requirements, the path must also be manipulable. Similar to the visualisation, this task is handled by the PathItem inheritance. In this case, two abstract methods are involved: Duplicate and Transform (Fig. 3.2e). Duplicate makes sure that when a Path is copied, all data are replicated into a new memory space to avoid any assignment errors. The Transform method modifies the location stored in a PathItem using homogenous transformation in input [24]. It can be noted that if a PathItem does not contain any location information such as Wait (Fig. 3.2c), then the Transform method has merely no effect. Thanks to these two functions, users can manipulate paths after generating them, increasing flexibility into user's interactions.

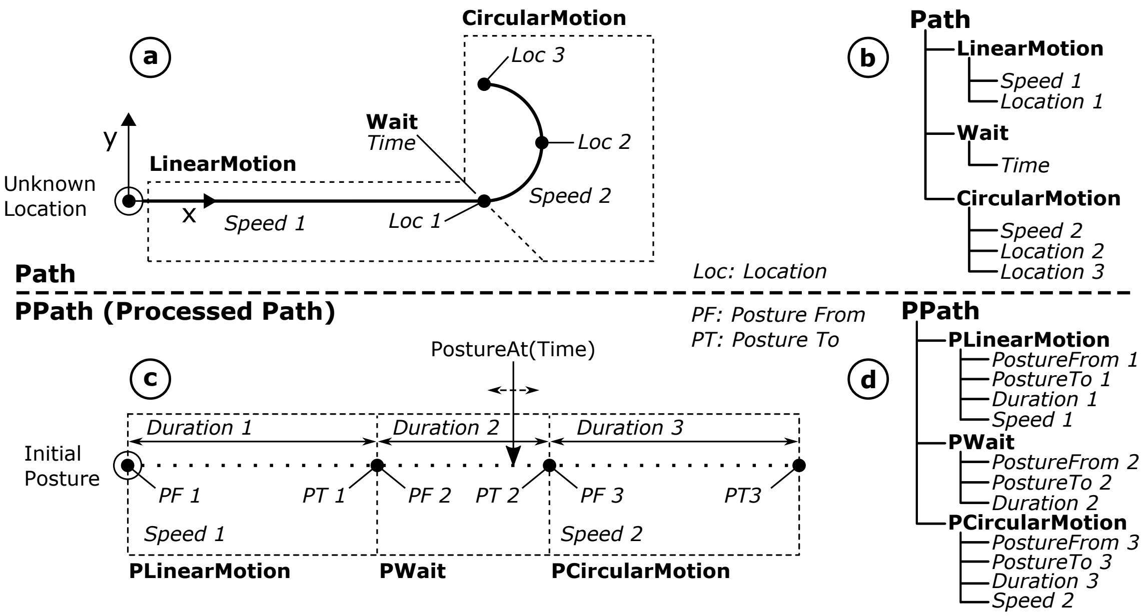


Figure 3.3: Path vs PPath: Representation of a trajectory by the Path object (a-b) and its evolved PPath version (c-d)

It should be noted that many other methods can be added to this Path class to facilitate the PGFW's integration into a dedicated research purpose. For example, methods such as Save and Load can be developed to allow Path to be shared through a standard file system.

This presented Path is the PGFW's central element allowing users to manipulate paths as objects. However, to accurately generate a path, it is crucial to facilitate the creation process. To achieve this, the next section presents a PathAPI solution.

3.2.2 PathAPI: Path creation

The PGFW is an open solution allowing developers to instantiate presented objects as desired. However, the purpose of this paper is to support researchers to study and develop an automated path generator for WAAM. For this reason, it is primordial to simplify the Path creation through a dedicated interface called PathAPI.

Without the PathAPI, users have to create a Path and all the PathItems separately and then add each PathItem to the Path, following the correct order. This process can be beneficial in a complex software solution but requires users to handle many programming concepts.

Therefore, the PathAPI aims to facilitate the path generation by combining all these operations into a single entity, the Path object. In this purpose, each PathItem has an associated public method in the Path class (Fig. 3.2a). For example, the PathItem Wait has an associated method in the Path class called M_AddWait. This method instantiates the corresponding PathItem and adds it directly to the PathItem list of the Path. Thus, as can be seen later on Fig. 3.5(b.2), the Path creation is only composed of two steps: first, a Path instance is created, then, actions are added. Moreover, creating paths into a script only requires importing the Path class.

The PathAPI primary function is to simplify essential path building, but it can also offer shortcuts to build more complex path structures. For example, the deposition path is a relatively complex structure containing several PathItems which require a specific order to operate correctly (Fig. 3.4). Thus, to simplify user's interaction, a dedicated method called Add_Weld (Fig. 3.2a) is available in the Path class, so users can generate the entire deposition path in a single line of code by merely providing the requested information.

With the object Path and its PathAPI interface, the PGFW can create, visualise and manipulate paths in a 3D platform. However, a Path only describes the behaviours of the

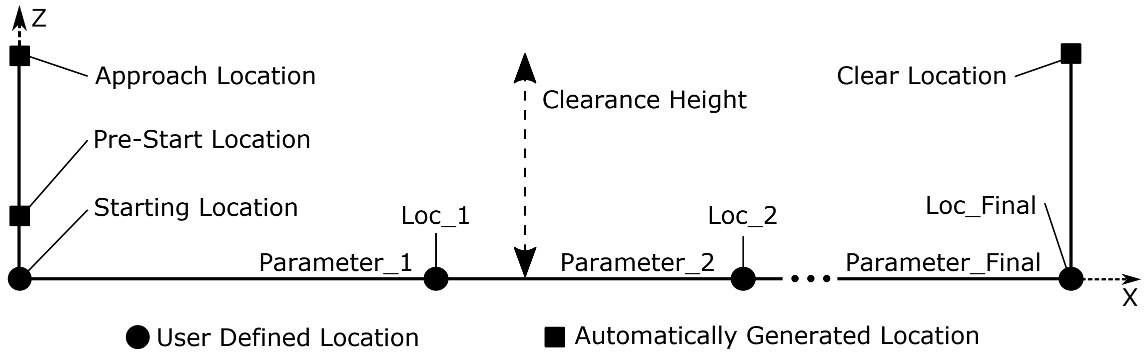


Figure 3.4: Weld path structure (Add_Weld(...))

deposition tool. Therefore, the following section introduces the ProcessedPath (PPath) which determines manipulator behaviours along a given Path.

3.2.3 PPath: Manipulator behaviour and simulation

A path has no purpose if it cannot ultimately drive an actual manipulator, which requires a machine program generated explicitly for the given manipulator. Nevertheless, this code can only be computed if the manipulator behaviours are understood and simulated. This behaviours estimation is regulated in the PPath (Processed Path) object (Fig. 3.2f).

PPath and Path are inherently linked, in fact, PPath is a more evolved version of the path to describe the same trajectory. However, where the Path only defines the motion of the end effector in three dimensions (Fig. 3.3a), the PPath describes the entire manipulator motions in as many dimensions as the manipulator requires and cannot, therefore, be represented in a 3D environment (Fig. 3.3c). Nevertheless, it is possible to display the manipulator posture at any time along the PPath.

Instead of PathItem, the PPath is made of PPathItems (Fig. 3.3d). A PPathItem (Fig. 3.2g) is also an updated version of the PathItem, and, for an operational framework, each PathItem requires its own PPathItem. It is left to the developer to select which data will be transferred from the PathItem to the PPathItem. However, when created, the PPathItem has to determine the posture at the beginning and at the end of the represented action as well as the duration required to achieve this action. These members will facilitate the simulation process. It should be highlighted that because the PPath is a PPathItem, the recursivity potentially built in a Path is conserved in the PPath.

The PPath primary purpose is to determinate the manipulator behaviour at any time along the path (Fig. 3.3c). This process is achieved through the PostureAt method overridden by each PPathItem, which returns the manipulator posture based on the inputted time. It is the developer responsibility to specify how each action determines the manipulator behaviour. However, in most of the cases, the manipulator kinematic solver is a crucial element in this method since it can calculate the manipulator posture for a given location and configuration (Fig. 3.2i). This kinematic solver is accessible to the PostureAt method because each PPathItem contains a Manipulator object.

Calculating the manipulator posture at a given time is really the main purpose of the PPath. However, to make this object more simulator friendly, a few methods can be easily added (Fig. 3.2f). For example, the MeshAt method takes meshes from the Manipulator object (Fig. 3.2h) and relocates duplicated meshes using the ForwardKinematic method (Fig. 3.2i) and the given posture. This method is particularly useful since the simulation is mainly about displaying manipulators in a 3D environment. However, simulation also notifies users of potential issues happening along the path. For example, the method LimitAt using the Manipulator Limits (Fig. 3.2h) determines if the manipulator is out of its own axis limits at a given posture. Similarly, using a 3D collision detection algorithm [25], the method ClashAt determines if the manipulator is clashing the environment at a given posture. These two methods are combined into the FullReport method, which calculates at a given interval the potential issues and notifies them into a report. This report is formatted following the Graphical User Interface (GUI) requirements.

A simulation is a communication tool between the framework and its users. Nevertheless, the primary purpose of understanding manipulator's behaviours along a path is to generate the code driving this manipulator accurately. In this purpose, the PPath class contains a method to generate the code. However, this method is merely a shortcut to the manipulator PostProcessor, which is detailed in the next section.

3.2.4 PostProcessor: Machine code generation

The ultimate step towards a fully functional WAAM framework is the ability to drive any type of manipulator, from simple three-axis CNC machines to sophisticated six-axis robots. Moreover, because the WAAM technology can be used on any manipulators, it is crucial to facilitate the implementation of new manipulators. These capabilities are managed through the PostProcessor class (Fig. 3.2j).

The PostProcessor has a unique objective in this framework: to generate the code that will drive the desired machine following precisely the users' intentions. Thus, the PostProcessor makes sure all information required by the controller during the deposition is included in a file and formatted as specified. This is achieved by combining a PostProcessor developed explicitly for the given manipulator and the PPath describing the behaviour of this manipulator along the path.

Therefore, as can be seen on Fig. 3.2j, in the PostProcessor abstract class, each PPathItem has an associated method returning a list of strings and taking in input the PathItem associated with. For example, the GC_Wait function takes in input a PWait object. Once overridden, these methods return lines of code describing the associated actions in the manipulator programming language. This structure simplifies the development of new PostProcessor because all these code generator methods are grouped into a single class. It should be highlighted that each manipulator may not be able to implement all the actions available in the Path class. This is fine as long as the Path instance created for this Manipulator does not contain any of these actions. If it were the case, an exception would be raised.

The entry point of the code generation process is the GenerateCode method (Fig. 3.2j). This method varies according to the post-processor overridden but mainly organises the file format and calls the GC_PPath method to generate the path code. The GC_PPath main purpose is to make sure that for each PPathItem, contained in the PPath, the associated post-processor method is called and that the PPathItem is transferred in the input. It is left to the developer to define how this method is achieved; it can be using a simple switch algorithm or by adding a call back method into the PPathItem abstract class. Thus, in the GC_PPath method, going through each PPathItem, lines of code are assembled into a list until it adequately describes the desired path. Finally, when the end of the path is reached, the GenerateCode method combines all the lines of code according to the post-processor requirements and returns it as a list of strings to the GUI. However, it can be noted that the post-processor can also propose to write the code in a machine formatted file at a specified location on the computer or even uploading it directly to the controller if this one is compatible with network communication (Fig. 3.2j).

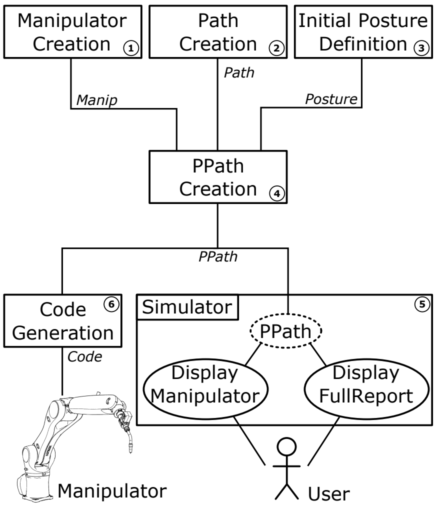
With this PostProcessor structure added to the PPath and the Path solution, developers have all the information to build the WAAM framework. Nevertheless, to correctly develop this solution, it is fundamental to understand these elements interactions. For this reason, the next section is presenting the PGFW's process.

3.2.5 PGFW: Process description

To clarify the interactions of the presented objects, this section describes the process to operate the PGFW items correctly. This process is represented in a diagram, which is attached to a C# code example following this process (Fig. 3.5).

Thus, as can be seen on the Fig. 3.5(a.1), the PGFW's process starts with the manipulator creation. This step (Fig. 3.5(b.1)) is mainly about combining manipulator related information. So, developers, first, choose a KinematicSolver and a PostProcessor from a list provided by their own class. Then, meshes representing the manipulator in 3D need to be imported through the 3D environment. Finally, the manipulator localisation, defined by the user, completes the required data to generate a manipulator instance. It should be noted that this step can be simplified by the introduction of a manipulator library where information such as Kinematic solver, PostProcessor and meshes would be saved into dedicated files.

Parallel to the manipulator creation, developers have to create a Path. Since the purpose of the PGFW is to study Path generation, this step would usually be processed in



a. Process flowchart

```
public void Process()
{
    # Manipulator Creation
    KinematicSolver ks = KinematicSolver.Robot_6_Axes;
①   PostProcessor pp = PostProcessor.ABB;
    Manipulator manip = new Manipulator(_Location, _Meshes, _Limits,ks,pp);

    # Path Creation
    Path path = new Path();
②   path.Add_Linear(_Location);
    path.Add_Wait(_Duration);
    path.Add_Weld(_Data);

    # Initial Posture Definition
③   Posture initPos = [0,0,0,0,0,0];

    # PPath Creation
④   PPath pPath = new PPath(manip, path, initPos);

    # Simulation
    Posture posture = pPath.PostureAt(_Time);
⑤   Mesh[] meshes = pPath.MeshAt(posture);
    Report report = pPath.LimitAt(posture);
    FullReport fullReport = pPath.FullReport(_Interval);

    # Code generation
⑥   List<String> code = pPath.GenerateCode();
}
```

b. C# example

Figure 3.5: Framework process

a dedicated software or script. However, a simple example of Path generation using the PathAPI (Section 3.2.2) is presented in Fig. 3.5(b.2).

Before creating the PPath instance, an initial posture has to be defined since a PPath describes manipulator behaviours from a starting to an ending posture. This posture is usually decided by defining, on the actual manipulator, a standard posture also called home position, used to start any new job.

Finally, with all this information, the object PPath can be instantiated. This step is rather straightforward since it only requires combining all this data into the PPath constructor.

By integrating this PPath object into a simulator interface (Fig. 3.5(a.5)), the deposition can be simulated thanks to the methods presented in Section 3.2.3 such as PostureAt or LimitAt (Fig. 3.5(b.5)).

Parallel to the simulation, the PPath can trigger the code generation (Fig. 3.5(a.6)) and even send the result directly to the manipulator if required (Section 3.2.4).

Thus, following this presented process, developers can now build a complete PGFW framework which will provide path management, simulation and post-processing. However, to produce a fully functioning WAAM platform, the framework has to be implemented in a 3D environment. Therefore, the following section proposes an implementation into Rhinoceros and Grasshopper.

3.3 Implementation in Rhinoceros and Grasshopper

3.3.1 Rhinoceros and Grasshopper

Rhinoceros 3D and its extension Grasshopper have been chosen to implement this PGFW because of their unique development environment allowing a fast experimental development that can also be quickly deployed to a professional environment. Additionally, given that Grasshopper is parametric design software, integrating the PGFW on this platform provides users with direct feedback on any of their interactions with the system, which is a key element when developing experimental work. Finally, this affordable platform offers a robust framework to compute geometrical process, and its intuitive graphical interface allows users of any levels to quickly understand its operating process. While it also pleases high-skill developers as it can integrate complex coded algorithms in multiple programming languages.

Thus, the graphical interface is made of two windows (Fig. 3.6). On the left, Rhinoceros displays all the 3D elements such as the designed paths and the computed manipulators, which can be visualised similarly to any CAD software. On the right, Grasshopper acts like a dashboard where users can interact with the system and define a script to generate paths.

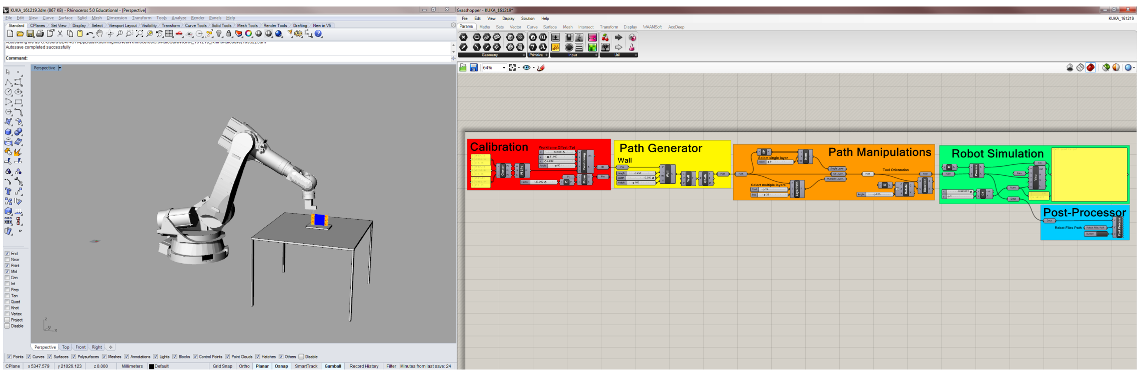


Figure 3.6: Rhinoceros and Grasshopper

Rhinoceros and Grasshopper attributes make this environment ideal for research purposes. However, integrating external tools to fit the GUI best requires a particular implementation strategy. Therefore, to use the PGFW in this platform, the following section presents an overall integration solution.

3.3.2 Implementation

The implementation stage is crucial to the perceived quality of the software. Indeed, the primary purpose of the implementation is to ensure that all the framework features are transferred to the platform while respecting its interface requirements and concept.

Grasshopper facilitates plugins integration by providing an Application Programming Interface (API), giving access to data and key methods of this platform. Moreover, a plugin template is provided where each entry point is well defined. Thanks to this accessibility, third-party software components can be developed, distributed and commercialised to extend Rhinoceros and Grasshopper capabilities.

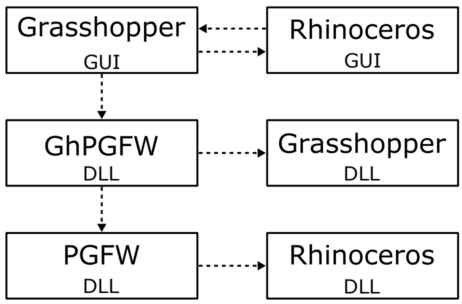


Figure 3.7: Implementation architecture

As a result, using this plugin solution, the PGFW can be efficiently implemented to Grasshopper. However, as can be seen on the Fig. 3.7, two Dynamic-Link Library (DLL) have been developed to integrate the PGFW. Indeed, the entire proposed solution is contained in the PGFW DLL, which uses the Rhinoceros framework to process geometrical computing. Then, the GhPGFW DLL is a framework used as a bridge between the core DLL and the GUI. In this bridge, all data are converted into Grasshopper data and functions are reorganised to fit the Grasshopper interface. To achieve this conversion, the

GhPGFW requires access to both the PGFW and the Grasshopper framework. The purpose of this overall structure is to facilitate porting since only a new bridge would be required to connect the PGFW to a new platform.

3.3.3 WAAM platform: User point of view

From a user point of view, the WAAM platform is composed of 6 main parts (Fig. 3.8).

First of all (Fig. 3.8a), users have to describe, in Rhinoceros, the working environment used for the deposition stage. Thus, users are asked to draw the environment called a cell in which the manipulator is operating. This cell contains the tooling setup locking the part steady during deposition but also any external items that the manipulator can reach like the enclosure of the cell. All these drawings will allow the system to prevent collision between the manipulator, its tool and its environment. The clash detection accuracy of the system is therefore related to the drawing precision. Additionally, Grasshopper requires the manipulator configuration. This setup consists in choosing from libraries the manipulator and the tool to use for the deposition, as well as defining the manipulator position relative to the drawing made in Rhinoceros. In this configuration step, the manipulator starting position can also be modified.

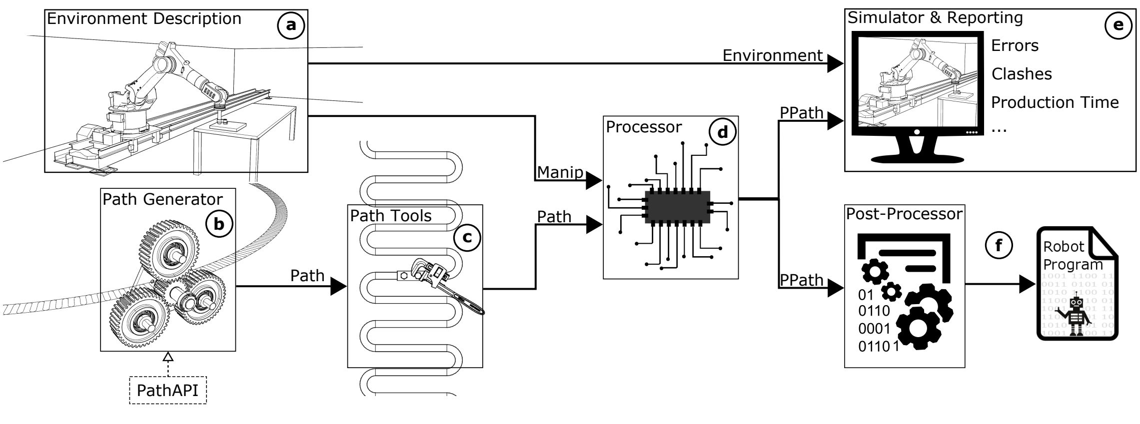


Figure 3.8: Grasshopper WAAM platform: User point of view

Parallel to the Environment Description, the Path Generator (Fig. 3.8b) is a C# Script using the PathAPI to generate a Path (Section 3.2.2). This path planning script can be a single function written by the user himself; a predefined script available in a feature library or even a complex path planning solution developed by an industrial partner, in any case, the output is a path compatible with the PGFW.

Before processing the path, users have the opportunity to manipulate the given path using the available path toolbox (Fig. 3.8c). Thanks to the inherent proprieties of the Path (Section 3.2.1), users can relocate the path to a specific position relative to their Environment Description using standard robotic calibration processes. Additionally, they can duplicate the path to build a set of the targeted part simultaneously or even merge multiple paths together.

At this stage, the working environment is described, and a path has been generated. Therefore, this data can be joined to generate a ProcessedPath (PPath) (Fig. 3.8d). This stage is fully automated and does not require any user intervention. Once generated, the PPath is dispatched to two distinctive entities: the simulator and the post-processor.

In the last stage, using the PPath, users can simulate the deposition process (Fig. 3.8e). Indeed, using a slider in Grasshopper, users can visualise, in Rhinoceros, the manipulator at any time along the defined path. Additionally, information like clashes and reached limits are communicated through the colours of the displayed manipulator. Moreover, a full-text report is displayed in Grasshopper to inform users about potential issues along the path and practical information such as operating time or deposited weight.

Finally, the post-processor (Fig. 3.8f) can be activated at any time by the user. This post-processor will save on the computer a machine formatted code file to the given file path or upload codes to the controller if an IP address is supplied.

Using this WAAM platform, researchers can now concentrate on developing path planning solution as presented in the next section.

3.4 Application: Single deposition wall

The PGFW's objective is to assist researchers in their path strategy development by providing a complete PathAPI to simply generate paths and a straightforward platform to produce them quickly. To demonstrate that the PGFW achieves its targets, the development of a feature is presented in this section.

A feature represents a parametrised geometry associated with a path strategy. It can also be seen as a script coded with the PathAPI (Fig. 3.9), which, based on some inputs, can generate the optimum path to build the targeted geometry. Thus, because the PathAPI is used, the output of this script is a path compatible with the WAAM platform.

In this example, the development of a single deposition wall is presented. This feature is a cuboid (Fig. 3.10) built by accumulating deposition lines (Fig. 3.9). However, to ensure a high-quality deposition, each layer is made of three stages: ignition, stability, and termination. Each of those stages requires an appropriate travel speed as well as a set of deposition parameters such as current and wire feed speed [26]. Moreover, to avoid error accumulation, the deposition direction is flipped on each layer.

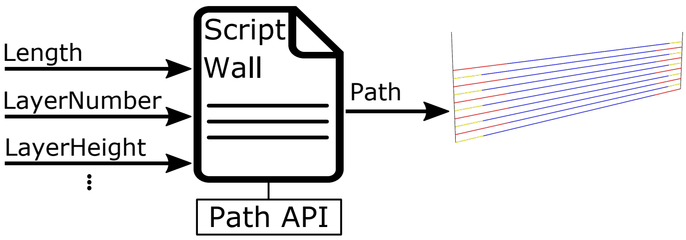


Figure 3.9: Feature definition

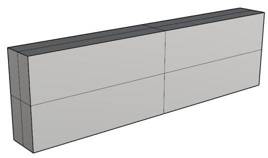


Figure 3.10: Cuboid

Before introducing the script solution (Section 3.4.4), its crucial components are presented: the locations calculations (Section 3.4.1), the single path generation function (Section 3.4.2) and the application of transformations (Section 3.4.3). Finally, to test the obtained result, the transition between the path and the part is also presented in Section 3.4.5.

3.4.1 Locations calculation

The Path ability to be relocatable is a crucial element to simplify development. Indeed, thanks to this attribute, users can create a path using the most convenient reference frame to calculate all the locations contained in the path, and later translate the path to its final position.

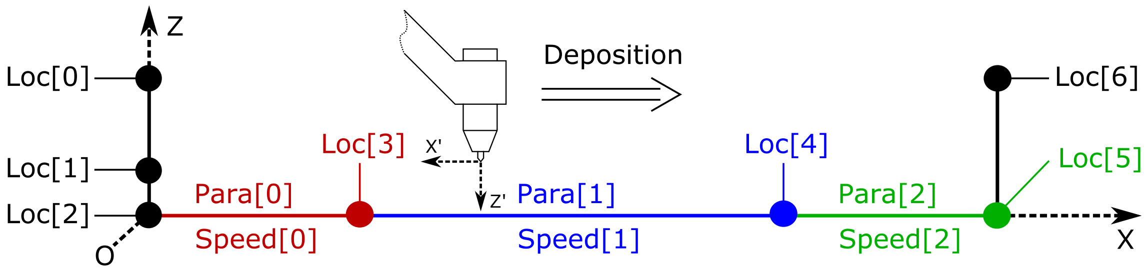


Figure 3.11: Details of a single layer path (The path is divided into three zones, indicated by different colours in the figure)

In the presented example, to generate a single deposition layer, the path has to go through seven consecutive locations, and the reference frame is positioned at the bottom left of the path (Fig. 3.11). To calculate all the locations, positions and orientations are calculated separately. Thanks to the reference frame location, positions are straightforward to determine using inputs and global parameters (Tab. 3.1). Regarding orientations, since the tool is kept straight along the path, all locations have an identical orientation. It needs to be pointed out to the reader that in this example, the ABB standard orientation system is used (Fig. 3.11) but any standard can be used in the PGFW as long as it is kept constant over all the path generators.

Loc[0]=(0, 0, Clearance)	Loc[3]=(0.25*Length, 0, 0)	Loc[5]=(Length, 0, 0)
Loc[1]=(0, 0, Pre-Start)	Loc[4]=(0.75*Length, 0, 0)	Loc[6]=(Length, 0, Clearance)
Loc[2]=(0, 0, 0)		

Table 3.1: Locations definition

Finally, once all positions are created, and orientation is defined, those data can be combined into a set of locations. Those locations are then returned to the master script to later generate a layer path as presented in the following section.

3.4.2 Layer path generator

The Path recursivity enables developers to split a path generator into smaller convenient tasks facilitating development architecture. Thus, in this example, a function called Layer is implemented to generate a path which represents a single deposition line.

As can be seen in Fig. 3.12, the Layer function takes as input the locations calculated previously, as well as the speeds and parameters defined by the user. Consequently, using those inputs and the PathAPI, this function makes sure that relevant actions are correctly congregated and associated with the appropriate parameters. Some of the parameters used in this function, such as _ApproachSpeed or _CoolingTime, are called global parameters. These are presented as constant but are in fact, configurable by the user.

```
public Path Layer(Location[] pLoc, Double[] pSpeed, Parameter[] pPara)
{
    // Path Creation
    Path path = new Path();
    path.Add_Linear(pLoc[0], _AirSpeed);
    path.Add_Linear(pLoc[1], _ApproachSpeed);
    path.Add_LStartArc(pLoc[2], _ApproachSpeed, pPara[0]);
    path.Add_LArcOn(pLoc[3], pPara[0], pSpeed[0]);
    path.Add_LArcOn(pLoc[4], pPara[1], pSpeed[1]);
    path.Add_LStopArc(pLoc[5], pPara[2], pSpeed[2]);
    path.Add_Linear(pLoc[6], _AwaySpeed);
    path.Add_Wait(_CoolingTime);

    return path;
}
```

Figure 3.12: Description of the Layer function

This layer path generator is separated from the locations definition stage because locations are calculated only once, whereas this function is repeated for each layer. This repetition allows the process to vary deposition parameters along layers to guarantee a better result.

However, using this method, every layer paths are generated to the same location. Therefore, as presented in the next section, transformations are applied to each layer to adapt their locations.

3.4.3 Transformations

A transformation is a tool frequently used by developers to create concise algorithms. In the single deposition wall example, two of those transformations are repetitively applied and presented in this section.

In this paper, transformation is defined as an operation that affects the locations contained in a path. The PGFW can handle any transformation standards, but in this example, homogeneous transformations [24] are used since they are broadly used in robotics.

In this example, to ensure building stability, the deposition direction is iteratively inverted (Fig. 3.9). To achieve this operation, a flipping transformation (Tf) is alternately applied to the path generated by the Layer function. This transformation (Fig. 3.13) is the combination of a 180-degree rotation around the Z-axis and a translation on X vector of the length value (L). Thus, using this transformation on the path repositions each location in the correct order but also reorients the tool to follow the new deposition direction.

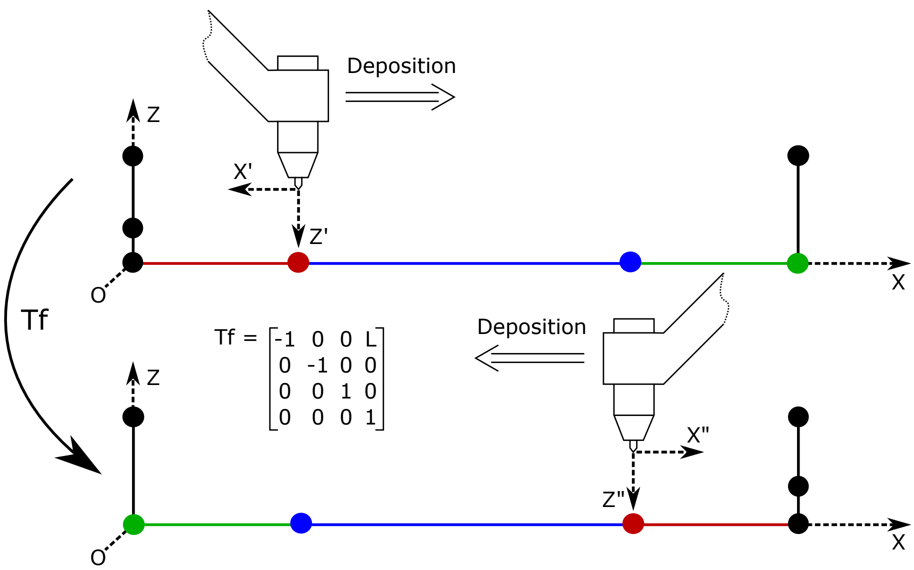


Figure 3.13: Flipping transformation (Tf)

A second more straightforward transformation is used to translate the path created on the reference frame to its correct height. This operation is achieved by a simple translation on the Z-axis of a value defined by the targeted height (Tz).

However, these transformations need to be adapted to each layer. Therefore, to manage the creation and relocation of layer paths, an algorithm is presented in the next section.

3.4.4 Master script

Using the previously presented functions and transformations, the single deposition wall feature example can finally be implemented in a script.

To offer flexibility to users, many inputs are required to run this proposed script. In fact, to develop the appropriate user interface, two input types are distinguished: first, information related to the geometry description, such as the wall length, the number of layers and the height of each layer; then, data linked to the path characterisation such as travel speeds, deposition parameters and cooling times.

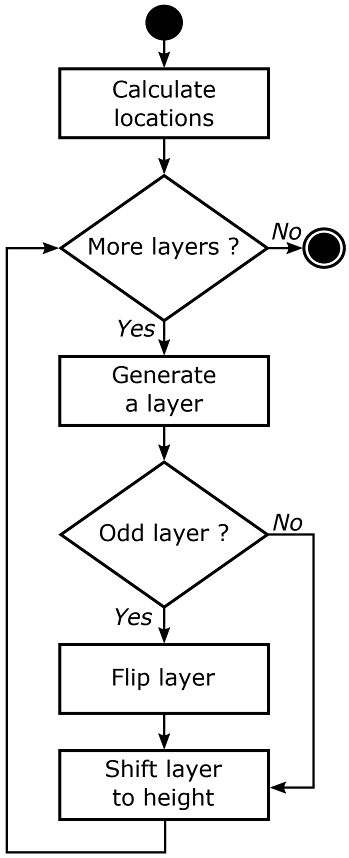


Figure 3.14: Path generator algorithm

However, the path planning strategy is given by the structure of the script itself usually described with an algorithm. In this example (Fig. 3.14), the script starts by determining the locations using the process explained in Section 3.4.1. After this initialisation stage, a loop, limited by a given number of layers, is started. For every iteration, the program generates a layer using the Layer function (Section 3.4.2). Then if the layer index is odd, this layer is flipped using the (Tf) transformation (Section 3.4.3). Finally, the layer, flipped or not, is translated to the correct height using the (Tz) translation (Section 3.4.3) and added to the wall path. Once all layers have been built, the script returns a path describing the full wall path (Fig. 3.9).

Thanks to this script generating a Path, users can now visualise and manipulate their achievement into a 3D environment. However, testing their newly developed solution requires using the complete WAAM platform, as shown in the following section.

3.4.5 From path to part

The PGFW enables researchers to developed efficiently new path strategies. However, the strategy capacity is mainly related to the quality of the parts it can build. Fortunately, using a WAAM platform also empowers developers to quickly test their paths by simulating deposition and generating machine code.

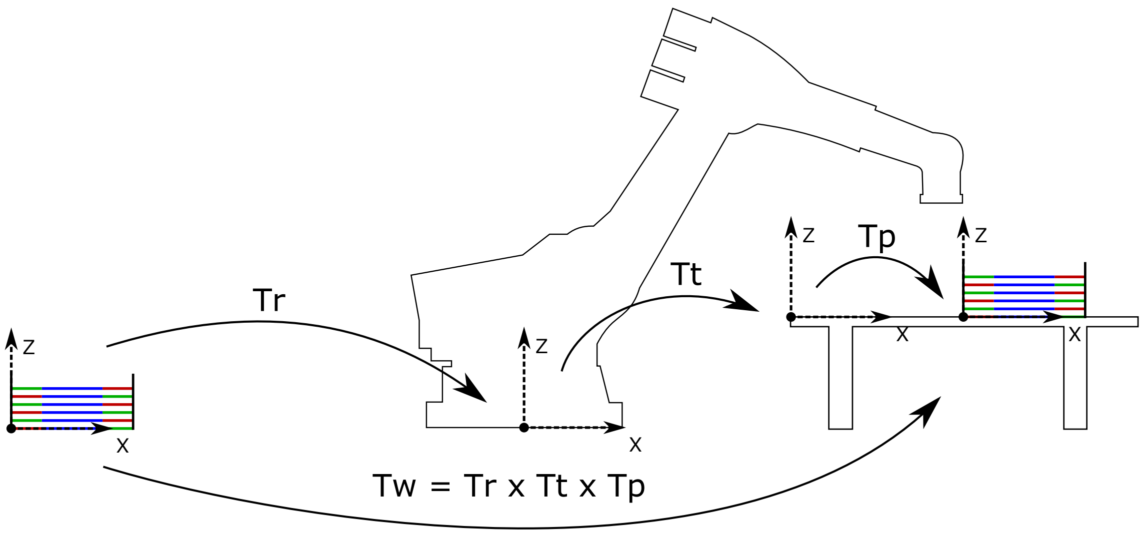


Figure 3.15: Path to part: Transformations

Following the presented feature example, an exhaustive path has been generated in its own reference frame. To accurately simulate this feature deposition, the path location has to precisely replicate the actual deposition environment. This operation is achieved using a process called calibration, which can be divided into three steps (Fig. 3.15). The first step is to identify the transformation between the path reference frame and the manipulator reference frame. This transformation (Tr) should be simple to calculate since the user himself defines both of these frames. The second step requires users to measure using the real manipulator the transformation (Tt) between this one and the workspace. The workspace is a flat surface where the deposition is occurring, usually materialised by a table. However, this step is only required during cell installation (Section 3.2.5). Finally, an additional transformation (Tp) can be defined to adjust the wall position on the table. This step can be estimated in the 3D environment or measured on the table if accuracy is required. Thus, by combining all those transformations, the path obtained previously can be relocated to its deposition stage.

Consequently, after relocating the wall, users can simulate the deposition to control the entire operation, and, finally generate a machine code to build the desired wall (Fig. 3.16)

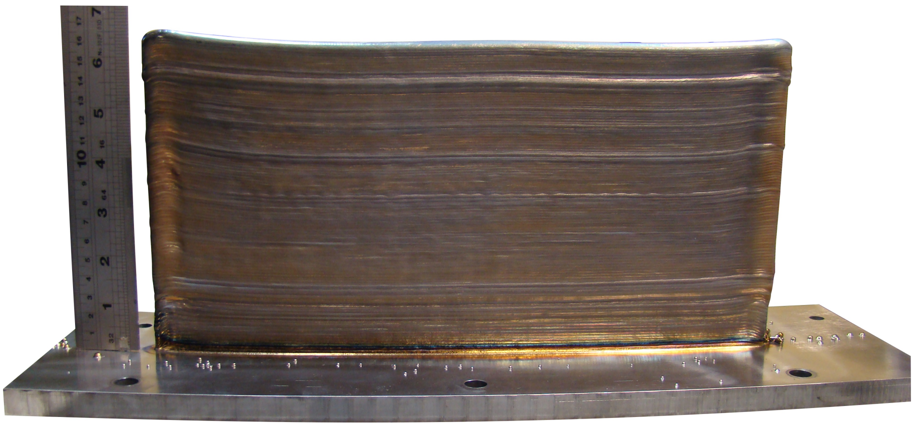


Figure 3.16: Wall built using single deposition strategy

3.5 Conclusion and future work

In this paper, the Path Generator Framework for WAAM (PGFW) is introduced to provide a basis for future WAAM development. This innovative solution combines into a single framework not only the ability to create, manipulate and visualise paths designed for WAAM but also to turn these paths into an actual part by integrating simulation and post-processors. Moreover, the path generation process is simplified and gathered into a PathAPI, so researchers with any programming skill levels can easily develop path planning solutions, focusing only on WAAM requirements. Compared to traditional CAM software, the PGFW does not contain any patterns or predefined path constraints which can influence the path development into a machining-like solution. Instead, the PGFW is a complete freeform path design tool allowing users to create innovative path planning strategies compatible with the specific requirements inherent to arc welding deposition. Thus, using the detailed methodology presented in Section 3.2, the PGFW has been implemented into Rhinoceros 3D and its plugin Grasshopper to create a platform offering users complete flexibility, fast experimental development and intuitive graphical interface (Section 3.3). This paper also demonstrates the efficiency of the presented solution by detailing the path planning development of a single deposition wall feature, from the path generation to the part building (Section 3.4). This example illustrates the ability given to users to easily develop complex path planning and rapidly run production. However, it is important to notify that the finish part quality cannot be directly related to the PGFW since it also involves the path strategy and the deposition parameters chosen by the user.

Based on this software, more features will be developed in the future and gathered into a library to provide users with adjusted solutions to promptly build basic geometries. Additionally, the latest investigations are focusing on developing a process adapted to WAAM requirements to generate the path of complex geometries with minimum user intervention. Ultimately, these investigations will aim for a fully automated path planning solution for WAAM.

References

[1] M. Coykendall, John and Cotteleer, Mark and Holdowsky, Jonathan and Mahto. 3D opportunity in aerospace and defense: Additive manufacturing takes flight. *A Deloitte series on additive manufacturing*, 1, 2014.

[2] I. Gibson, D. W. Rosen, and B. Stucker. *Additive Manufacturing Technologies*. Springer US, 2010.

[3] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A tool-path generation strategy for wire and arc additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 73(1-4):173–183, jul 2014.

[4] S. W. Williams, F. Martina, a. C. Addison, J. Ding, G. Pardal, and P. Colegrove. Wire + Arc Additive Manufacturing. *Materials Science and Technology*, 32(7):641–647, may 2016.

[5] J. Mehnen, J. Ding, H. Lockett, and P. Kazanas. Design study for wire and arc additive manufacture. *International Journal of Product Development*, 19(1/2/3):2, 2014.

[6] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A practical path planning methodology for wire and arc additive manufacturing of thin-walled structures. *Robotics and Computer-Integrated Manufacturing*, 34:8–19, aug 2015.

[7] R. Dwivedi and R. Kovacevic. Automated torch path planning using polygon subdivision for solid freeform fabrication based on welding. *Journal of Manufacturing Systems*, 23(4):278–291, jan 2004.

[8] Y. Zhang, Y. Chen, P. Li, and A. T. Male. Weld deposition-based rapid prototyping: a preliminary study. *Journal of Materials Processing Technology*, 135(2-3):347–357, apr 2003.

[9] P. Kazanas, P. Deherkar, P. Almeida, H. Lockett, and S. Williams. Fabrication of geometrical features using wire and arc additive manufacture. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 226(6):1042–1051, jun 2012.

[10] D. Ding, Z. Pan, D. Cuiuri, H. Li, N. Larkin, and S. van Duin. Multi-Direction Slicing of STL Models for Robotic Wire-Feed Additive Manufacturing. In *International Solid Freeform Fabrication Symposium 2015*, 2015.

[11] D. Ding, Z. Pan, D. Cuiuri, and H. Li. Wire-feed additive manufacturing of metal components: technologies, developments and future interests. *The International Journal of Advanced Manufacturing Technology*, 81(1-4):465–481, oct 2015.

[12] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM). *Robotics and Computer-Integrated Manufacturing*, 31:101–110, feb 2015.

[13] D. Ding, Z.-X. Pan, D. Cuiuri, and H.-J. Li. Process planning for robotic wire and arc additive manufacturing. In *2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA)*, volume 363, pages 2000–2003. IEEE, jun 2015.

[14] D. Ding, Z. Pan, D. Cuiuri, H. Li, and N. Larkin. Adaptive path planning for wire-feed additive manufacturing using medial axis transformation. *Journal of Cleaner Production*, 133:942–952, oct 2016.

[15] D. Ding, Z. Pan, D. Cuiuri, H. Li, N. Larkin, and S. van Duin. Automatic multi-direction slicing algorithms for wire based additive manufacturing. *Robotics and Computer-Integrated Manufacturing*, 37:139–150, feb 2016.

[16] D. Ding, Z. Pan, D. Cuiuri, H. Li, S. van Duin, and N. Larkin. Bead modelling and implementation of adaptive MAT path in wire and arc additive manufacturing. *Robotics and Computer-Integrated Manufacturing*, 39:32–42, jun 2016.

[17] D. Ding, C. Shen, Z. Pan, D. Cuiuri, H. Li, N. Larkin, and S. van Duin. Towards an automated robotic arc-welding-based additive manufacturing system from CAD to finished part. *Computer-Aided Design*, 73:66–75, 2016.

[18] P. A. Colegrove, J. Donoghue, F. Martina, J. Gu, P. Prangnell, and J. Hönnige. Application of bulk deformation methods for microstructural and material property improvement and residual stress and distortion control in additively manufactured components. *Scripta Materialia*, 135:111–118, jul 2017.

[19] P. A. Colegrove, H. E. Coules, J. Fairman, F. Martina, T. Kashoob, H. Mamash, and L. D. Cozzolino. Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling. *Journal of Materials Processing Technology*, 213(10):1782–1791, oct 2013.

[20] J. Donoghue, J. Sidhu, A. Wescott, and P. Prangnell. Integration of Deformation Processing with Additive Manufacture of Ti-6Al-4V Components for Improved β Grain Structure and Texture. In *TMS 2015 144th Annual Meeting & Exhibition*, pages 437–444. Springer International Publishing, 2015.

[21] J. J. Craig. *Introduction to Robotics: Mechanics and Control*. Addison-Wesley, second edi edition, 1989.

[22] J. A. Rehg. *Introduction to robotics: a systems approach*. Prentice Hall PTR, 1985.

[23] M. Brady. *Robot Motion: Planning and Control*. MIT Press, 1982.

[24] R. P. Paul. *Robot Manipulators: Mathematics, Programming, and Control : the Computer Control of Robot Manipulators*. MIT Press, 1981.

[25] P. Jiménez, F. Thomas, and C. Torras. 3D collision detection: A survey. *Computers and Graphics*, 25(2):269–285, 2001.

[26] F. Martina, J. Mehnen, S. W. Williams, P. Colegrove, and F. Wang. Investigation of

the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V. *Journal of Materials Processing Technology*, 212(6):1377–1386, 2012.

Chapter 4

Paper B

"A feature-based path planning approach for Wire + Arc Additive Manufacturing"

Florent Michel[a], Helen Lockett[b], Jialuo Ding[a], Stewart Williams[a]

[a] *Welding Engineering and Laser Processing Centre, Cranfield University, Cranfield MK43 0AL, UK*
[b] *Open University, Walton Hall, Kents Hill, Milton Keynes MK7 6AA, UK*

Abstract Wire + Arc Additive Manufacturing (WAAM) is a rising manufacturing process which, thanks to its high-rate deposition and unlimited build volume, has undeniably become a genuine challenger in the field of medium to large metallic deposition. The ultimate step for a large commercial deployment of the WAAM technology is the development of a path planning software solution to facilitate the intricate use of WAAM technology. As it can be seen in the literature, a straightforward solution for this issue is to propose users predesigned paths associated with specific geometries. Thus, this paper proposes a definition of the feature-based approach to path planning and presents its benefits and its limits as a viable commercial tool. Furthermore, the Cranfield University features library is introduced as a feature-based path planning solution in a research environment. Finally, through the detailed descriptions of the proposed path planning strategies for walls and hollow asymmetric shapes, the fundamental rules inherent to WAAM technology are highlighted.

Keywords WAAM; Wire and Arc Additive Manufacturing; Path planning; Toolpath generation; Feature; Feature-based

4.1 Introduction

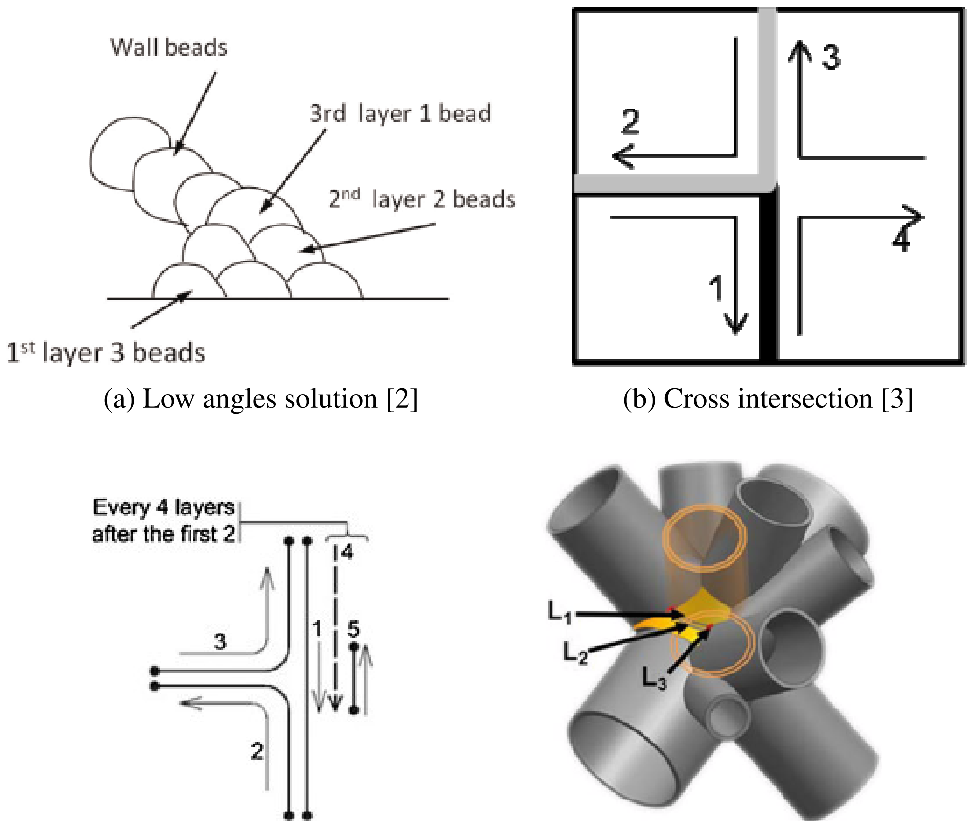
Wire + Arc Additive Manufacture (WAAM) is a growing manufacturing technology which builds metallic parts using direct feed process. Using an arc as heat source and wire as feedstock gives WAAM high deposition rates and structural integrity. Furthermore, WAAM technology is composed of standard off-the-shelf equipment, making it a relatively inexpensive manufacturing process. Combining low costs to high deposition rates confers WAAM a potentially unlimited build deposition, imposing WAAM as an indisputable challenger in the field of medium to large metallic deposition [1].

Yet, to make good use of the WAAM efficiency, adapted path planning solutions are required. However, unlike most Additive Manufacturing (AM) processes, path generation for WAAM can be particularly challenging due to the inherent characteristics of the welding deposition. During the development phase, a common way to study path planning solutions has been to design paths for specific 3D geometries. This feature-based approach can be seen as a limited solution since it allows users to build only a narrow range of geometries, but it assures to users an accessible and successful part building.

The main asset of developing features is that it allows the path designer to solve building issues by implementing upstream corrections. For example, in the attempt of building inclined walls, Kazanas et al. [2] proposed the creation of a pyramidal shape at the base of the wall to avoid a hump formation occurring at a later stage (Fig. 4.1a). Thus, using the predictive advantages of the feature-based approach, Kazanas et al. [2] also demonstrated their ability to build complex geometry using WAAM technology such as the enclosed structure.

A particular challenge in building parts with WAAM is to control the peculiar behaviour of intersection between two distinct deposition sections. In their study, Mehnen et al. [3] showed that building a cross structure using a constant deposition pattern, across the layers, would lead to the accumulation of a depression. Instead, thanks to a feature-based solution, they proposed a rotating pattern (Fig. 4.1b) which eliminates the depression accumulation. A similar approach has been used by Venturini et al. [4] to build, in this case, a T-Crossing feature (Fig. 4.1c). This solution, however, adds a compensation deposition every four layers to counter the depression accumulation.

Additionally, Yili et al. [5] showed that using features and repeating a simple path strategy can enable the creation of highly complex geometries such as multi-directional pipe joint (Fig. 4.1d).



(a) Low angles solution [2] (b) Cross intersection [3]

(c) T-intersection [4] (d) Pipe joints [5]

Figure 4.1: Path planning methods for feature-based approach

Thus, this study aims to define what a feature is and discuss its benefits either as a deployment tool for WAAM technology but also as a long-term commercial solution. Furthermore, this paper presents the Cranfield University features library and its contribution to a WAAM research centre. Finally, through the path planning description of walls and hollow axisymmetric features, the fundamental path planning rules for WAAM are highlighted.

4.2 Features definition

In this research, a feature is a parametrised geometry associated with one or multiple path strategies. It can also be seen as a script coded with the relevant path generator framework, such as the Path Generator Framework for WAAM (PGFW) presented in a previous research paper (Chap 3). Based on some inputs defined by the user, this script can generate the optimum path to build the targeted geometry (Fig. 4.2). Thus, the primary output of this script is a path compatible with the designated robotic software. The second script output is a 3D representation of the targeted geometry. This output is optional but can help users to represent their objective visually.

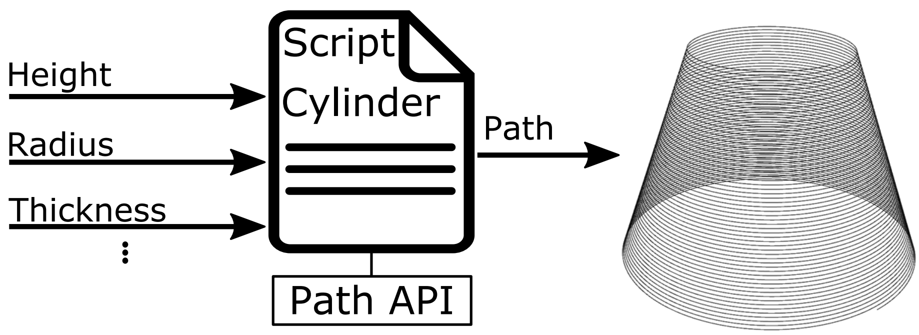


Figure 4.2: Script definition

The primary purpose of using features is to avoid having to build a path repetitively when the target geometry has a similar shape. Obviously, to be useful, features need to be as flexible as possible. Then, the goal of the feature developer is to integrate into the script as many inputs as possible, while keeping the optimum path in the entire range of input.

The direct benefit of the feature concept is that it separates the knowledge and expertise of WAAM (the latter being essential to produce quality parts) from the operation line. As a result, operators can build parts by merely choosing a feature and defining its sizes and other available characteristics, without requiring expert skills in WAAM, CAD or coding. Additionally, features are grouped into a library, making each newly developed feature an extension of capabilities for all users.

Thus, features play a significant role in the commercialisation of WAAM technology since they enable industries to order tailored features from WAAM experts. Indeed, by defining the targeted geometry and identifying their variability needs, feature developers can create new features that will fulfil both the industrial and the WAAM requirements. Industries can, therefore, build parts using WAAM technologies with little or no specialised training.

4.3 WAAM features for laboratory experimentation

In Cranfield University, features such as straight walls and cylinders are commonly built for experimental development of the WAAM technology. However, researchers do not necessarily have the coding experience necessary to develop their own path. Moreover designing paths can potentially be a time-consuming task. Therefore, a feature library has been developed to fulfil the researchers' needs. As it can be seen on Fig. 4.3, this library is composed of two features: walls and hollow axisymmetric shapes, both containing three associated path strategies which are described in the following sections.

It needs to be pointed out to the reader that, in the Cranfield feature library, the controls given to users over the features configuration are, with the exception of geometrical parameters, mostly concentrated on the deposition parameters due to the fact that researchers are selecting optimised parameters related to their experiment. However, features created for industrial purposes will more likely focus on geometrical characterisation and deposition parameters will be predefined.

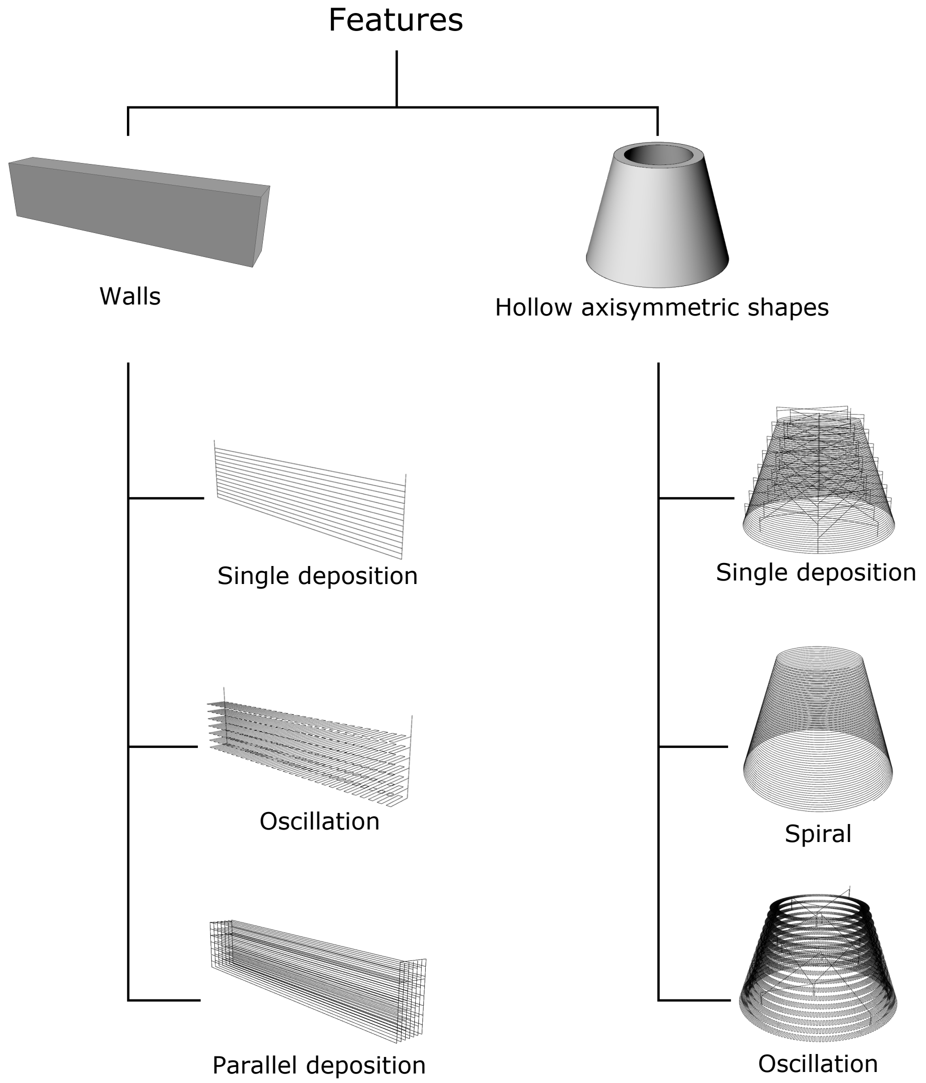


Figure 4.3: Features library in Cranfield University

4.4 Walls

To create a feature, users need to first define the geometric dimensions of the chosen feature. The wall feature geometry is a cuboid (Fig. 4.3) and can, for that reason, be defined by these three parameters: length, width and height.

As mentioned previously, feature can potentially be built using different path strategies. Indeed, concerning the wall feature, three strategies are here available: single, oscillated and paralleled deposition (Fig. 4.4). The single deposition should be used to build walls with a limited width relative to the welding technology used [6, 7]. On a larger wall, a single deposition bead cannot fill the entire width of the wall. As a result, alternative strategies should be considered, such as oscillated or parallel deposition. The choice between these two deposition strategies is, however, left to the WAAM designer.

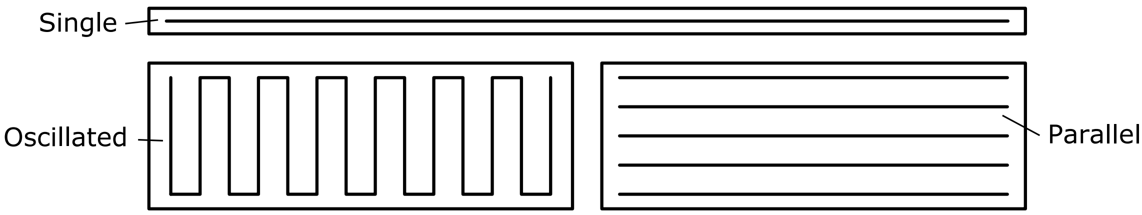


Figure 4.4: Description of the three path strategies available for walls

Other than these characteristics, the three path strategies presented here are based on a layer-by-layer deposition method and are, consequently, sharing the same fundamental deposition rules inherent to the WAAM technologies. These rules are presented below.

Variable section

A section defines a continuous deposition path, from the arc ignition to its termination. On a simple feature like a wall, a layer is only made of a single section. In this case, layers and sections are, therefore, representing the same entity. However, it is essential to understand that more complex geometries like the T-crossing feature can contain multiple sections in a single layer (Fig. 4.5). In this situation, the torch is paused and retracted at the end of the first section. Then the torch is placed at the beginning of the second section before starting the arc and the deposition.

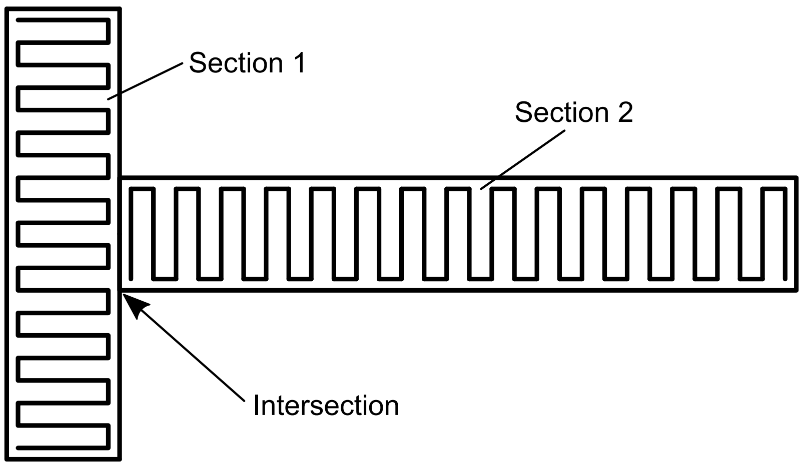


Figure 4.5: T-Feature layer containing multiple sections

The deposition behaviour of a section is profoundly different from other traditional AM technologies such as Fused Deposition Modeling (FDM). The heat accumulation produced by the arc has, indeed, a direct impact on the deposited bead shape. Yet, because the heat is fundamentally different at the beginning and at the end of the deposition, some corrections have to consequently be taken to avoid a discontinuity in the bead shape along the deposition [8].

Thus, to reach a uniform deposition of sections, the concept of zones is introduced on all the path strategies (Fig. 4.6). A zone is a set of movements, identified by a colour, which are sharing the same deposition parameters. These deposition parameters can slightly vary according to the welding equipment but are mostly defining the travel speed (TS), the wire feed speed (WFS), and the current (A).

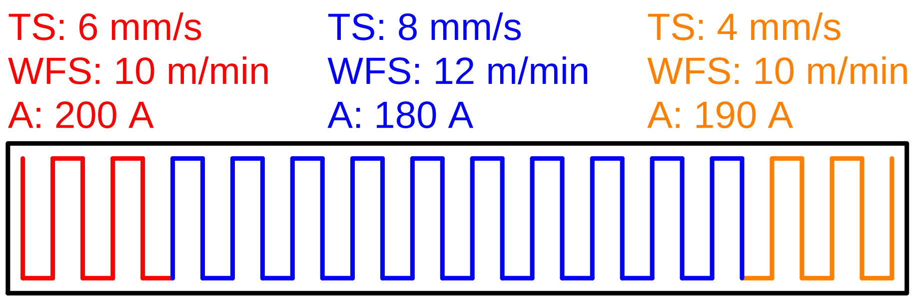


Figure 4.6: Zones definition

Thus, a simple section, as in the case of the wall feature, will necessarily contain three zones allowing users to set deposition parameters adapted to the deposition behaviours along the section. Furthermore, the length of each zone can be defined since it can vary like the deposition parameters according to the welding equipment and the material deposited. It should be noted that, in some cases, a section can contain more than three zones to accommodate some other alteration like the intersection of another section (Fig. 4.5).

This variable section control, thanks to the zoning concept, allows users to assure uniform deposition of a single layer. However, layer after layer, the repetition of a deviation as small as it could be, will quickly accumulate into a significant anomaly. To avoid this issue, additional rules presented in the following sections should, therefore, be applied.

Alternating deposition direction

As seen above, the deposition of a section has the tendency to create a hump at the start and a depression at the end, regardless of the path strategy used. As it can be seen on Fig. 4.7, the accumulation of these errors will certainly become visible after the deposition of numerous layers. Thus, to overcome this issue, a simple but effective solution consists of alternating the deposition direction for each layer (Fig. 4.8).

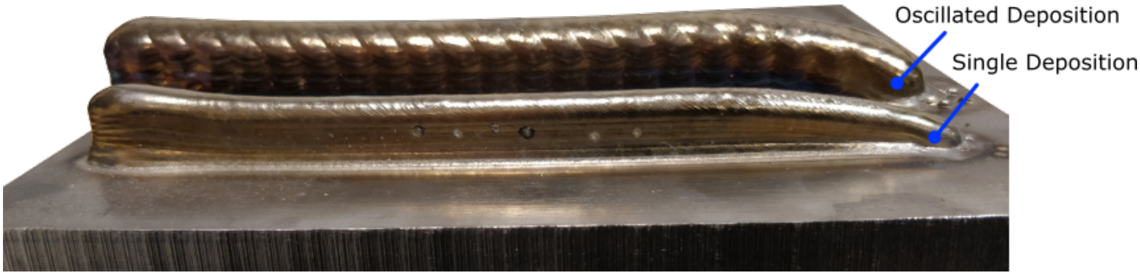


Figure 4.7: Hump and depression accumulation

Independent layer parameters

It can be thought that once the deposition parameters have been optimised to build a uniform first layer, repeating those parameters on every layer, while alternating the deposition direction, would create a regular deposition across layers. Unfortunately, that is without taking into account the variation of heat dissipation across layers. Indeed, when building the first layer, the material is deposited directly on the substrate, which is usually a large metallic part. At this step, the heat produced by the arc is quickly dissipated into the substrate removing energy from the weld pool [9]. This fast dissipation will however continuously slow down as layers are built on the top of each other until it reaches an equilibrium stage.

As a result, this behaviour requires users to adapt the deposition parameters to each layer until the equilibrium point is reached, after which, the same parameters can be repeated. Thus, it is fundamental that the path strategy integrates individual layer parameters (each of those containing its own set of zones). However, a feature can easily

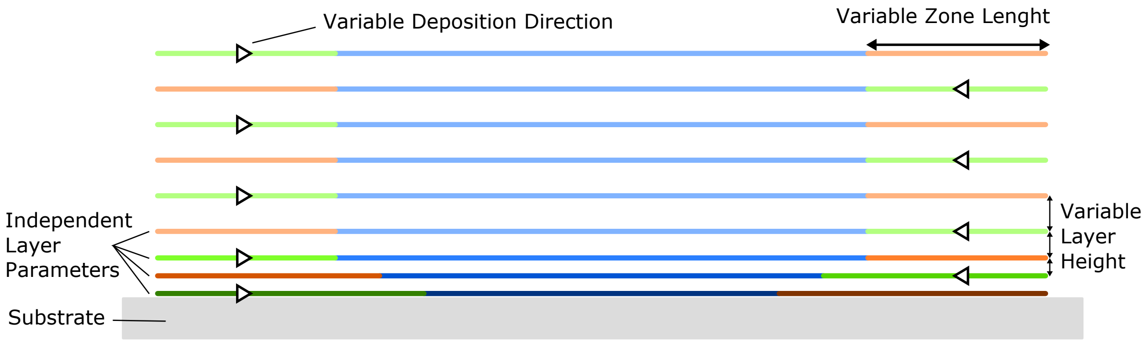


Figure 4.8: Fundamental requirements for WAAM layers deposition

contain up to hundreds of layers, and in practice, the equilibrium can be reached reasonably quickly (around five layers). Therefore, the solution proposed in our features is to define only the first layers which need varying parameters. The last layer setup will then be automatically repeated until it reaches the predefined height of the feature (Fig. 4.8).

Variable layer height

The heat dissipation variation and the adjustments of parameters across layers impact the deposition thickness of each layer significantly. For that reason, it is fundamental to associate the layer height with the independent layer's parameters so that the deposition of the following layer will start at the expected height (Fig. 4.8).

4.5 Hollow axisymmetric shapes

To define the hollow axisymmetric feature dimensions, three approaches are available to users. First, conical shapes can be described using top and bottom diameters as well as the height and the thickness of the geometry (Fig. 4.9a). Then, a free-form axisymmetric shape with constant thickness can be defined by drawing an opened planar curve on the ZX plane associated with a given thickness (Fig. 4.9b). Finally, to add a variation of thickness to the feature, users can draw a closed planar curved on the ZX plane (Fig. 4.9c). Even though the last method can create all the hollow axisymmetric shapes, it is essential to also offer straightforward solutions for the most common situations.

Similar to the wall feature, three path strategies (Fig. 4.3) are available to build hollow axisymmetric parts. However, these strategies can be categorized into two fundamentally different approaches: the layer-by-layer deposition and the continuous deposition.

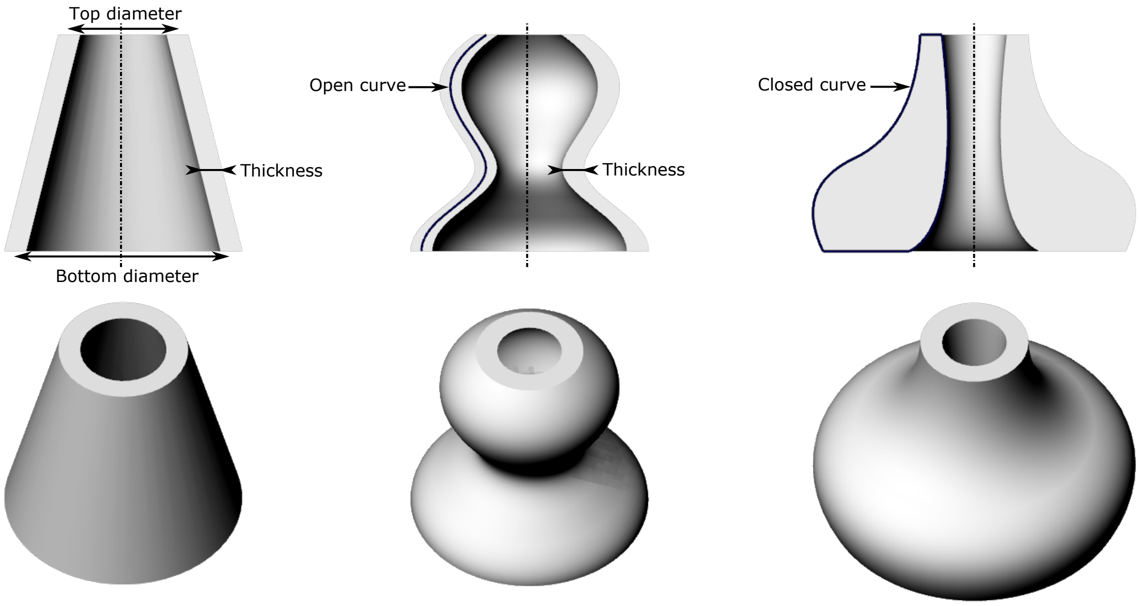


Figure 4.9: Geometrical definition of axisymmetric shapes

Layer-by-layer deposition

Like walls, hollow axisymmetric parts can be built using the single and oscillated deposition strategies based on a layer-by-layer approach. These path strategies share, therefore, the same fundamental principles enumerated previously. Thus, to guarantee a uniform deposition, each layer is made of three zones, and its deposition direction is alternated. Moreover, like the walls, the deposition parameters and heights of the first layers can be configured independently to adjust the heat dissipation variation across layers (Fig. 4.10).

Yet, unlike the walls, the deposition of an axisymmetric layer starts and terminates to the same location. The problem is that the start/end point of each layer is stacking on the top of each other across layers deposition. This situation can create the accumulation of errors leading to irregularities or worth to structural failures (Fig. 4.11). To overcome this issue, the single and oscillated deposition strategies for hollow axisymmetric parts contain

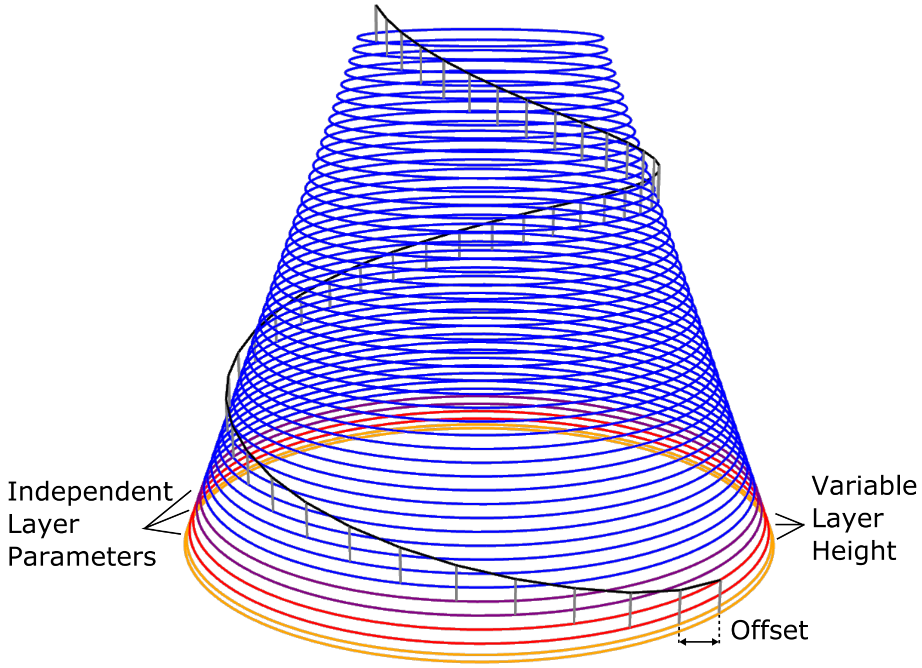


Figure 4.10: Key requirements to build axisymmetric shapes

the ability to offset the starting location of each layer at a regular interval determined by the user (Fig. 4.10).

The oscillated deposition of a circular path can also, on its own, create unbalanced results since the external perimeter is longer than the internal one (Fig. 4.12). As a result, using a constant deposition-rate along the oscillated path will end up depositing not enough material on the outside and too much in the inside. The error is directly proportional to the oscillation width and will accumulate across layers, which can lead to severe defects. To counterbalance this effect, each oscillation cycle is divided into eight zones as it can be seen on Fig. 4.12. Thus, the deposition parameters of each zone can be adjusted to increase the amount of material deposited on the outside and decrease it on the inside. To clarify; only eight sets of parameters need to be configured on each layer as these zones are repeated following the oscillation cycle. It should be noticed that the number of zones can be increased if more detailed adjustments are required.

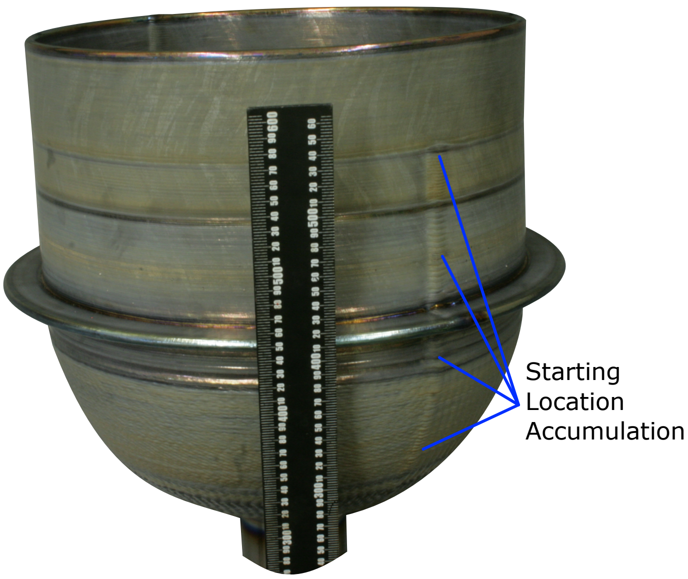


Figure 4.11: Fix starting location effect

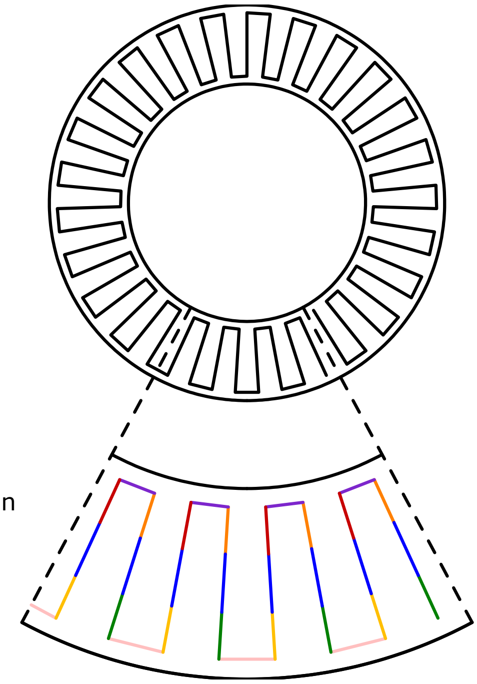


Figure 4.12: Oscillation zones for axisymmetric parts

Continuous deposition

The hollow axisymmetric feature also includes a notably different path strategy called spiral. Unlike its counterparts, the spiral path strategy is not part of the layer-by-layer deposition family, but instead, could be defined as a continuous single deposition process.

As opposed to layer-by-layer deposition, continuous deposition does not contain any interruption along the path of the entire part. Having no discontinuities removes potential errors related to the arc ignition or disruption and, instead, benefits from the arc stability. To emphasise these advantages, the continuous path should also avoid sudden changes of direction or parameters [10, 11]. However, these constraints over the path make the continuous deposition limited in its ability to build complex geometry.

Alternative continuous depositions, like for example the stepper, are feasible. This path strategy consists in depositing a single flat layer and jumping without interruption to the next layer. However, even though the jump ramp can be adjusted; the spiral deposition is, in any case, a smoother deposition.

A spiral deposition is, nonetheless, a perfect strategy to build hollow axisymmetric parts with a thin and constant thickness. However, it is necessary to highlight the fact that most manipulators cannot implement helix or spiral motions as they are not standard operations in the industry. Consequently, to realise a spiral feature, compatible with all manipulators, the generated path has to be an approximation of the geometrical representation made of standard robotic movements such as circular or linear motions. In this case, six circular arcs per revolution are used to approximate the helical paths since they can achieve a close approximation with significantly fewer motions than linear motions which help to prevent manipulator saturation.

If continuous deposition eliminates discontinuities issues, the heat dissipation variation has still a substantial impact on the deposition stability. The spiral strategy offers, therefore, the ability to define individual deposition parameters for the few first revolutions (Fig. 4.13). Since there is no layer in this situation, the first revolutions are distinguished by zones. Furthermore, users can also adapt individual height per revolution, which acts like a layer height (Fig. 4.13).

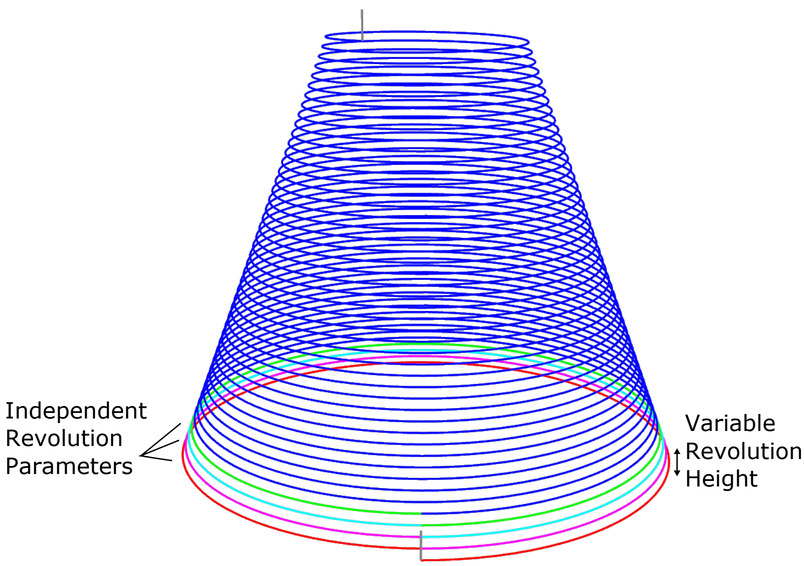


Figure 4.13: Key requirements for spiral deposition

4.6 Conclusion

In this paper, features have been defined as a parametric geometry associated with one or multiple path strategies. The presented benefit of the feature-based approach can be summarised in that it separates the actual WAAM expertise from the operation line allowing, therefore, a straightforward deployment of the WAAM technology primarily as a commercial tool. However, features are inherently limited by a narrow range of geometries since each new feature requires a substantial amount of research and development. Additionally, the Cranfield University feature library was introduced, and its significant role in supporting researchers in their WAAM related studies was presented. Finally, throughout the description of path strategies allowing the fabrication of walls and hollow axisymmetric shapes, fundamental rules have been highlighted. These rules are the bases of path planning for WAAM and are reiterated below.

- All sections require at least three sets of parameters to better control the deposition behaviour at the start and at the end of the section.
- The deposition direction has to alternate for each layer to avoid error accumulation.
- The first few layers require individual deposition parameters to adjust the deposition to the heat dissipation variation across layers.
- Layer height needs to be adjustable to also adapt the deposition to the heat dissipation variation across layers.
- The circular oscillated path requires distinct sets of parameters on the outside and the inside of the circle to assure a uniform deposition.

Acknowledgements

The authors would like to express their gratitude to the WAAMMat programme industry partners (www.waammat.com) for supporting this research financially.

References

[1] S. W. Williams, F. Martina, a. C. Addison, J. Ding, G. Pardal, and P. Colegrove. Wire + Arc Additive Manufacturing. *Materials Science and Technology*, 32(7):641–647, may 2016.

[2] P. Kazanas, P. Deherkar, P. Almeida, H. Lockett, and S. Williams. Fabrication of geometrical features using wire and arc additive manufacture. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 226(6):1042–1051, jun 2012.

[3] J. Mehnen, J. Ding, H. Lockett, and P. Kazanas. Design study for wire and arc additive manufacture. *International Journal of Product Development*, 19(1/2/3):2, 2014.

[4] G. Venturini, F. Montevecchi, A. Scippa, and G. Campatelli. Optimization of WAAM Deposition Patterns for T-crossing Features. *Procedia CIRP*, 55:95–100, 2016.

[5] D. Yili, Y. Shengfu, S. Yusheng, H. Tianying, and Z. Lichao. Wire and arc additive manufacture of high-building multi-directional pipe joint. *International Journal of Advanced Manufacturing Technology*, pages 1–8, 2018.

[6] F. Martina, J. Mehnen, S. W. Williams, P. Colegrove, and F. Wang. Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V. *Journal of Materials Processing Technology*, 212(6):1377–1386, 2012.

[7] P. M. Sequeira Almeida and S. Williams. Innovative process model of Ti-6Al-4V additive layer manufacturing using cold metal transfer (CMT). In *21st Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2010*, pages 25–36. University of Texas at Austin (freeform), 2010.

[8] J. Xiong, Z. Yin, and W. Zhang. Forming appearance control of arc striking and extinguishing area in multi-layer single-pass GMAW-based additive manufacturing. *International Journal of Advanced Manufacturing Technology*, 87(1-4):579–586, 2016.

[9] B. Wu, D. Ding, Z. Pan, D. Cuiuri, H. Li, J. Han, and Z. Fei. Effects of heat accumulation on the arc characteristics and metal transfer behavior in Wire Arc Additive Manufacturing of Ti6Al4V. *Journal of Materials Processing Technology*, 250(July): 304–312, 2017.

[10] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A tool-path generation strategy for wire and arc additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 73(1-4):173–183, jul 2014.

[11] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A practical path planning methodology for wire and arc additive manufacturing of thin-walled structures. *Robotics and Computer-Integrated Manufacturing*, 34:8–19, aug 2015.

Chapter 5

Paper C

"A modular path planning solution for Wire + Arc Additive Manufacturing"

Florent Michel[a], Helen Lockett[b], Jialuo Ding[a], Filomeno Martina[a], Stewart Williams[a]

[a]*Welding Engineering and Laser Processing Centre, Cranfield University, Cranfield MK43 0AL, UK*
[b]*Open University, Walton Hall, Kents Hill, Milton Keynes MK7 6AA, UK*

Abstract Wire + Arc Additive Manufacturing (WAAM) has proven its capability to build medium to large metallic parts thanks to its high-rate deposition and its potentially unlimited build volume. Moreover, the low-cost equipment and the ability to deposit various metals make WAAM a strong candidate to become a standard industrial process. However, like all Additive Manufacturing (AM) technologies, the key to manufacturing suitable parts lies in the generation of an optimised path which guarantees a uniform defect-free deposition. Most AM technologies have been able to use traditional path strategies derived from CNC machining, but the specificities inherent to the arc deposition make the use of those solutions unreliable across a variety of topologies. Nevertheless, studies have shown that superior results can be achieved by using a feature-based design approach, but developing a path strategy for each new geometry would be a very time-consuming task. Therefore, this paper introduces the Modular Path Planning (MPP) solution which aims to incorporate the modularity of feature-based design into the traditional layer-by-layer strategy. Thus, by dividing each layer into individual deposition sections, this method allows users to adapt the path planning to the targeted geometry allowing the construction of a wide variety of complex geometries. Moreover, this paper proposes a software implementation which limits user interventions and reduces user inputs to basic CAD modelling operations.

Keywords WAAM; Wire and Arc Additive Manufacturing; Path planning; Toolpath generation

5.1 Introduction

In the past 30 years, Additive Manufacturing (AM) has gradually evolved from prototype applications to parts production by improving manufacturability and reducing lead time [1]. Even though AM is already used in many commercial processes, its full potential might appear in the near future, bringing a significant societal impact [2].

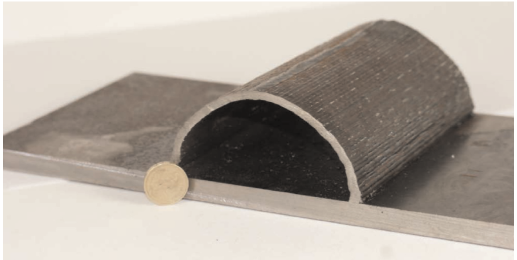
Among numerous AM technologies, Wire + Arc Additive Manufacture (WAAM) stands out, especially in the field of medium to large metallic deposition. Indeed, by combining arc welding tools with standard robotic manipulators, WAAM provides a potentially unlimited build volume and a high-rate deposition of various metals, such as steel, aluminium alloys or titanium alloys [3].

Post-processing consolidation treatments like Hot Isostatic Pressing (HIP), which reduces porosity and lack of fusion, can be difficult to apply to large components due to the absence of sufficiently-big HIPing facilities. For this reason, defect-free deposition is essential to build primary structures that require high-structural integrity. Ding et al. [4, 5] have shown that, in WAAM, the quality of deposition is fundamentally linked to the tool path strategy used. Therefore, the WAAM technology requires a dedicated software approach to generate optimised paths, thus guaranteeing uniform deposition and ultimately enabling a complete commercial solution. In fact, many studies have focused on this particular topic from which two mains approaches can be distinguished.

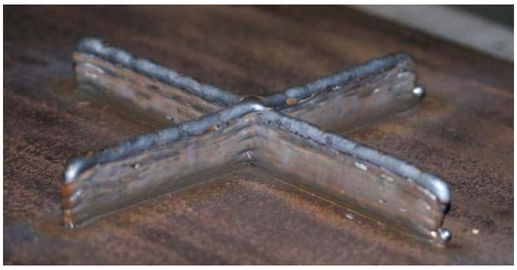
The first approach is to slice a geometry and to generate a path using the same path planning strategy, for each resulting layer. Although this solution has been successfully used on other AM process such as FDM [6], it is not directly applicable to WAAM, which has specific requirements inherent to arc welding deposition. Indeed as Ding et al. describe in their research [4, 5], several path characteristics such as discontinuities, sharp turns and overlaps contribute to an unstable deposition that, layer after layer, can lead to a catastrophic failure. These limits have been understood for a long time, in fact, early studies [7, 8] have designed path planning strategies for WAAM that generate continuous paths. Unfortunately, removing discontinuities increases other factors like sharp turns. For these reasons, Ding et al. introduced several path planning strategies [4, 5, 9, 10] limiting simultaneously all the faulty factors in a path to improve deposition. Nevertheless, in this approach, all the proposed solutions apply the same path planning strategy regardless of the layer shape. Yet, the higher the topological complexity of a geometry, the more discontinuities and sharp turns are likely to appear. Thus, the resulting quality can vary substantially according to the geometry.

The alternative approach is the feature-based design introduced by Kazanas et al. [11]. In their research, they demonstrated WAAM's ability to build complex parts like enclosed structures by designing a path strategy that fits the requirement of this particular targeted shape. This solution has been then followed by the development of cross structures [12], T-crossing features [13] and more recently, multi-directional pipe joints [14] (Fig. 5.1). Thus, this approach has shown that designing a path strategy ad hoc for a given topology guarantees the deposition quality; however, this solution requires a time-consuming path design research for each new part, which is incompatible with the purpose of AM.

Furthermore, one must bear in mind the fundamental differences between powder-bed AM and directed-energy deposition AM. In the former, the layer height is fixed by the downward movement of the build platform and the consistency between thickness of the sliced layers in pre-processing, and thickness of the layer built is somehow always ensured. The latter, instead, is closer to micro-casting, and numerous factors can influence



(a) Enclosed structure [11]



(b) Cross intersection [12]

(c) T intersection [13]

(d) Pipe joints [14]

Figure 5.1: Structures examples build using a feature-based design approach

the shape of the deposited bead (width and height). One of these factors is the local variation in the part geometry. This means that even if the same set of parameters is used, the resulting bead geometry can vary. Imagine a linear deposit; in such a case there is a balance between energy introduced, energy conducted away, energy used to melt the wire, and energy used to melt the underlying material. In this steady state, the resulting geometry does not change. However, when that linear structure changes into an intersection, the energy balance is disturbed; more heat is conducted away; the melt pool would shrink resulting in thinner wall width, and larger layer height, if no compensation is applied to the process parameters. Therefore it is absolutely essential that parameters are changed ad hoc to compensate for such variation and to ensure that the geometry obtained is the same as that expected per sliced CAD file, and no errors are accumulated throughout the build. This is also why simple reverse-machining strategies, which fill the sliced layers, cannot be applied.

To tackle these challenges, this paper introduces a new approach to generate paths for

WAAM of complex 3D geometries. The proposed solution, called Modular Path Planning (MPP), integrates the adaptability of the feature-based design into a more efficient layer-by-layer path planning solution. Thus, it will be shown how this solution guarantees a uniform layer deposition, leading to high-quality part building, and with limited effort in the pre-processing stage.

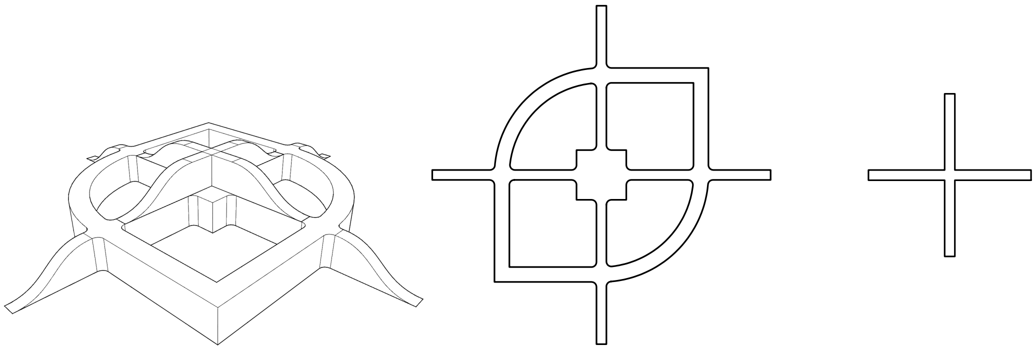
The following Section presents the MPP concept and defines the rules and the decomposition process to guarantee the uniform deposition of a layer. Then, Section 5.3 describes the MPP implementation that reduces user inputs to basic CAD modelling operations. To describe the entire solution, an application example is presented in Section 5.4. Section 5.5 compares the MPP to a traditional path solution and shows its ability to build complex parts for industry. Finally, in Section 5.6, the benefits and limits of the presented solution are discussed, followed, in Section 5.7 by the conclusion and the presentation of future work.

5.2 Theoretical approach

5.2.1 Slicing

As introduced previously, the MPP aims to integrate modularity into the popular layer-by-layer deposition strategy. Therefore, like the traditional approach, the first step consists of slicing the 3D Computer Aided Design (CAD) model into layers. However, it should be highlighted that the deposition thickness is not necessarily the same for each layer. For instance, the heat dissipation variation within the first layers has a critical impact on the layer height [15]. The slicing interval could, thus, compensate for this issue.

The result of this slicing operation is a set of layers represented as 2D geometries. As it can be seen on Fig. 5.2, these layers extracted from a single 3D CAD model can have substantial topology variation. Therefore, applying the same path planning solution to these diverse topologies will lead to disparate results. For this reason, the MPP allows the definition of a path planning strategy for each layer.



(a) Perspective view (b) Extracted layer 1 (c) Extracted layer 25

Figure 5.2: Example of topology variation

5.2.2 Segmentation

Segmentation is the fundamental idea of the MPP to integrate modularity into the path design process. Indeed, where a traditional approach would apply a single path planning on the entire layer, the MPP requires users to segment the given layer into sub-parts called sections (Fig. 5.3) to then generate individual paths.

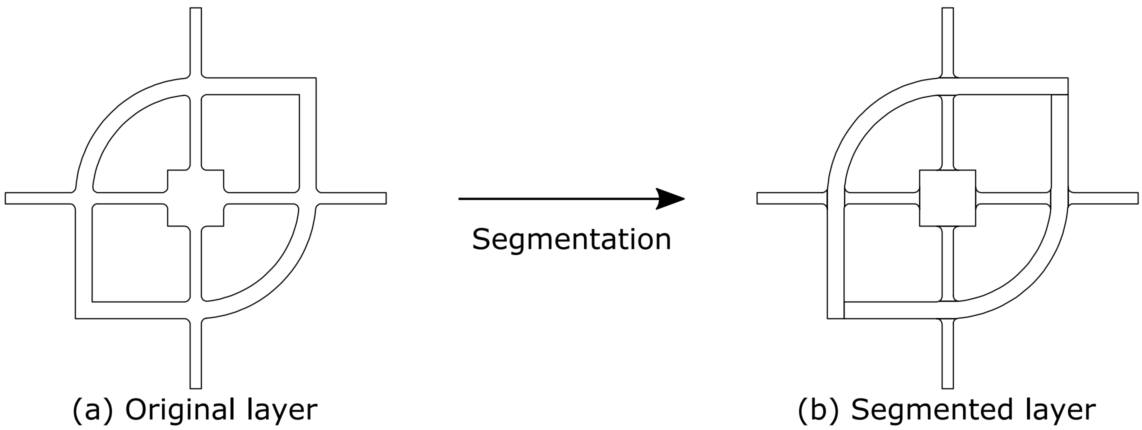


Figure 5.3: Example of a layer segmentation

The purpose of this segmentation step is to create a set of sections shaped into basic geometries, usually narrow rectangular shapes, to facilitate their deposition. However, the optimum segmentation is determined based on experience and is highly dependent on the part geometry. Nevertheless, some basic rules need to be followed. For example, if curved trajectories can be deposited, sharp turns should be avoided, and instead replaced by corner intersections (Fig. 5.4). Similarly, if a slight width variation does not alter the deposition (Fig. 5.5a), an abrupt width variation can create irregular paths (Fig. 5.5b) leading, layer after layer, to significant defects. Therefore, to avoid those irregularities, it is preferred to divide this part in multiple sections (Fig. 5.5c).

The sections shape is fundamental to provide a controlled deposition but, to assure uniform deposition of the entire layer, it is also crucial to provide particular attention to the intersections topology since poor junctions can create critical defects in the final part. As it can be seen on Fig. 5.6, many junction configurations are possible when using only parallel and oscillated paths. Some of these intersections can be more complicated to deposit than others as they are more likely to produce defects. In any case, an appropriate research study should be conducted on each intersection type to determine deposition parameters that will assure a defect-free junction.

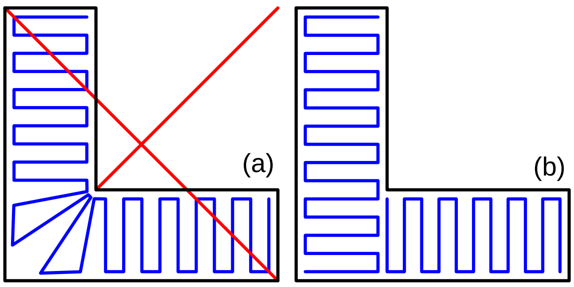


Figure 5.4: Sharped turn (a) vs corner division (b)

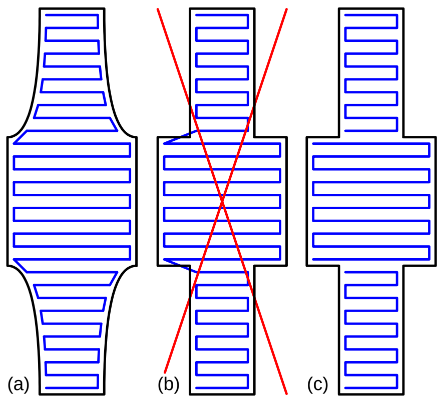


Figure 5.5: Path generation through width variation

5.2.3 Path planning

Once the layer has been segmented, a path can be generated in each section. An advantage of the segmentation is that, compared to the traditional approach, multiple path planning strategies can be used across a single layer to best fit the requirement of each section.

Any path planning strategies can be used to build those individual paths, however, the oscillated path (Fig. 5.13a) is the most recommended since it can handle width variation and slight curve very well, and therefore its deposition is easier to control. Nevertheless, the parallel path (Fig. 5.13b) can also be an adequate alternative, especially when used to build narrow shapes since it produces smoother surface waviness [16]. Still, interconnections can be more problematic when using parallel paths.

5.2.4 Zoning

As mentioned previously, although path design improves the deposition uniformity significantly, appropriate deposition parameters are essential to control the deposition. Deposition parameters depend on the geometry; on the location within a part; on the material being deposited and on the chosen WAAM sub-process (MIG, TIG, plasma, etc). For those reasons, the MPP adopts a concept of zones: where a zone, identified by a colour, contains a particular set of parameters (Fig. 5.7a) to be specified by the user after the path planning phase.

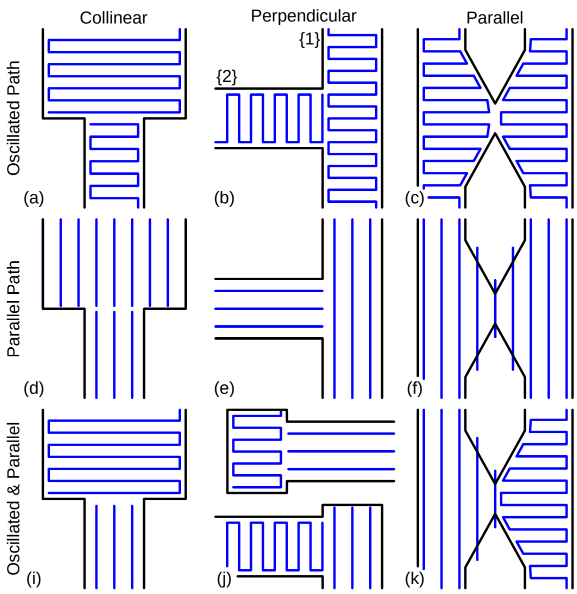


Figure 5.6: Path intersection examples

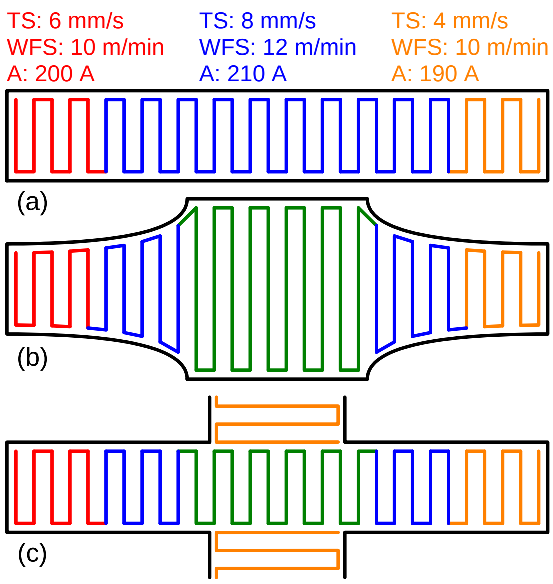


Figure 5.7: Zones definition

Thus, as it can be seen on Fig. 5.7a, a simple straight wall contains three zones to accommodate the different thermal conditions in the stages of deposition start, steady state, and end. This must be done whichever path is used: single bead, oscillated or parallel. Additionally, if a section contains a notable width variation requiring specific deposition parameters, a zone can be defined to account for that change in width, and to manually adapt the parameters locally (Fig. 5.7b). However, this situation could also be solved by using an algorithm that would calculate automatically the parameters needed to produce the desired layer width and height. Finally, because the heat dissipation is drastically different at the intersections, it is crucial to create zones at those locations (Fig. 5.7c), as explained in the Introduction Section.

5.2.5 Layer path

Once a path has been generated for all sections, they are combined into a single layer path. However, it is important to highlight that the deposition is not continuous along the entire layer. Instead, when reaching the end of a section, the deposition is stopped and the torch moves to the starting point of the following section with the arc off and without feeding any material (Fig. 5.8).

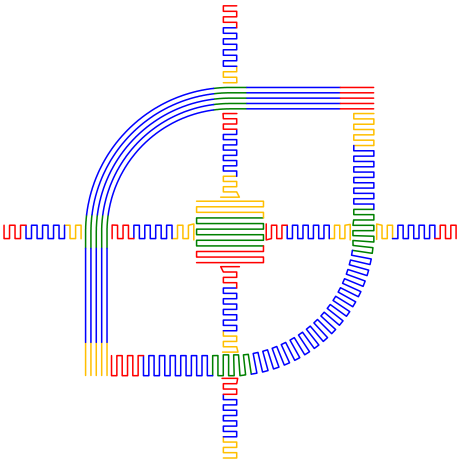


Figure 5.8: Layer path

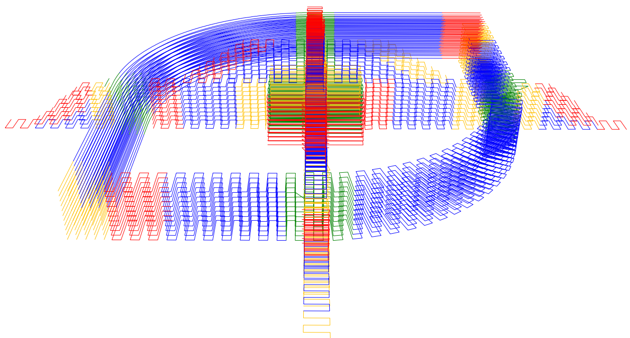


Figure 5.9: Full part path

Sorting algorithms [17] can be used to reduce downtime by defining a better order of deposition. Yet, a particular deposition order can benefit some intersections. Indeed, in the case of the perpendicular intersection of oscillated paths (Fig. 5.6b), depositing section 2 after section 1 helps to melt the waving border at the junction reducing risk of voids. Moreover, the deposition sequence has a significant impact on distortion [18, 19] and should, then, be taken into consideration to minimise buckling risk.

Finally, once the path of the first layer is made, the same methodology can be applied to each following layer, generating a set of layers that can be combined to build the entire part (Fig. 5.9).

As shown, building complex geometries of various topologies can be achieved thanks to the presented MPP. However, applying the proposed solution can be challenging in practice. Indeed, the path planning of a single layer can already be a complex and time-consuming process: partitioning on its own involves many highly-technical CAD modelling operations. Therefore, repeating this operation for each layer of a standard-size part, which can contain hundreds of layers, multiplies the effort required to build the entire part by as much. The next Section proposes an implementation of the MPP that reduces the operational complexity to basic CAD inputs and really minimises user's interventions.

5.3 Practical approach

5.3.1 Slicing

The central operation in the slicing stage is to extract the boundaries of the geometry at a given height. Actually, most 3D CAD frameworks contain a function that is able to compute the intersections between geometry and a plane. Therefore, to build the layers, a list of planes is first generated following the deposition direction from bottom to top. As explained previously, the gap between each plane is not necessarily constant but instead defined by a user input. Then, by using the intersection function, a layer is extracted for each plane, resulting in a stack of layers.

5.3.2 Building Strategy (BS)

The MPP solution aims to build a part by individually generating the path of each layer. However, as explained previously, the path planning of a layer can be laborious since it consists of partitioning the layer into simple sections (Segmentation); generating the appropriate paths for each section (Path planning) and integrating zones into each section (Zoning). Therefore, to avoid complex CAD modelling operations, the following Sections introduce a three-step process called Building Strategy (BS) (Fig. 5.10). This process offers users the ability to outline the desired layer path configuration with basic CAD inputs while, in the background, the application processes the technical CAD operations to generate the actual path.

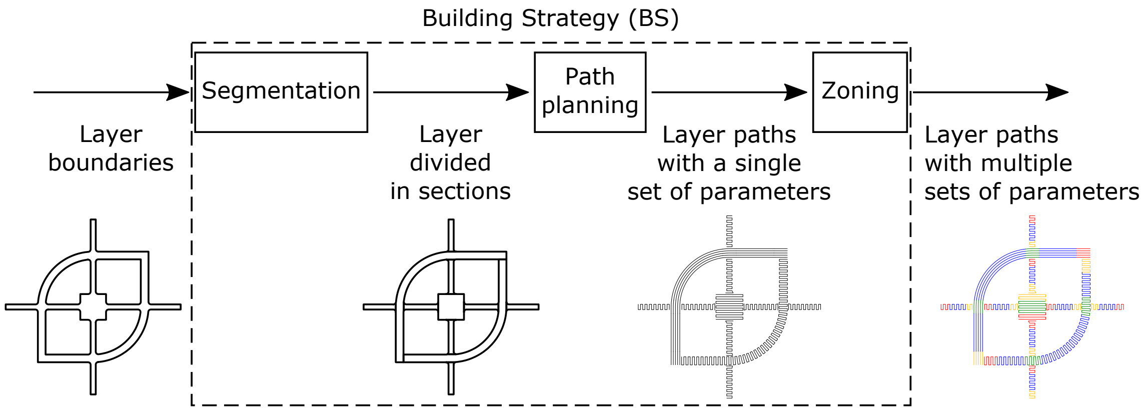


Figure 5.10: Building Strategy flowchart

Segmentation

For their first intervention, users are asked to identify each section of an extracted layer by following the rules defined in the theoretical approach (Section 5.2). Firstly, the active layer is shown in the background (Fig. 5.11a). Secondly, the user overlays planar closed-curves on the targeted sections (Fig. 5.11b). Thirdly, following the user's input, the software extracts automatically and instantaneously the sections (Fig. 5.11c) by applying a boolean intersection function (Fig. 5.12).

The result of this operation is multiple empty sections represented by their boundaries as planar closed curves (Fig. 5.10). However, no path can be generated yet since it requires an additional user intervention as described in the following Section.

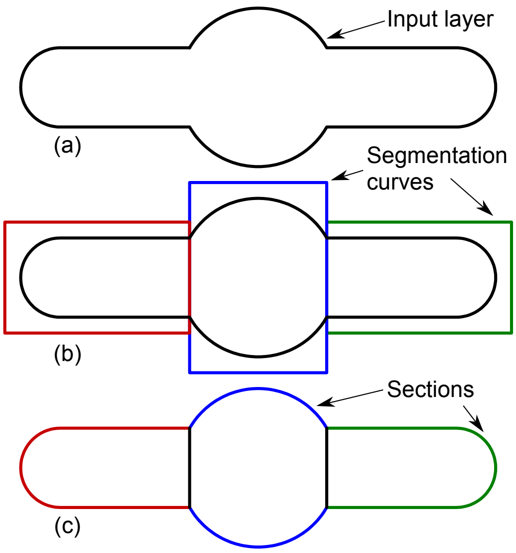


Figure 5.11: Segmentation process

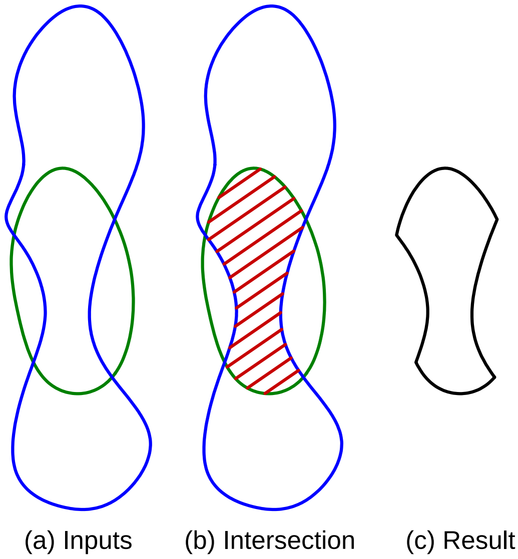


Figure 5.12: Boolean intersection function

Path planning

Once the layer is divided into sections, a path planning strategy needs to be applied to each section to generate paths. As mentioned previously, any path planning solution could potentially be implemented, however, in this paper only the oscillated and parallel deposition strategies are presented (Fig. 5.13). In general, at this point, users pick the best deposition strategies between those available, to best meet the requirements of the targeted geometry.

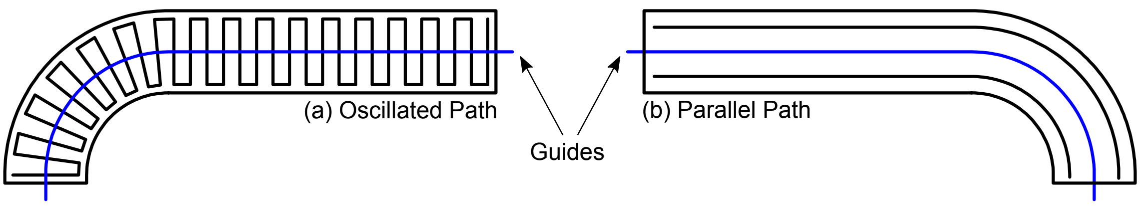


Figure 5.13: Guides definition and path strategy examples

However, given that sections are mere planar closed surfaces, other information is needed. Firstly, the user must specify the direction of travel by drawing a guide. As it can be seen in Fig. 5.13, a guide is a planar curve that specifies the deposition direction. If the oscillated path has been selected, it will be produced by generating an oscillation perpendicular to the guide-line, and with constant step-advancement. If the parallel path has been selected, a series of equidistant paths parallel to the guide will be produced. Moreover, intersections between the guide and the section boundary will represent the start and stop of the deposition. In fact, the guide must intersect the section's boundary exactly twice.

The result of this operation is an automatically generated path for each section (Fig. 5.10). It is essential to understand that these paths are not interconnected; meaning that during the deposition stage the manipulator will go from a path to another by stopping the deposition and retracting the end-effector.

However, as stated previously, using a single set of deposition parameters within a section will most likely lead to a poor deposition quality. Therefore, it is crucial to give the path the ability to change its deposition parameter along the path thanks to the zoning step described in the next Section.

Zoning

In the theorical approach (Section 5.2.4), a concept of zones has been presented to facilitate the integration of various deposition parameters across sections assuring a uniform deposition. The zoning method, presented here, allows users to define zones intuitively within a section.

By default, the path generated in a section is automatically associated with a zone (Fig. 5.14a), meaning that all movements in this newly generated path are sharing the same deposition parameters. From this state, the user can split the main zone in two by simply locating a point on the path (Fig. 5.14b). Thus, knowing the location of the point, the software regenerates a new path and changes the parameters dataset reference whenever it passes over a splitting point. This process can then be repeated to generate the necessary number of zones (Fig. 5.14c).

Alternatively, users can zone the path by defining a length at the beginning and/or at the end of this path (Fig. 5.14d). The benefits of this solution are detailed in Section 5.3.3 but are mainly related to the fact that arc-based deposition requires particular parameters

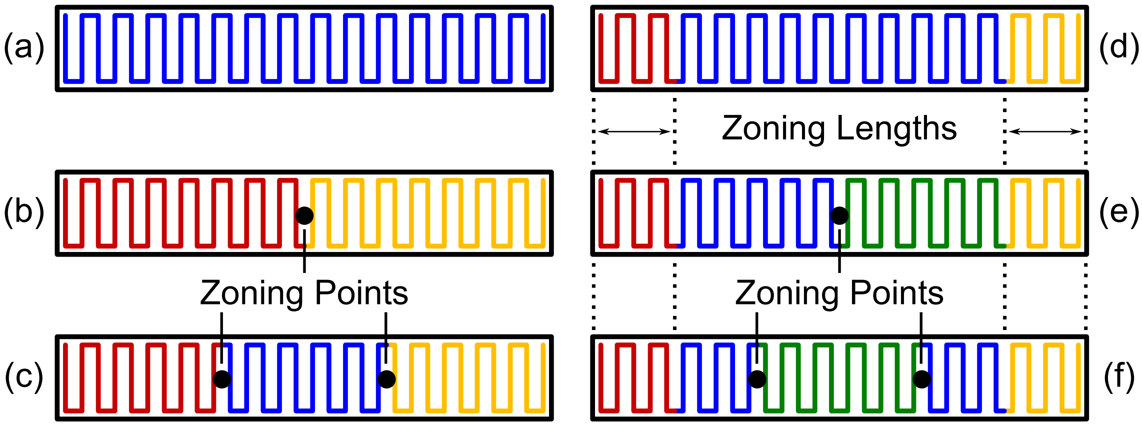


Figure 5.14: Zoning

at the ignition and termination stages for a limited length.

Finally, it is important to notice that both of these alternatives can be used simultaneously (Fig. 5.14f), giving substantially more flexibility to the user throughout the process.

At this stage, all required inputs for building a layer are completed, and the software can, therefore, combine all the generated section paths into a single layer path (Fig. 5.10). However, although this process is fast and straightforward to produce a single layer, repeating it over hundreds of layers can still be tedious.

5.3.3 Mask and 3D zoning

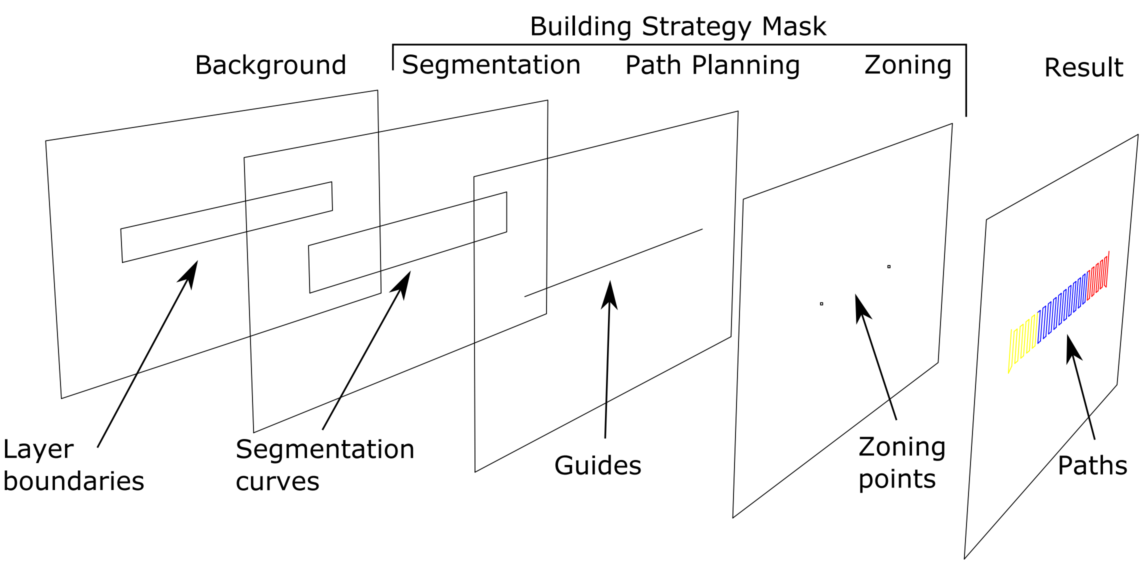
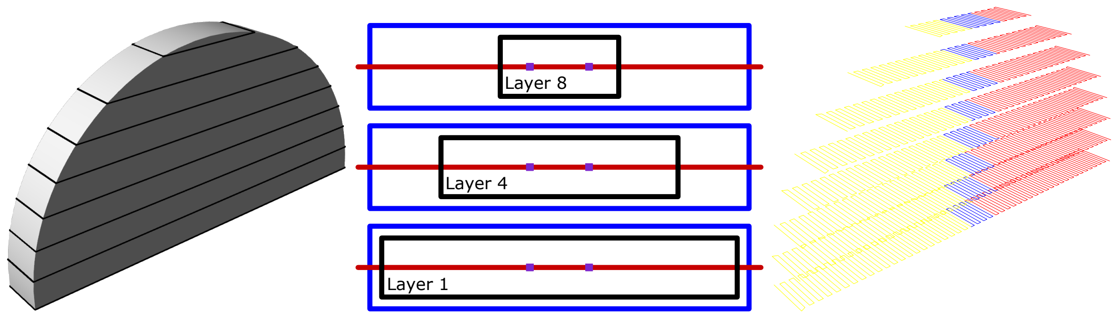


Figure 5.15: Definition of the Building Strategy mask

All the inputs needed to generate the path of a layer can be grouped into one entity, the mask (Fig. 5.15). The advantage of this approach is that the same mask can be used over multiple layers. In fact, as it can be seen on Fig. 5.16, even when each extracted layer is slightly different (Fig. 5.16a), applying a unique mask to all layers (Fig. 5.16b) results in a path accommodating layer boundaries and users' instructions, for each layer (Fig. 5.16c).



(a) Extracted layers (b) Building Strategy mask (c) Resulting paths

Figure 5.16: Application of a single mask across multiple layers

In fact, this mask property is at the core of the MPP to reduce user's interventions. Indeed, once users have defined the first layer mask, the software solution can automatically apply this mask to the following layers. However, if the input geometry contains various layer topologies as can be seen on Fig. 5.17, the program may fail to generate a path: for instance, when a single segmentation curve would produce two independent closed sections. In this situation, the software raises an exception, stops the path generation and asks users to create a new Building Strategy (BS) mask for the failed layer. This new mask is then used to generate automatically the current and following layers until a new exception is raised or the last layer is reached. Please note that users have the opportunity to integrate a new BS mask at any layer. Indeed, in some situations, although the software correctly generates a path using the previous mask, users can consider having a better alternative for the current and following layers.

The mask concept also enables 3D zoning. Indeed, the zoning process described in Section 5.3.2 provides two alternatives to define a zone using zoning points or zoning lengths. If this can seem redundant in 2D, this combination gives the user better control

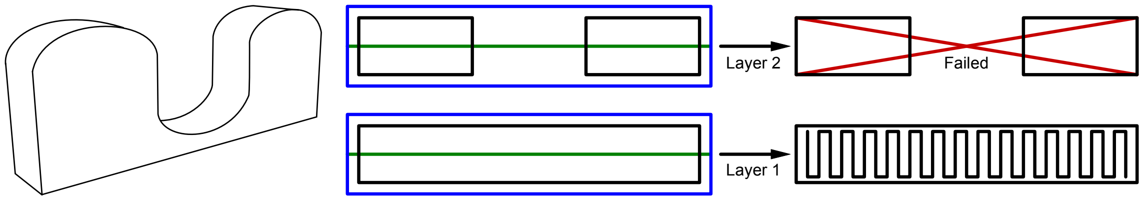


Figure 5.17: Example of a failing mask application

over the zoning definition of a 3D CAD model. Indeed, having the ability to mix points and lengths enables the user to define which zones can vary when the boundaries are changing across layers. To clarify the 3D zoning control, a simple example is shown on Fig. 5.18. In this example, zoning lengths are applied to the section to accommodate the arc welding behaviour at the ignition and termination of the deposition (Green and Red). Additionally, zoning points are located in the middle of the section to define a particular zone (Yellow zone) as an intersection. The result of this combination is that the green, yellow and red zones keep a constant length over the different layers, while the blue and purple zones adapt their length. In such a way, users can easily control the zones configuration across multiple layers.

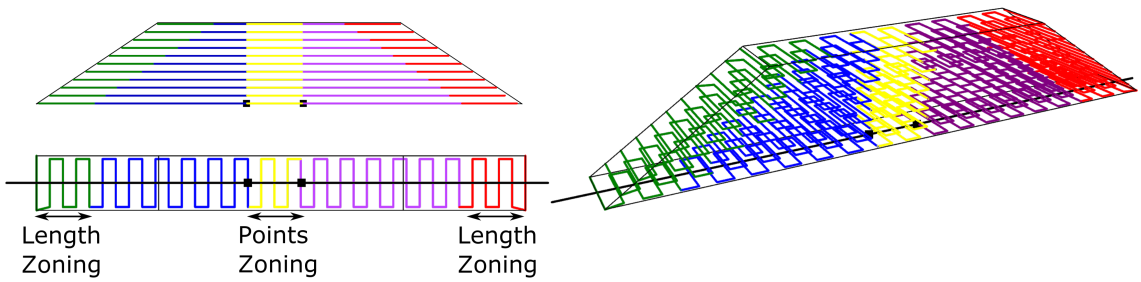


Figure 5.18: Example of the 3D Zoning application

5.3.4 Deposition parameters

Deposition parameters are deliberately omitted throughout the MPP process, so the user can focus entirely on the path architecture. Indeed, users are only asked to describe when those parameters need to be changed using the zoning method (Section 5.2.4).

To facilitate their implementation, in parallel to the path generation, the software generates an empty XML file that is structured to reflect the path architecture.

As shown in Fig. 5.19, the XML file is structured consistently to the MPP process. It contains a node for each layer; within each node, there are sections; within each section, there are the different zones, also identified by their colour; and inside the zones, the user then inputs the various deposition parameters (f.i. Current, Wire Feed Speed (WFS), Travel Speed (TS), etc).

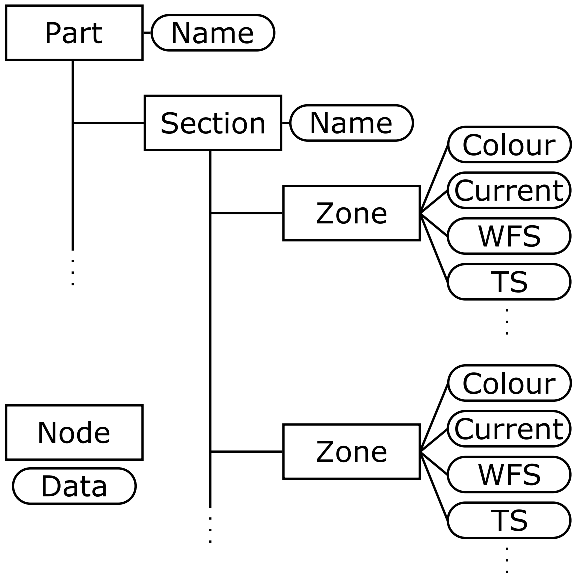


Figure 5.19: XML structure of the deposition parameters

Using an XML file enables users to fill parameters directly in the file, making it a simple and fast interface for experimental purposes. However, using the XML solution also facilitates the development of graphical interfaces enabling a commercial product, potentially. Moreover, having structured data storage will allow, in future, to automatically fill parameters by developing dedicated algorithms.

5.4 Application

In this Section, a complete step-by-step example of the MPP solution is presented using the geometry seen in Fig. 5.2. To generate this example, the MPP method has been implemented into the Rhinoceros 3D software and its extension Grasshopper. This extension facilitates the development of innovative solutions thanks to its intuitive and powerful interface.

The first step is to slice the input geometry into layers: to achieve it, users define the various layer heights (Section 5.2.1) and the slicing orientation. The resulting layers are then automatically aligned on the top view (Fig. 5.20), waiting for the user to start the next step.

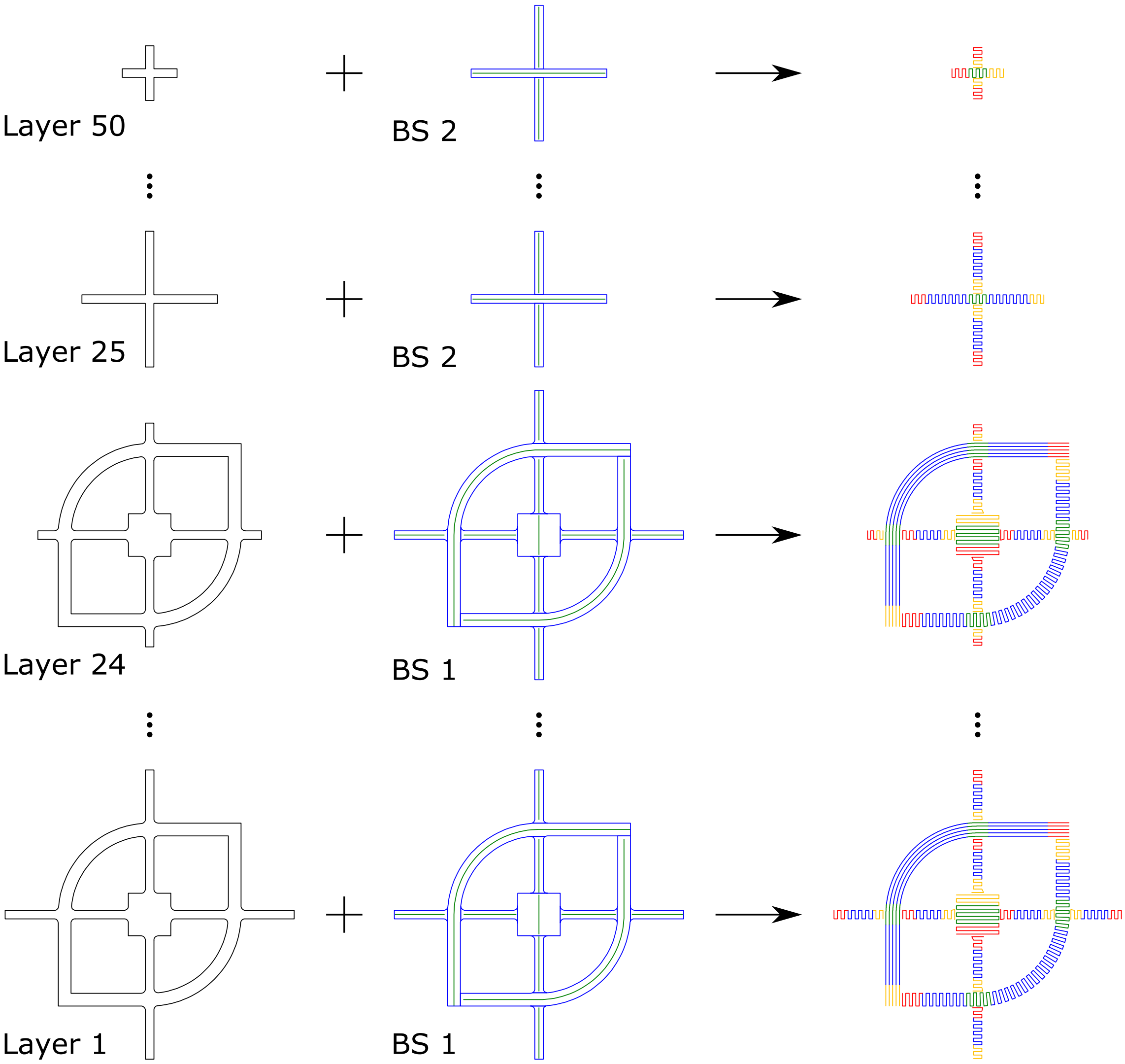


Figure 5.20: Description of the Modular Path Planning process

From this stage, users are asked to define the mask of the first layer by following the three-step BS process described previously (Section 5.3.2). By drawing segmentation curves, guides and zoning points over the layer, the software generates the first path automatically (Fig. 5.20). Users can then verify the result and modify their inputs if required.

The first mask is applied automatically to the following layers until an exception is raised (Section 5.3.3). In this example, the program fails to generate the layer 25 since this layer topology is drastically different from layer 24. Therefore, users are asked to draw a second mask (BS 2) that fits the requirement of layer 25. Using the second mask, the program resumes the path generation from layer 25 until the last one.

When all layers are successfully processed, all the paths are automatically grouped into a single path as seen previously in Fig. 5.9 (Section 5.2.5). At this stage, users can inspect the resulting path of the entire geometry and, if needed, can modify an input mask. Any modification would then be applied to all the layers impacted by this mask.

Before starting the actual deposition process, users have to define the deposition parameters by filling the XML file generated automatically with the path (Section 5.3.4). Once all the parameters are set, the path can be processed by a robotic software solution to generate the appropriate machine code, which will be used to finally start manufacturing.

5.5 Validation

A test-piece, shown in Fig. 5.21, was designed to validate the MPP approach. For comparison, the test-piece was also built using a path planning strategy available in the academic literature. The deposition parameters for the Ti-6Al-4V alloy were chosen based on the target baseline bead width and height of 6 mm and 1.5 mm, respectively. Regardless of the approach, eight layers were deposited to attempt reaching the desired height of 12 mm.

Four different tests were performed. The first test used the adaptive path planning method described by Ding et al. [9], which can be seen as a contour method when applied to this cross shape example (Fig. 5.22a). The process parameters were kept constant throughout the deposition. Fig. 5.22b shows the resulting component. Extensive presence of keyhole defects can be appreciated throughout. Fig. 5.22c shows a side view of the same component; the irregular height of the deposit can be seen.

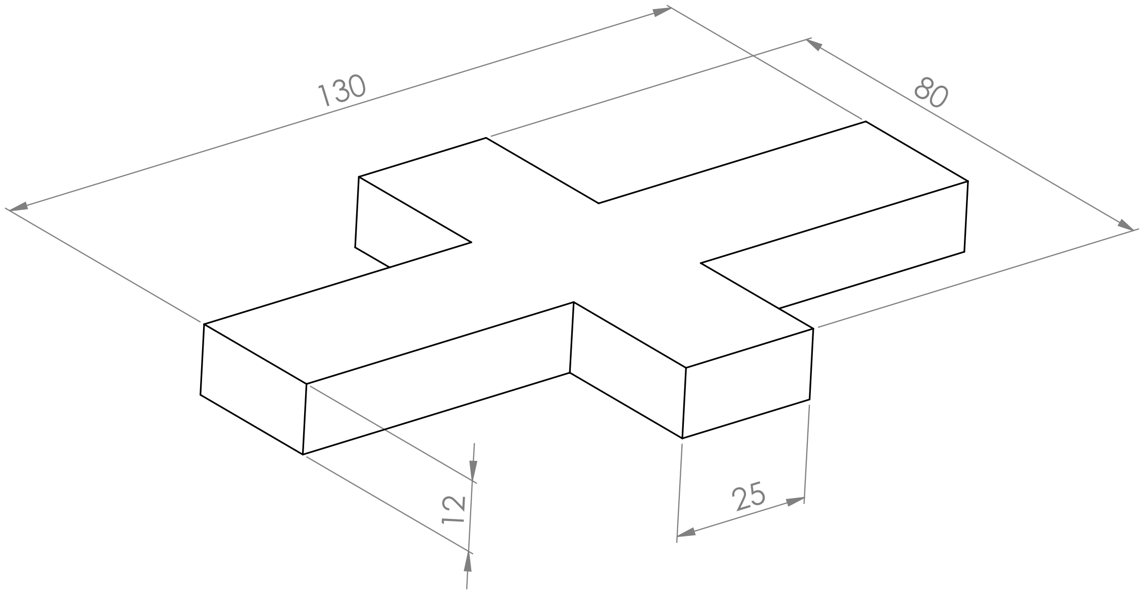


Figure 5.21: Test piece designed to validate the MPP approach. All dimensions in mm.

The second test used the same method as the first attempt (Fig. 5.22a), although parameters were different from the baseline ones, to try and avoid the defects seen previously. Fig. 5.22d shows the resulting component. Keyhole defects could still be found, although the height of the deposit is certainly more stable (Fig. 5.22e).

The third test used the MPP approach, albeit with segmentation only, and no zoning (Fig. 5.22f). Fig. 5.22g shows the resulting component. A small keyhole defect could still be found, but the height of the deposit was very stable (Fig. 5.22h). However, please note the lower height at the ends of the part.

Finally, the fourth test used the MPP approach with both segmentation and zoning applied (Fig. 5.22i). Fig. 5.22j shows the resulting component. No defects can be seen, and the height of the deposit is stable (Fig. 5.22k); the part ends are less steep as well.

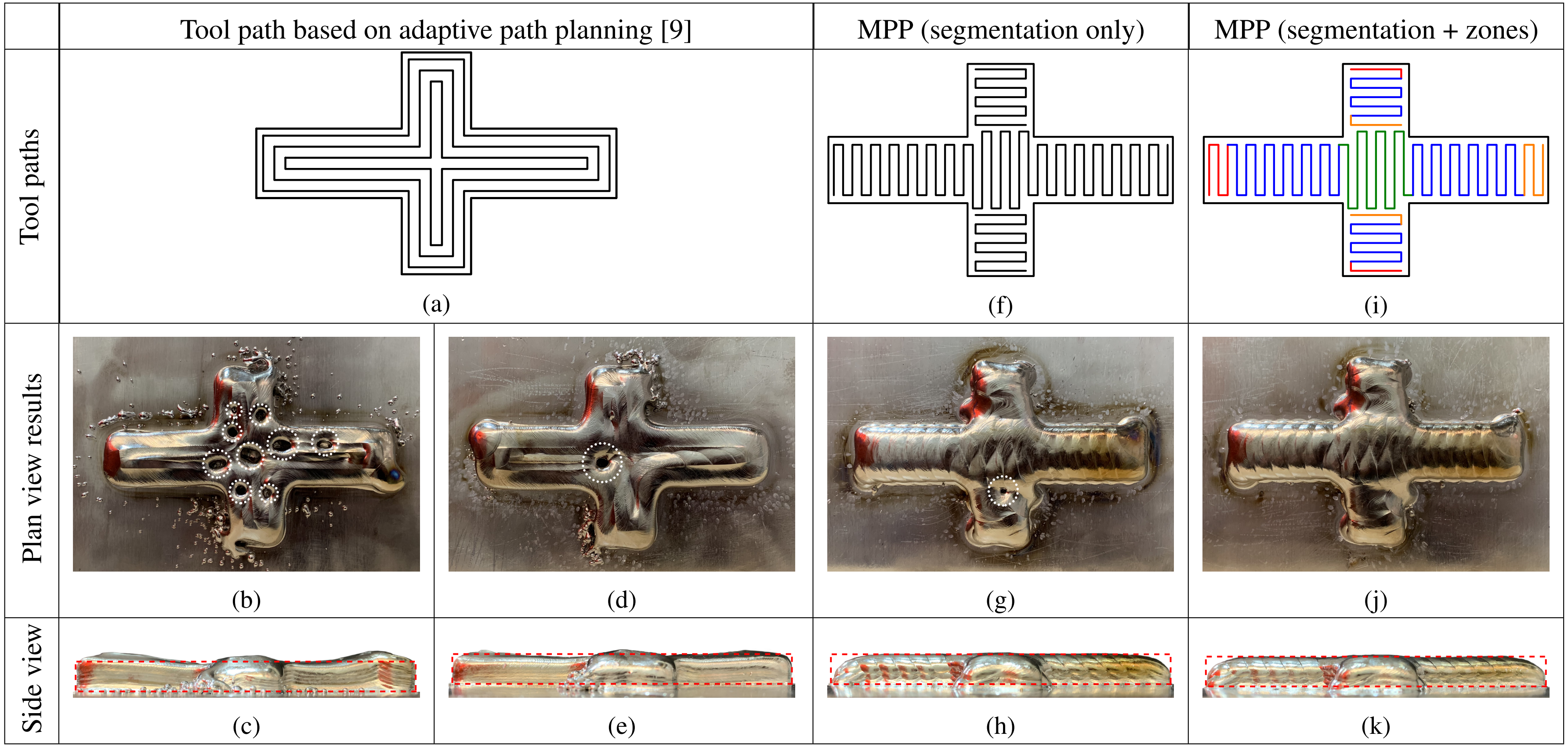
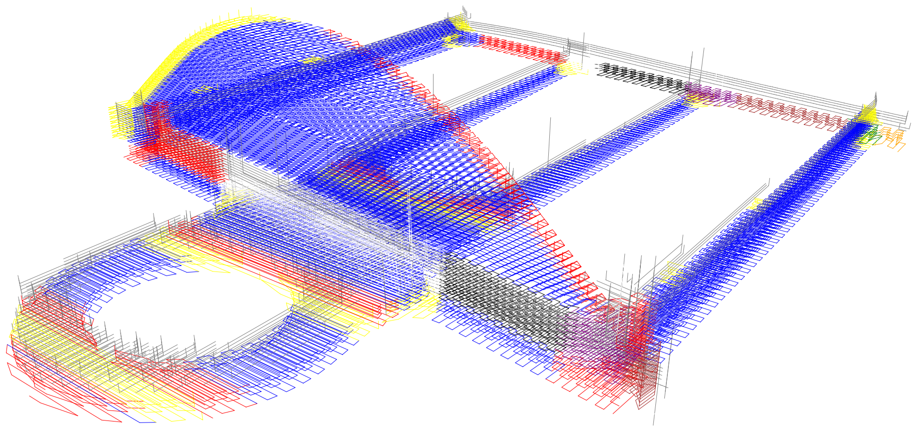
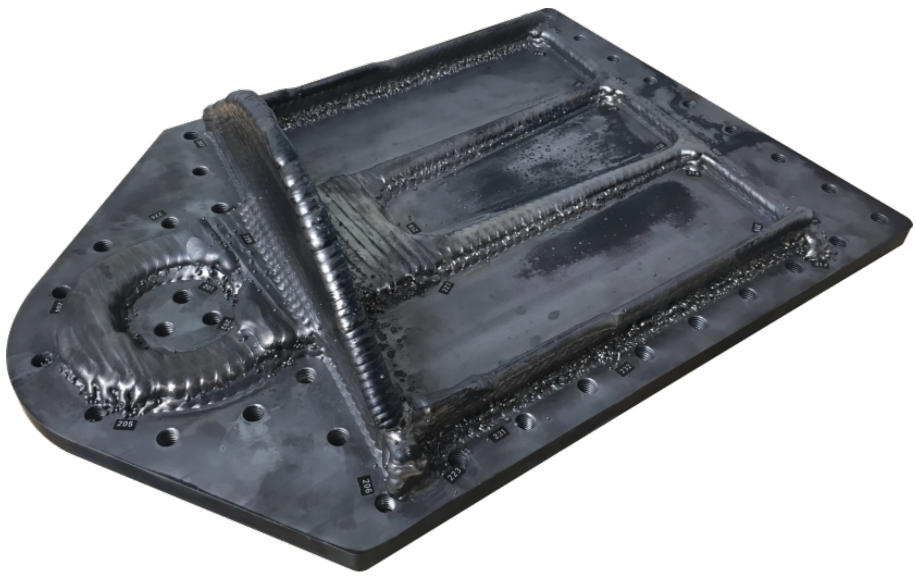


Figure 5.22: Validation study. The circles indicate keyhole defects; the red bounding boxes indicate the profile of the target geometry

Taking the validation one step further, an Airbus A320 aft pylon bracket mount was built. The tool path plan is shown in Fig. 5.23a, while the resulting component is shown in Fig. 5.23b. Please note this part was also in-process cold-worked, as described by Martina et al. [20]; the tool-path-planning for the in-process cold-work was performed with the same MPP software used for the deposition. Unfortunately, the finish-machined component cannot be shown due to confidentiality issues. The machined component showed no defects. A detailed presentation of this building process can be found in Appendix A.



(a) Tool path plan; the color scheme indicates the zones



(b) Final part; the dark color is a result of the heat treatment

Figure 5.23: A320 aft pylon bracket mount built for Airbus

5.6 Discussion

The proposed MPP solution has been shown to be highly flexible as it can integrate a variety of parameters to fit material and deposition technology requirements. It can also integrate new path planning solutions to increase its ability to build new topologies. Moreover, because the MPP solution is a layer-by-layer deposition strategy, it can integrate and plan the path of post-deposition-treatments such as rolling [21, 22], peening [23] or even machining [24, 25]. Therefore, this presented solution has a strong expansion potential as it can easily be adapted to new materials and processes.

However, to successfully build a part, it is also essential that the part design complies to the rules explained by Lockett et al. [26]. Moreover, to build parts containing overhang components, subdivision solutions [27–29] should be used beforehand to divide the geometry into buildable sub-features. Finally, in some cases, especially regarding simple building like cones, it can be more appropriate to use path strategies that take advantages of 5 axis depositions to follow the curve of the part, as shown by Hascoet et al. [30].

It should be noted that the definition of process parameters is beyond the scope of this paper. Instead, the software provides dedicated inputs so users can define those parameters. Indeed, such parameters depend on the process and the material used and, as such, would require extensive studies on their own [31, 32]. Similarly, parameters related to the path construction, such as stepover or bead-overlap, should be determined through experiments that define the deposition profile [10, 33–35].

Finally, as previously stated, the MPP approach differs substantially from the other tool-path-planning approaches published so far within the world of AM; however, the MPP is actually quite similar to what is done, in general, when planning the machining paths of a component in its entirety. In traditional CAM software, a part is divided into a number of manufacturing features each of which may have different process parameters, tools, etc. The CAM software then creates a toolpath for each of these manufacturing features and then stitches the different paths together into longer larger path that is encoded into the NC program. Previously-published tool-path-planning approaches treat a sliced layer as if it were a single manufacturing feature, which they try to fill with a path, according to a certain desirability criterion and do not consider the need for local changes to process parameters depending on the feature geometry. This approach work well for powder based additive manufacturing and FDM using polymers, but is too limited for complex WAAM deposition.

Our approach proposes that the ”traditional” feature-based machining tool-path planning approach should be taken also in the case of AM, and a layer should be subdivided into simpler building blocks whose paths are then merged in an overall piece of code. This enables the definition of feature-specific tool paths, which on the one hand requires a certain amount of manual work, but on the other hand it ensures the level of control needed to program whatever geometry with the right focus on structural integrity.

5.7 Conclusion and future work

This paper introduces a new path planning solution for WAAM called Modular Path Planning (MPP) that can be used to build a large variety of complex topologies. Because, in WAAM, the quality of deposition is fundamentally linked to the tool path strategy used, this proposed solution guarantees a uniform deposition by dividing a layer into a basic set of geometry that simplifies deposition prediction. Thus, by combining the efficiency of the layer-by-layer deposition strategy to the adaptability of the feature-based approach, this path generator offers the ability to use a diversity of material and deposition processes, and assures that the MPP solution can evolve and therefore become a standard path generator in a commercial WAAM solution. Moreover, the presented implementation of MPP allows users to build the path of a full part with limited and basic interventions.

The method has been used to manufacture a test-piece, shaped as a cross, and demonstrate the ability of the MPP solution to provide a more uniform deposition than traditional path planning solutions, which apply a single path strategy regardless of the geometry shape, such as the adaptive path planning strategy proposed by Ding [9]. Moreover, the production of a pylon bracket mount shows that the MPP solution can be applied to complex geometries while maintaining its deposition quality.

In the proposed solution, users are invited to intervene during the path generation process to adapt the path to the topology. Even though this step increases the path planning time, it is believed to be highly beneficial in terms of result quality; indeed, having a framework that enables the local change of process parameters is absolutely fundamental. Nevertheless, to achieve greater efficiency, future works will focus on making this step automatic, by integrating deep learning solutions, which will learn from user's interventions.

Acknowledgements

The authors are appreciative of EPSRC's NEWAM grant (EP/R027218/1). The support of David Steer, Andy Henstridge and Stephen Porter, all at Airbus UK, is also acknowledged. Finally, The authors would like to express their gratitude to the WAAMMat programme industry partners (www.waammat.com) for also supporting this research financially.

References

[1] M. Coykendall, John and Cotteleer, Mark and Holdowsky, Jonathan and Mahto. 3D opportunity in aerospace and defense: Additive manufacturing takes flight. *A Deloitte series on additive manufacturing*, 1, 2014.

[2] S. H. Huang, P. Liu, A. Mokasdar, and L. Hou. Additive manufacturing and its societal impact: A literature review. *International Journal of Advanced Manufacturing Technology*, 67(5-8):1191–1203, 2013.

[3] S. W. Williams, F. Martina, a. C. Addison, J. Ding, G. Pardal, and P. Colegrove. Wire + Arc Additive Manufacturing. *Materials Science and Technology*, 32(7):641–647, may 2016.

[4] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A tool-path generation strategy for wire and arc additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 73(1-4):173–183, jul 2014.

[5] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A practical path planning methodology for wire and arc additive manufacturing of thin-walled structures. *Robotics and Computer-Integrated Manufacturing*, 34:8–19, aug 2015.

[6] P. Kulkarni and D. Dutta. Deposition Strategies and Resulting Part Stiffnesses in Fused Deposition Modeling. *Journal of Manufacturing Science and Engineering*, 121(1):93, 1999.

[7] Y. Zhang, Y. Chen, P. Li, and A. T. Male. Weld deposition-based rapid prototyping: a preliminary study. *Journal of Materials Processing Technology*, 135(2-3):347–357, apr 2003.

[8] R. Dwivedi and R. Kovacevic. Automated torch path planning using polygon subdivision for solid freeform fabrication based on welding. *Journal of Manufacturing Systems*, 23(4):278–291, jan 2004.

[9] D. Ding, Z. Pan, D. Cuiuri, H. Li, and N. Larkin. Adaptive path planning for wire-feed additive manufacturing using medial axis transformation. *Journal of Cleaner Production*, 133:942–952, oct 2016.

[10] D. Ding, Z. Pan, D. Cuiuri, H. Li, S. van Duin, and N. Larkin. Bead modelling and implementation of adaptive MAT path in wire and arc additive manufacturing. *Robotics and Computer-Integrated Manufacturing*, 39:32–42, jun 2016.

[11] P. Kazanas, P. Deherkar, P. Almeida, H. Lockett, and S. Williams. Fabrication of geometrical features using wire and arc additive manufacture. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 226(6):1042–1051, jun 2012.

[12] J. Mehnen, J. Ding, H. Lockett, and P. Kazanas. Design study for wire and arc additive manufacture. *International Journal of Product Development*, 19(1/2/3):2, 2014.

[13] G. Venturini, F. Montevecchi, A. Scippa, and G. Campatelli. Optimization of WAAM Deposition Patterns for T-crossing Features. *Procedia CIRP*, 55:95–100, 2016.

[14] D. Yili, Y. Shengfu, S. Yusheng, H. Tianying, and Z. Lichao. Wire and arc additive manufacture of high-building multi-directional pipe joint. *International Journal of Advanced Manufacturing Technology*, pages 1–8, 2018.

[15] B. Wu, D. Ding, Z. Pan, D. Cuiuri, H. Li, J. Han, and Z. Fei. Effects of heat accumulation on the arc characteristics and metal transfer behavior in Wire Arc Additive Manufacturing of Ti6Al4V. *Journal of Materials Processing Technology*, 250(July): 304–312, 2017.

[16] J. Ding, F. Martina, and S. Williams. Production of large metallic components by additive manufacture issues and achievements. In *1st Metallic Materials and Processes: industrial challenges*, 2015.

[17] N. Ganganath, C.-t. Cheng, K.-y. Fok, and C. K. Tse. Trajectory planning for 3D printing: A revisit to traveling salesman problem. In *2016 2nd International Conference on Control, Automation and Robotics (ICCAR)*, volume 2, pages 287–290. IEEE, apr 2016.

[18] C. L. Tsai, S. C. Park, and W. T. Cheng. Welding Distortion of a Thin-Plate Panel Structure. *American Welding Society - Welding Journal*, 78(May):156–165, 1999.

[19] D. Deng and H. Murakawa. FEM prediction of buckling distortion induced by welding in thin plate panel structures. *Computational Materials Science*, 43(4):591–607, oct 2008.

[20] F. Martina, P. A. Colegrove, S. W. Williams, and J. Meyer. Microstructure of Interpass Rolled Wire + Arc Additive Manufacturing Ti-6Al-4V Components. *Metallurgical and Materials Transactions A*, 46(12):6103–6118, oct 2015.

[21] P. A. Colegrove, H. E. Coules, J. Fairman, F. Martina, T. Kashoob, H. Mamash, and L. D. Cozzolino. Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling. *Journal of Materials Processing Technology*, 213(10):1782–1791, oct 2013.

[22] P. A. Colegrove, J. Donoghue, F. Martina, J. Gu, P. Prangnell, and J. Hönnige. Application of bulk deformation methods for microstructural and material property improvement and residual stress and distortion control in additively manufactured components. *Scripta Materialia*, 135:111–118, jul 2017.

[23] J. Donoghue, J. Sidhu, A. Wescott, and P. Prangnell. Integration of Deformation Processing with Additive Manufacture of Ti-6Al-4V Components for Improved β Grain Structure and Texture. In *TMS 2015 144th Annual Meeting & Exhibition*, pages 437–444. Springer International Publishing, 2015.

[24] S. Akula and K. Karunakaran. Hybrid adaptive layer manufacturing: An Intelli-

gent art of direct metal rapid tooling process. *Robotics and Computer-Integrated Manufacturing*, 22(2):113–123, apr 2006.

[25] K. Karunakaran, S. Suryakumar, V. Pushpa, and S. Akula. Low cost integration of additive and subtractive processes for hybrid layered manufacturing. *Robotics and Computer-Integrated Manufacturing*, 26(5):490–499, oct 2010.

[26] H. Lockett, J. Ding, S. Williams, and F. Martina. Design for Wire + Arc Additive Manufacture: design rules and build orientation selection. *Journal of Engineering Design*, 28(7-9):568–598, sep 2017.

[27] D. Ding, Z. Pan, D. Cuiuri, H. Li, N. Larkin, and S. van Duin. Multi-Direction Slicing of STL Models for Robotic Wire-Feed Additive Manufacturing. In *International Solid Freeform Fabrication Symposium 2015*, 2015.

[28] D. Ding, Z. Pan, D. Cuiuri, H. Li, N. Larkin, and S. van Duin. Automatic multi-direction slicing algorithms for wire based additive manufacturing. *Robotics and Computer-Integrated Manufacturing*, 37:139–150, feb 2016.

[29] L. Nguyen, J. Buhl, and M. Bambach. Decomposition Algorithm for Tool Path Planning for Wire-Arc Additive Manufacturing. *Journal of Machine Engineering*, Vol.18(No.1):96–107, 2018.

[30] J.-Y. Hascoët, V. Querard, and M. Rauch. Interests of 5 Axis Toolpaths Generation for Wire Arc Additive Manufacturing of Aluminum Alloys. *Journal of Machine Engineering*, 17(3):51–65, 2017.

[31] K. Ayarkwa, S. Williams, and J. Ding. Investigation of pulse advance cold metal transfer on aluminium wire arc additive manufacturing. *International Journal of Rapid Manufacturing*, 5(1):44, 2015.

[32] F. Martina, J. Mehnen, S. W. Williams, P. Colegrove, and F. Wang. Investigation of

the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V. *Journal of Materials Processing Technology*, 212(6):1377–1386, 2012.

[33] Y. Cao, S. Zhu, X. Liang, and W. Wang. Overlapping model of beads and curve fitting of bead section for rapid manufacturing by robotic MAG welding process. *Robotics and Computer-Integrated Manufacturing*, 27(3):641–645, 2011.

[34] J. Xiong, G. Zhang, H. Gao, and L. Wu. Modeling of bead section profile and overlapping beads with experimental validation for robotic GMAW-based rapid manufacturing. *Robotics and Computer-Integrated Manufacturing*, 29(2):417–423, 2013.

[35] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM). *Robotics and Computer-Integrated Manufacturing*, 31:101–110, feb 2015.

Chapter 6

Paper D

"DeepWAAM: A deep learning approach for Wire + Arc Additive Manufacturing path planning"

Florent Michel[a], Helen Lockett[b], Jialuo Ding[a], Filomeno Martina[a], Stewart Williams[a]

[a] *Welding Engineering and Laser Processing Centre, Cranfield University, Cranfield MK43 0AL, UK*
[b] *Open University, Walton Hall, Kents Hill, Milton Keynes MK7 6AA, UK*

Abstract Wire + Arc Additive Manufacturing (WAAM) has recently proven its ability to become a crucial asset for industrial manufacturing in the field of medium to large metallic deposition, thanks to a high-rate deposition of various metals and a potentially unlimited build volume. Yet, a key element for a large commercial deployment is to offer users an intuitive path planning software, which can determine the optimal deposition strategy, whilst respecting WAAM's build rules. For this reason, in a previous paper, we introduced the Modular Path Planning (MPP) solution for WAAM, which enables users to build a large variety of components (from simple to complex shapes) all with high-quality integrity. The MPP approach differs from existing solutions because it features a unique segmentation step operated manually. This additional step in the path generation allows path designers to divide layers into more controllable deposition sections but requires them to have WAAM expertise. To overcome this drawback, this research demonstrates the feasibility of integrating a deep learning solution called DeepWAAM to perform the segmentation step automatically. Thus, this paper details the pipeline integration of the DeepWAAM solution into a CAD software environment; describes the data generation for training purposes; defines the Neural Network architecture; presents the promising results and finally discusses possible improvements for a potential commercial implementation.

Keywords WAAM; Wire and Arc Additive Manufacturing; Path planning; Toolpath generation; deep learning; machine learning; neural network; AI

6.1 Introduction

In the past few years, Wire + Arc Additive Manufacture (WAAM) has proven its ability to become a crucial asset for industrial manufacturers. Indeed, by combining arc welding tools and standard robotic manipulators, WAAM outperforms other Additive Manufacturing (AM) processes in the field of medium to large metallic part building thanks to its high-rate deposition and its potentially unlimited build volume [1].

As any AM technologies, WAAM required a dedicated path planning solution for it to be adopted by a large commercial community; its role is to define the optimum deposition strategy while respecting WAAM's build rules. Yet, to reach the widest community, such a solution has to keep a relatively simple and intuitive interface. The complexity of developing this kind of software can vary substantially according to the AM technology. For example, the path generation for Selective Laser Sintering (SLS) is pretty straightforward since, like a traditional printer, it consists of scanning the deposition area and turning on the laser where the deposition of parts or support is required [2]. In Fused Deposition Modeling (FDM), path planning can be relatively more complex [3], especially when it combines supports and structural reinforcement. However, FDM is quite robust, and its materials can accommodate deposition inaccuracies, especially at intersections. Instead, WAAM deposition quality is highly sensitive to the path strategy used [4, 5], making WAAM path planning software particularly challenging to design. In fact, many path planning solutions have been proposed from Zhang [6] and Dwivedi [7] in the early

2000s to more recently with the work of Ding [4, 5, 8, 9]. However, all those solutions share the application of only one path planning strategy, regardless of the topological complexity. Thus, this approach is hardly universal, and the building quality can vary substantially according to the geometry shape. To overcome this drawback, in a previous paper (Chap 5), we introduced the Modular Path Planning (MPP) solution for WAAM. In a simplified manner, the MPP solution consists of three steps: first the part is sliced into layers, then each layer is segmented into sections, and finally, a path is generated in each section (Fig. 6.1). The universality of the MPP lies in the segmentation stage and its modular nature. However, the segmentation pattern has to be performed manually by the user, and therefore, an expert user is required to produce high-quality paths for WAAM. Therefore, a solution is needed to reduce, or potentially eliminate, the human factor to promote the broadest commercial implementation of WAAM.

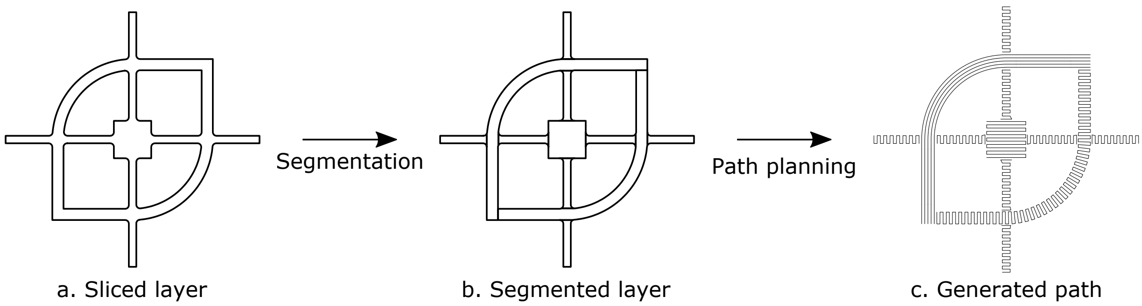


Figure 6.1: Description of the Modular Path Planning (MPP) strategy

Consequently, this paper introduces DeepWAAM: a deep learning solution which aims to generate optimal segmentation patterns for the MPP solution. Thus, in this paper, we describe the process to transform the Computer Aided Design (CAD) input into pictures and back. Then we try multiple Neural Network (NN) architectures, and we analyse the result obtained.

6.2 Methodology

6.2.1 Pipeline

As described previously, the goal of this research is to study the feasibility of using deep-learning tools to solve the segmentation step of the MPP solution in a CAD environment. However, if NNs could potentially process any formats since they are fundamentally computing numbers, studies in Machine Learning (ML) are focusing on standard formats like images. Thus, this section details the five-step pipeline seen in Fig. 6.2, allowing the integration of a standard ML solution into a CAD application.

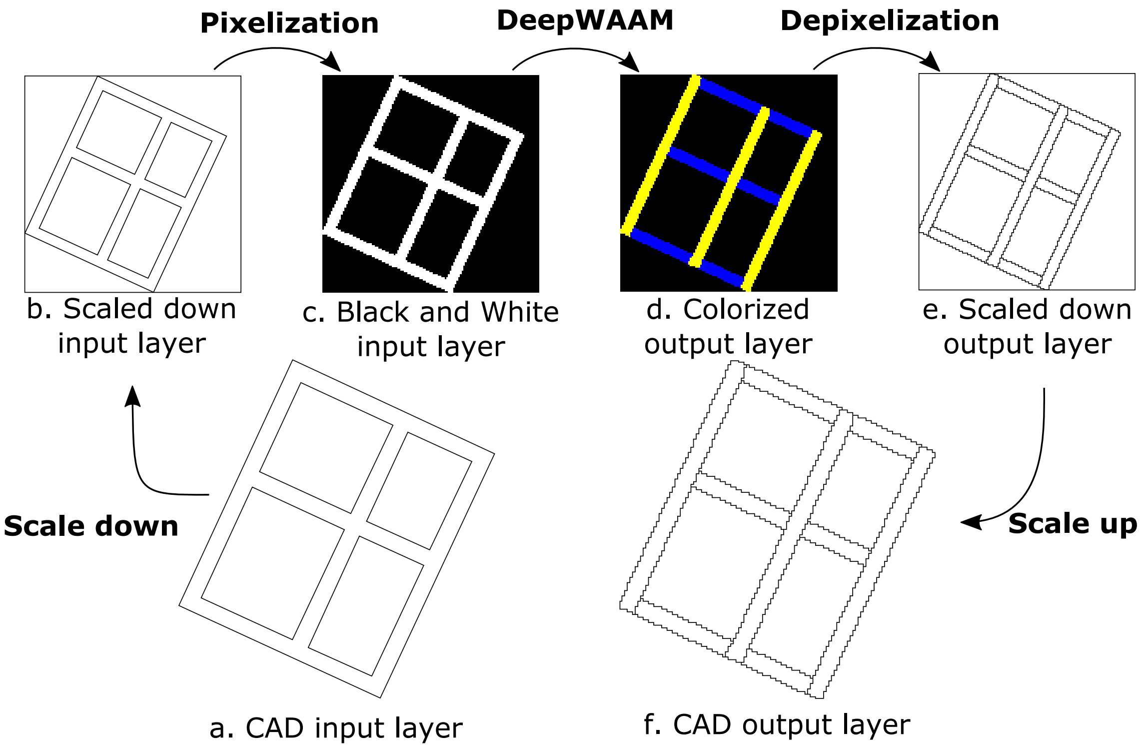


Figure 6.2: Integration of the DeepWAAM solution into a CAD environment

First, the 2D CAD representation of a layer (Fig. 6.2a), obtained after slicing the 3D CAD model, is scaled down to fit a 1 to 1 unit (Fig. 6.2b). This operation is crucial because a NN can only be trained and used on single image size.

The scaled layer is then pixelated to a black and white image (Fig. 6.2c). To do this operation, a grid of evenly distributed points (128 by 128 in our case) is superposed on the geometry. Each of these points is then tested and results as a white pixel if the point is inside the geometry or black if outside.

This black and white image is then fed to the NN, which generates in output the coloured version of this image. In this resulting image (Fig. 6.2d), each group of coloured pixels represents a section that will be then passed to the MPP software to generate individual paths.

Thus, the coloured image is depixalited meaning that the picture is converted back into a CAD layer model. To achieve it, curves are drawn surrounding each group of coloured pixels resulting in a set of closed curves representing the sections (Fig. 6.2e).

Finally, this new CAD layer is scaled up using the same ratio used in the first step (Fig. 6.2f).

It should be noted that the density of pixels used in this pipeline has an important impact on the final accuracy of the segmented layer. Thus, an increase in density will directly improve the resulting quality. However, as detailed in the next section, training a NN can be a slow process requiring lots of computational resources. In fact, in the case of image processing, the resources required for the training are proportional to the number of pixels. Yet, for this research, a single graphics card (GTX 1080) has been used, therefore, limiting our pixels density to 128x128.

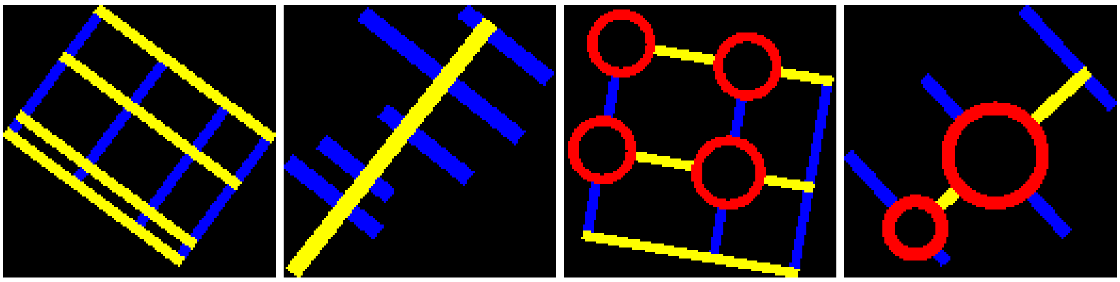
6.2.2 Data

Training

To produce any valid results, a NN has to, first, be trained. For this research, a supervised learning method has been used and can be briefly described as follows [10]: first, an input is applied to the NN, which outputs a response. This response is then compared to the desired output to measure the error. Finally, the network's synaptic weights are adjusted to minimise this error. This method is then repeated until the error becomes small enough for any given input.

The drawback of this learning approach is that it requires many training data to reach an acceptable level of accuracy. In traditional images segmentation, pictures are manually segmented and shared between communities [11] to limit the significant labour required for this operation. This solution is, however, impossible to achieve in our situation since it concerns a tiny niche and yet requires hundreds of thousands of examples at least.

Nevertheless, in this research, the transformation that we are trying to achieve is known as a one-way function [12] in the sense that if the segmentation of the image is hard to compute, its opposite function is very basic. Indeed, this function simply requires converting the coloured image into black and white or more accurately replacing each coloured pixel to white. Moreover, it is possible to randomly create a pre-segmented layer (Canvas) using a set of rules that we called scenario (Fig. 6.3).



(a) Table (b) Fishbone (c) TableCylinder (d) FishboneCylinder

Figure 6.3: Data samples representing each scenario

To illustrate this concept, the fishbone scenario (Fig. 6.3b) can be detailed as follows. In this scenario, a primary wall (yellow) of a random length is first built along the X-axis. Then, a random number of secondary walls (blue) are built along the first wall with for each a random position and length. Eventually, the full layer is randomly rotated. It should be noted that the width of those walls is also randomly defined at the start of the creation but is kept constant all along the creation of a canvas.

Thus, defining multiple sets of rules allows us to generate different topologies. For the purpose of this research, four scenarios have been developed (Fig. 6.3) to reflect the current WAAM production. Nevertheless, to assure a successful segmentation, all scenarios have a common rule, which is that two walls of identical colours cannot be in contact. For this reason, a third colour is introduced to identify cylinders since those features are in contact with both the primary and secondary wall.

Using those scenarios, a dataset of one million images per scenario is created and compacted to a binary file, upstream of the training stage. Thus, during the training, the NN is fed by images extracted from the binary file and the input image (Black and White) is created on the fly as it can be seen on Fig. 6.4.

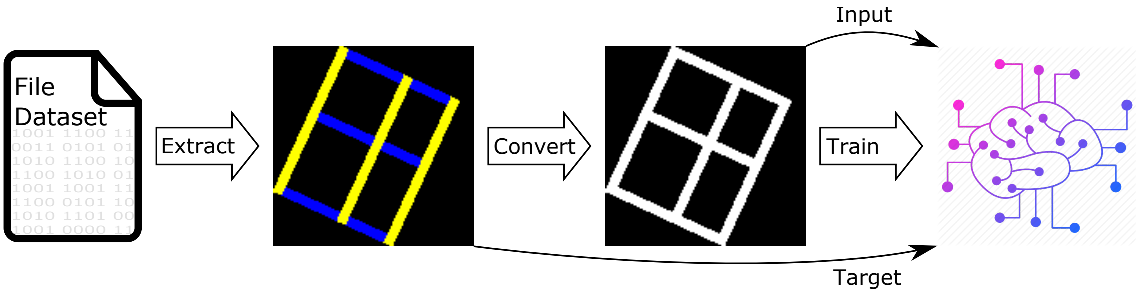


Figure 6.4: Training process

Validation

Additionally, to the training dataset, a validation dataset is required to correctly measure the NN efficiency. Those data are used during the training stage to evaluate periodically the NN performance. This evaluation allows us to follow the evolution of the training and to detect potential overfitting [13]. To properly operate, this dataset has to be composed of data not contained in the training set but representing a sample of this last one. Thus, the validation dataset is built similarly to the training set and is composed of one thousand canvases per scenario.

Testing

On the basis of good practice, a third dataset is built and is composed of data that are neither in the training set neither in the validation set. This test dataset, which has the same size as the validation one, is used solely after the training stage to generate results that will be analysed in Section 6.3.

6.2.3 Architecture

The process of segmenting an image is known, in the field of computer vision, as semantic segmentation [11, 14]. This tool has recently become very popular since it can intuitively extract complex information from pictures. Thus, semantic segmentation is used across a variety of application such as autonomous driving [15], medical imagery analysis [16] or human-computer interaction [17].

Because of this recent popularity, many NN architectures have been developed and compared to each other using common datasets [18]. Three of the most popular NNs (SegNet [19], U-net [20] and FCN [21]) have been implemented in this research to define the most efficient architecture for path planning segmentation. It should be noted, however, that whilst those implementations replicate the overall architecture, they may modify some aspects to fit the experiment requirements.

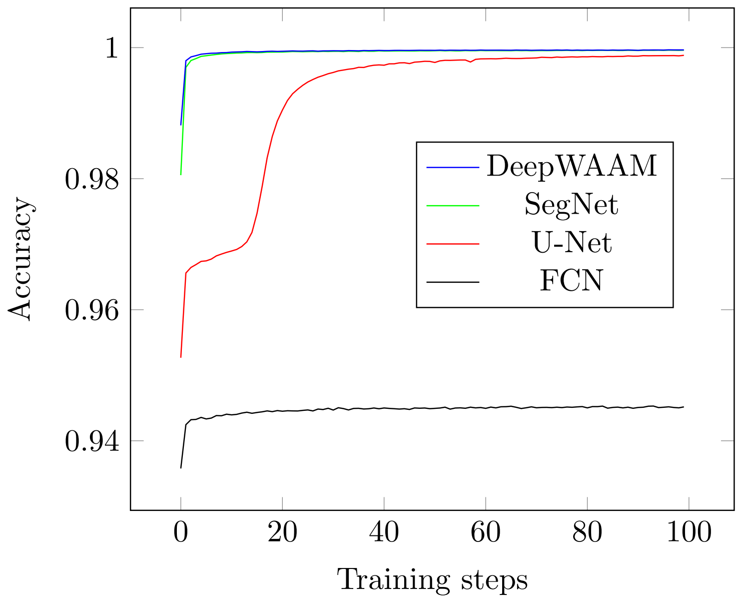


Figure 6.5: Learning evolutions of the four implemented architectures

The learning evolutions of the three implemented architectures are reported on Fig. 6.5. As explained previously, the NN accuracy is evaluated periodically during its training, 100 times in this case, and the accuracy represents the percentage of successfully colourised pixels on an entire validation set. From this graph, it can be seen that SegNet architecture performs better at the end of the training but is also faster to reach high accuracy than the two other solutions. After some fine-tuning, we obtained the DeepWAAM architecture, which slightly outperforms the SegNet solution.

The DeepWAAM architecture presented on Fig. 6.6 is designed as a symmetrical encoder-decoder NN with a constant 200 feature channels across the layers. In the encoder, each step is made of two 3x3 convolutions with batch normalisation and a rectified linear unit activation function, followed by a 2x2 max pooling operation with stride 2 for downsampling. In the decoder, each step contains an upsampling stage which uses the pooling indices from its symmetrical encoder step, followed by the same two convolution layers presented in the encoder. The NN terminates with a 1x1, stride 1 convolution layer with a sigmoid activation layer and four feature channels to adjust the results to the four possibilities: Background, Primary Wall, Secondary Wall and Cylinder.

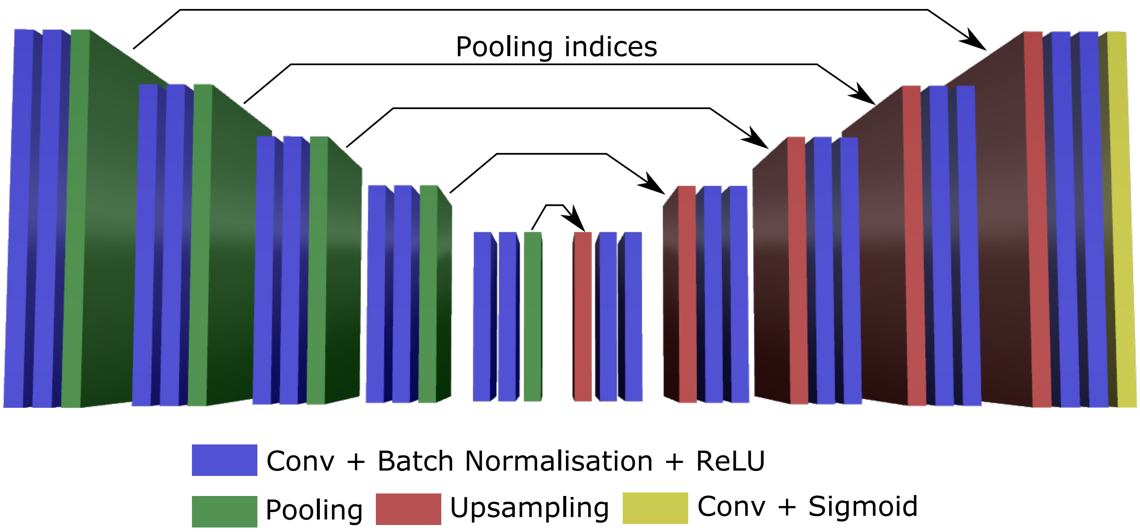


Figure 6.6: DeepWAAM architecture based on SegNet [19]

6.3 Results

In this paper, the Intersection over Union (IoU) metric, also known as the Jaccard similarity coefficient, is used to measure the accuracy of each class over a set of tests pictures. This metric is commonly used in the segmentation field and is defined by the following equation Eq. 6.1, where TP, FP and FN denote, respectively, the number of correctly classified pixels (True Positives), the number of pixels wrongly classified (False Positives) and the number of pixels wrongly not classified (False Negatives). Finally, the resulting IoUs of each class are averaged to calculate the mean Intersection over Union (mIoU) representing the overall performance of the NN on a dataset.

$$TP = \frac{TP}{TP+FP+FN} \tag{6.1}$$

To measure the accuracy of the DeepWAAM solution, the test dataset previously described has been run through the NN. Using the resulting segmented images, the Intersection over Union (IoU) of each class (Background, Primary Wall, Secondary Wall, Cylinder), as well as the mIoU, are calculated and listed in Tab. 6.1 under the name “All scenarios”. Additionally, since the test set is composed of a thousand images of each scenario, an individual measure of those scenarios are also presented to get a better understanding of the NN performances.

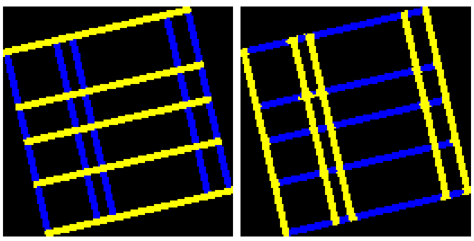
Scenario	Background	Primary wall	Secondary wall	Cylinder	mIoU
Table	99.99	98.93	98.03	–	98.99
Fishbone	99.99	99.13	99.57	–	99.57
TableCyl	99.99	98.98	98.25	99.32	99.14
FishboneCyl	99.99	98.55	99.01	99.41	99.24
All scenarios	99.99	98.93	98.83	99.36	99.28

Table 6.1: Results obtained for all classes and scenarios

Based on those results (Tab. 6.1), we can see that the NN has no difficulty to determine the background location. Those results are not surprising since a black pixel in input should simply output a black pixel, making it a straightforward function that the NN successfully resolved. Cylinders are also achieving high scores, which can probably be explained by their unique topology. Indeed, in the case of primary walls and secondary walls, the NN need to identify a wall, not only by its shape but also by its position relative to other features. Instead, the identification of the cylinder shape only is sufficient to determine its class.

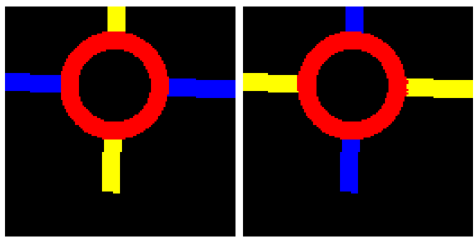
The overall results of each scenario are relatively similar, which is promising for real-world applications since it shows the ability of the NN to determine features out of a single scenario. Admittedly, scenarios containing cylinders have slightly better results, but this is simply because cylinders are, as mentioned previously, easier to identify which boosts the final result.

A good way to better understand the behaviour of the NN is to look at the failed results. Looking, therefore, at two of these failed canvases (Fig. 6.7 and Fig. 6.8), it can be seen that the NN has inverted the primary with the secondary walls and that it happened when the geometry is square. This error is, in fact, logical since during the random generation of the canvas, primary walls are built along the length and secondary walls along the width. Yet, when the length equals the width, the NN cannot distinguish primary and secondary walls, and ends up choosing randomly (or rather on inappreciable parameters) one over the other. In fact, the result given by the NN is not necessarily wrong, indeed, since the part is square, both directions would actually produce a valid path for WAAM. This ambiguity highlights a limitation of the proposed solution, which is not capable of learning the segmentation of square parts. However, an alternative approach to overcome this issue is presented in Section 6.5.



(a) Target (b) Output

Figure 6.7: Failed example: 37.34 mIoU



(a) Target (b) Output

Figure 6.8: Failed example: 49.76 mIoU

On the whole, the DeepWAAM solution reaches 99.11% mIoU on the entire test set. This result exceeds our expectation and actually shows that such a solution could be deployed in a WAAM path planning solution for industrial purposes. Nevertheless, there is no doubt that this result can be ameliorated to maybe reach 100% accuracy, as presented in the discussion (Section 6.5).

6.4 Practical application

To have a better idea of the DeepWAAM capabilities, the NN has been tested on a practical application. The part shown on Fig. 6.9 was chosen as it represents a typical part building application for WAAM. Once sliced into layers, four layer shapes can be distinguished. The DeepWAAM NN is therefore applied to each one of those layers.

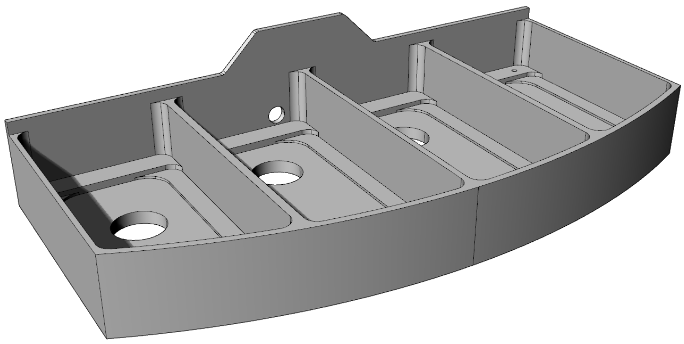
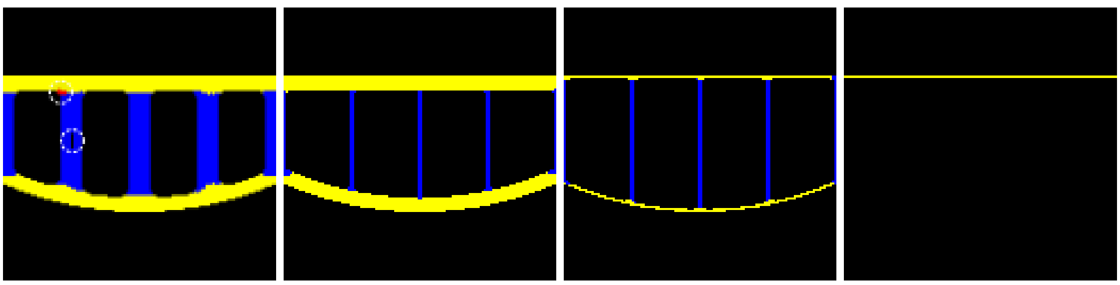


Figure 6.9: Typical part example built with the WAAM technology

As can be seen on Fig. 6.10, the DeepWAAM performed a highly accurate segmentation, very close to what a qualified WAAM user would achieve. It can, however, be highlighted that two localised errors appear on Fig. 6.10a (indicated by the dashed circles). These errors are marginal but could potentially lead to a flawed path in a fully automated path generator. To avoid such a problem, the DeepWAAM solution could be, instead, used as a supporting path planning tool which would suggest a segmentation pattern to the user. This last one could, therefore, decide to reject, modify or accept the segmentation pattern to, then, create the final path.



(a) Layer 1 (b) Layer 2 (c) Layer 3 (d) Layer 4

Figure 6.10: Results of the DeepWAAM application

6.5 Discussion

As a proof of concept, DeepWAAM NN has demonstrated its strong potential for future implementation in industrial purpose, but results have also revealed possible improvements.

The most straightforward improvement would be to use dedicated hardware to train the NN. Indeed, in this research, a single graphics card (GTX 1080) has been used, limiting the number of layers and their depth of the NN. Having access to better equipment would, therefore, increase the performance of the chosen architecture but would also facilitate the implementation of more complex architectures.

Indeed, another way to increase the DeepWAAM accuracy would be to choose a better architecture for it. In this research, three of the most popular architectures have been tested (SegNet [19], U-net [20] and FCN [21]) but those solutions are relatively old in this fast-developing field. Therefore, more recent and more performant solutions such as DeepLabv3 [22] or MSCI [23] would theoretically perform better at segmenting path for WAAM.

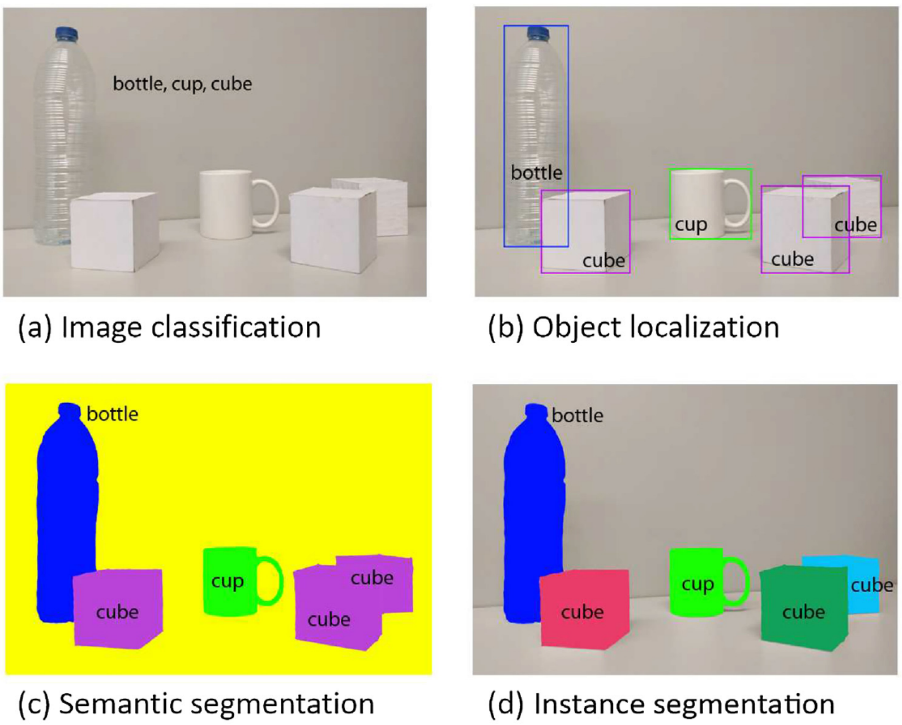
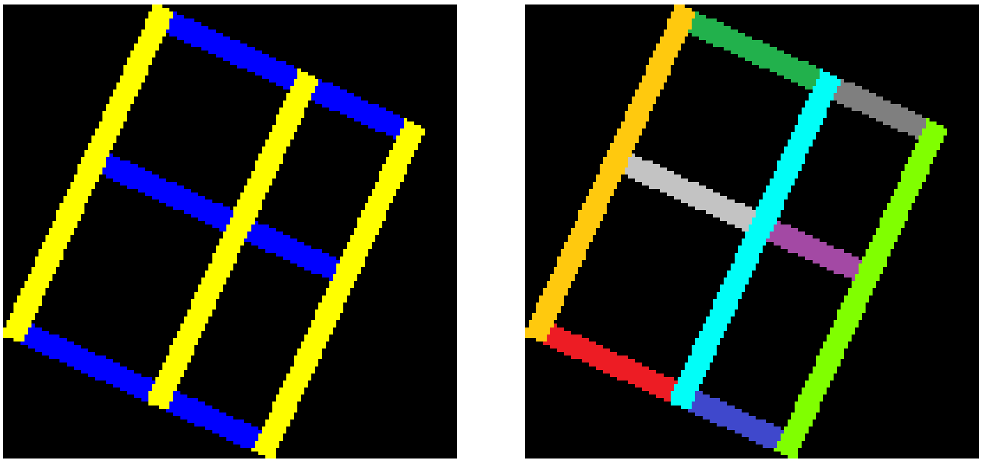


Figure 6.11: Evolution of object recognition [11]

However, Semantic Segmentation can be too limited to resolve all path planning challenges, as in the case of square parts highlighted in the previous section. Nevertheless, a new field called Instance Segmentation has recently emerged [24]. In this field, NNs are not only able to distinguish different classes but also to instance each individual object in a class (Fig. 6.11). In our case, using this new approach would avoid having to distinguish between primary and secondary walls, instead, it would give a new colour for each instance of a wall (Fig. 6.12), which would enable the implementation of more complex scenarios such as three walls joining into a single point.



(a) Semantic segmentation (b) Instance segmentation

Figure 6.12: DeepWAAM: Semantic segmentation vs Instance segmentation

Finally, it seems reasonable to think that those presented architectures could be modified to better fit the specific requirements of path planning segmentation. Indeed, all those NNs are used to segment real-life pictures and to extract complex objects such as bicycle, car, chair, etc. Yet, those objects are made of complex shapes and textures which contrast with the basic geometries and sharp edges contained in path segmentation. It should, therefore, be possible to lighten those large architectures into a more efficient solution for our purpose.

6.6 Conclusion and future work

In this paper, we demonstrated the feasibility of using deep-learning solutions to produce segmentation patterns for WAAM. To achieve the development of DeepWAAM, a pipeline has been designed to integrate an image processing NN into a CAD software environment. Moreover, a training data generator has been developed to produce numerous canvases reflecting the current WAAM production. Finally, multiple NN architectures have been implemented and compared to each other to determinate the optimum solution for path planning segmentation.

The results obtained in this research have shown that this concept could already be potentially used in an industrial environment since the DeepWAAM accuracy is superior to 99%. Yet, many improvements have been discussed confirming that with a deeper study such a solution could be implemented directly into the MPP presented in a previous paper (Chap 5). Thus, in the future, a fully automated path generator for WAAM is conceivable thanks to the integration of deep-learning solutions such as DeepWAAM.

Acknowledgements

The authors would like to express their gratitude to the WAAMMat programme industry partners (www.waammat.com) for supporting this research financially.

References

[1] S. W. Williams, F. Martina, a. C. Addison, J. Ding, G. Pardal, and P. Colegrove. Wire + Arc Additive Manufacturing. *Materials Science and Technology*, 32(7):641–647, may 2016.

[2] Y. Shi, W. Zhang, Y. Cheng, and S. Huang. Compound scan mode developed from subarea and contour scan mode for selective laser sintering. *International Journal of Machine Tools and Manufacture*, 47(6):873–883, 2007.

[3] P. Kulkarni and D. Dutta. Deposition Strategies and Resulting Part Stiffnesses in Fused Deposition Modeling. *Journal of Manufacturing Science and Engineering*, 121(1):93, 1999.

[4] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A tool-path generation strategy for wire and arc additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 73(1-4):173–183, jul 2014.

[5] D. Ding, Z. Pan, D. Cuiuri, and H. Li. A practical path planning methodology for wire and arc additive manufacturing of thin-walled structures. *Robotics and Computer-Integrated Manufacturing*, 34:8–19, aug 2015.

[6] Y. Zhang, Y. Chen, P. Li, and A. T. Male. Weld deposition-based rapid prototyping: a preliminary study. *Journal of Materials Processing Technology*, 135(2-3):347–357, apr 2003.

[7] R. Dwivedi and R. Kovacevic. Automated torch path planning using polygon subdivision for solid freeform fabrication based on welding. *Journal of Manufacturing Systems*, 23(4):278–291, jan 2004.

[8] D. Ding, Z. Pan, D. Cuiuri, H. Li, and N. Larkin. Adaptive path planning for wire-feed additive manufacturing using medial axis transformation. *Journal of Cleaner Production*, 133:942–952, oct 2016.

[9] D. Ding, Z. Pan, D. Cuiuri, H. Li, S. van Duin, and N. Larkin. Bead modelling and implementation of adaptive MAT path in wire and arc additive manufacturing. *Robotics and Computer-Integrated Manufacturing*, 39:32–42, jun 2016.

[10] S. V. Kartalopoulos and I. N. N. Council. *Understanding Neural Networks and Fuzzy Logic: Basic Concepts and Applications*. Wiley, 1996.

[11] A. Garcia-Garcia, S. Orts-Escolano, S. Oprea, V. Villena-Martinez, P. Martinez-Gonzalez, and J. Garcia-Rodriguez. A survey on deep learning techniques for image and video semantic segmentation. *Applied Soft Computing Journal*, 70:41–65, 2018.

[12] H. Delfs and H. Knebl. *Introduction to Cryptography*. Springer-Verlag Berlin Heidelberg, 2007.

[13] I. Goodfellow, Y. Bengio, and A. Courville. *Deep Learning*. MIT Press, 2016.

[14] Y. Guo, Y. Liu, T. Georgiou, and M. S. Lew. A review of semantic segmentation using deep neural networks. *International Journal of Multimedia Information Retrieval*, 7(2):87–93, 2018.

[15] A. Ess, T. Mueller, H. Grabner, and L. van Gool. Segmentation-Based Urban Traffic Scene Understanding. *Procedings of the British Machine Vision Conference 2009*, pages 84.1–84.11, 2009.

[16] D. D. Patil, S. G. Deore, and S. Bhusawal. Medical Image Segmentation: A Review. *Ijcsmc*, 2(1):22–27, 2013.

[17] M. Oberweger, P. Wohlhart, and V. Lepetit. Hands Deep in Deep Learning for Hand Pose Estimation. *CoRR*, abs/1502.0, 2015.

[18] M. Everingham, S. M. Eslami, L. Van Gool, C. K. Williams, J. Winn, and A. Zisserman. The Pascal Visual Object Classes Challenge: A Retrospective. *International Journal of Computer Vision*, 111(1):98–136, 2014.

[19] V. Badrinarayanan, A. Kendall, and R. Cipolla. SegNet: A Deep Convolutional Encoder-Decoder Architecture for Image Segmentation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 39(12):2481–2495, 2017.

[20] O. Ronneberger, P. Fischer, and T. Brox. U-Net: Convolutional Networks for Biomedical Image Segmentation. In *Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015*, pages 234–241. Springer International Publishing, 2015.

[21] J. Long, E. Shelhamer, and T. Darrell. Fully convolutional networks for semantic segmentation. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, 07-12-June:3431–3440, 2015.

[22] L.-C. Chen, G. Papandreou, F. Schroff, and H. Adam. Rethinking Atrous Convolution for Semantic Image Segmentation. *CoRR*, abs/1706.0, 2017.

[23] D. Lin, Y. Ji, D. Lischinski, D. Cohen-or, and H. Huang. Multi-Scale Context Intertwining for Semantic Segmentation. *Eccv*, 2018.

[24] J. Dai, K. He, and J. Sun. Instance-aware Semantic Segmentation via Multi-task Network Cascades. *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, pages 3150–3158, 2016.

Chapter 7

Overall Discussion

7.1 Research overview

The purpose of this thesis was to investigate a new path planning solution for WAAM that can fulfil the industry requirements and assure quality deposition of a large variety of complex geometries. In this purpose, the state-of-the-art of the WAAM path planning field was first identified to highlight the main research gaps and the current techniques used in WAAM to build parts. Thus, path planning strategies have been studied from the origin of the WAAM technology as it quickly appeared to be a challenge for the deployment of this technology since traditional path planning methods from subtractive manufacturing would not be able to manage the specificity of the welding deposition. Not many studies had targeted this challenge. The deepest and the most recent research on the subject has been conducted by Donghong Ding, from the University of Wollongong, who has analysed the WAAM paths requirements and has proposed new alternatives. His most advanced strategy is called adaptive path planning. This method automatically generates a path to fill each layer similarly to the contour deposition but driven by the Medial Axis Transformation (MAT). Although this solution can be considered as the state-of-the-art, it has not been adopted by the global industrial consortium yet. In this literature review, we also showed that, in parallel with Ding's work, many studies had investigated WAAM part building by proposing methods to build targeted geometries or features. This alternative solution, which we defined as the feature-based approach, does not attempt to provide a path strategy that could be used to build any geometrical shapes in contrast with the path strategies research. Nevertheless, those studies provide fundamental knowledge regarding the path generation for WAAM.

In the prospect of investigating path planning solutions for Wire + Arc Additive Manufacture (WAAM), the lack of path generators adapted to this specific technology quickly appeared as a difficulty slowing down the research process substantially. These conditions led us naturally to the development of the Path Generator Framework for WAAM (PGFW) (Chapter 3). Compared to conventional robotic software, this framework is entirely built around the WAAM requirements and can extend the capabilities of any 3D modelling software to visualise and manipulate WAAM paths. It also simulates manipulators behaviour and generates appropriate machine codes for any manipulators and welding equipments. This tool turned out to be crucial throughout this PhD research as it evolved through the research to allow the creation of innovative path planning strategies. Frameworks are, however, complex code libraries, primarily designed for software developers. Although the PGFW offers some accessible functionalities like the PathAPI, such a solution still require extensive software engineering knowledge. Therefore, it is not sufficient as it is to facilitate the deployment of WAAM technology.

Before investigating path planning solutions for complex geometry building, it was necessary to learn the specific requirements of path planning strategies for WAAM. In this purpose, the feature-based approach (Chapter 4) was an adequate solution as it concentrated the fundamental rules inherent to the arc deposition into simple geometry shapes. Thus, this study determined that all deposition sections require at least three sets of parameters to better control the deposition behaviour at the start and the end of each section; that the deposition direction has to alternate for each layer to limit accumulation errors; that the first few layers require individual deposition parameters to adjust the deposition to the heat dissipation variation across layers; and that the layer height needs to be adjustable to also adapt the deposition to the heat dissipation. Then, this tacit knowledge has been explicitly converted into a feature library composed of walls and hollow axisymmetric shapes. Although this study mainly focused on gaining experience into the WAAM requirements, the feature library proved to be an essential software tool as both a research and commercial solution. Indeed, the development of simple features guarantees high-quality deposition for known shapes allowing a fast and straightforward deployment of the WAAM technology. However, the feature-based approach is inherently limited to a narrow range of geometries which restraints its potential commercial impact.

Thanks to the capabilities of the PGFW and the knowledge acquired throughout the development of features, a solution to path planning for WAAM called Modular Path Planning (MPP) has been proposed in the Chapter 5. Traditional path generation strategies for WAAM presented in the literature have in common to fill each deposition layer by using the same path strategy to the layer regardless of the layer shape. This method considerably increases the risk of producing unpredictable deposition behaviour leading to a resulting quality, which can vary substantially according to the geometry. Instead, the MPP introduces a new strategy which consists of dividing the geometry into simpler sections shapes. These individual sections offer a better deposition control that guarantees uniform deposition of layers as experienced with features.

The validation activities demonstrated that the MPP offers higher quality deposition than traditional path planning strategies for WAAM. Indeed, the experiment presented in the Chapter 5 showed that compared to the state-of-the-art, the MPP produces a more uniform deposition in a sense that a constant height along the deposition trajectory can be achieved. Moreover, the proposed solution reduces significantly defects such as voids in the deposition. Although the comparison was made on simple cross-shaped test parts, the MPP has also proved its ability to be applied to more complex geometries while maintaining its deposition quality and fulfil industry requirements (Appendix A).

The MPP performance, however, requires input from a WAAM expert during the path generation process, which increases the processing time. Although this is believed to be highly beneficial in terms of result quality, a faster and fully automated path planning method like the state-of-the-art could be preferred in an industrial context. The MPP strategy would not be able to impose itself as the standard path planning solution for WAAM as long as it does not offer similar speed and autonomy. For this reason, a practical implementation was also presented in the Chapter 5 to limit user interventions and reduce user inputs to basic CAD modelling operations. The realisation of an aircraft pylon part in relation with an industrial partner (Appendix A) has shown that this implementation allows the production of complex parts with only limited users interventions. Nevertheless, the gap between a partially and a fully automated MPP is still to fill.

To overcome this issue, the feasibility of integrating deep learning solutions into the MPP strategy has been studied in Chapter 6. Indeed, in the past few years, deep learning research has revolutionised the entire image processing field, including image segmentation. Since the geometrical division operated in the MPP strategy can be seen as a 2D segmentation process, it was logical to try integrating deep learning efficiency directly into the MPP solution. Thus, in this study, a pipeline was first designed to integrate an image processing Neural Network (NN) into a CAD software environment. Then, a training data generator has been developed to produce numerous canvases reflecting the current WAAM production. Finally, the DeepWAAM NN was developed, trained using the newly generated canvases database, and ultimately, tested. The results obtained have shown that the integration of a deep learning solution into the path generation for WAAM can be achieved. In fact, the developed DeepWAAM NN already performs at a commercial requirement level as it can generate segmentation patterns with an average accuracy superior at 99% on the test dataset built for that purpose. To the best of our knowledge, it is the first time that a deep learning approach has been applied to path planning for WAAM. Although it has proved to be efficient, this study was conducted over a limited variety of geometries and used only low resolution of layer images (128x128 pixels) due to hardware restriction limiting the complexity of parts. This solution should, therefore, be extended to a wider variety of geometries and processed with adapted hardware before being integrated into the MPP strategy.

In summary, this PhD research has successfully achieved its main objective to produce algorithms and structures allowing the future development of commercial software. Indeed, although the PGFW is planned to remain as an open platform for research purpose, a commercial MPP solution is currently under development and should reach the market in the near future. Concerning the feature library and the DeepWAAM tool, both of these tools are currently reserved for experimental use within Cranfield University but have, also, a commercial potential.

7.2 Contribution to knowledge

The development of the PGFW has filled the lack of path generators adapted to the WAAM requirements. This approach is not limited to WAAM and can be generalised to all processes using manipulators, especially in unusual solutions like peening or rolling.

The development of manufacturing features has highlighted the fundamental rules inherent to the arc deposition and has shown that associating a path strategy to a given geometry would guarantee quality and facilitate the deployment of the WAAM technology.

The main contribution of this thesis is undoubtedly the introduction of a new path planning strategy for WAAM. The MPP has demonstrated that it can produce higher deposition quality that the state-of-the-art and that it can be applied to complex geometries while maintaining its deposition quality, within industry requirements.

The DeepWAAM study has demonstrated for the first time that deep learning solutions can be integrated into the path planning process for WAAM. Results have shown that the NN can produce accurate segmentation patterns and could, consequently, replace the user intervention in the MPP strategy. These results are, therefore leading the way to a fully automated path generator for WAAM.

7.3 Impact on future applications

The PGFW has been developed to become the basis for future WAAM path planning development and aims to support all future developments of path strategies for WAAM. Moreover, the PGFW is an open and flexible solution that can be adapted to all processes. These characteristics could, then, lead to the development of an open-source platform to support the research in all areas associated with path planning.

The feature library presented in this thesis has already a local impact as it is used daily at Cranfield University to help researchers building simple geometry and studying deposition characteristics. Nevertheless, features have also the ability to become a standard format that could be shared between CAM software. This format could, as a result, be the base of a new commercial strategy where research centres could embed their WAAM expertise into licensed features and sell them through a dedicated platform.

Since the crucial issue to solve, for a commercial WAAM system, is the generation of optimised paths, the MPP strategy aims to become the ultimate standard solution for WAAM. In fact, a commercial version, essential for industrial deployment, is currently under development.

Finally, DeepWAAM has an obvious potential to be fully integrated into a commercial version of the MPP strategy through the development of an instance segmentation solution as discussed in this dissertation. Though, the deep learning technology has also the potential to impact more deeply the path generation for WAAM. Indeed, in the future, deep learning solutions could be used to predict the best deposition parameters automatically to produce high-quality parts.

Chapter 8

Conclusion and future work

8.1 Conclusion

The aim of this present work that consisted of investigating and developing a new path planning solution adapted to the WAAM's constraints has been addressed successfully. In particular, the research objectives have been achieved:

- The current state-of-the-art of the Wire + Arc Additive Manufacture (WAAM) path planning field was identified, and it was found that there are no existing path planning solutions that automatically generate a deposition path for WAAM that will guarantee a high-quality part.
- A path planning framework structure, compatible with any manipulators, materials and welding technologies, was developed to facilitate new path strategies development of various processes including in priority the WAAM technology.
- A feature library allowing the deposition of basic geometries, such as walls and cylinders, has been developed and is detailed in Chapter 4. This study also showed the significant role of the feature-based approach that allows the fast and straightforward deployment of the WAAM technology either in a commercial or research environment.

- A novel path planning solution for WAAM, which incorporates the modularity of feature-based design into the traditional layer-by-layer strategy, is presented. Thus, the Modular Path Planning (MPP) has demonstrated its ability not only to provide a more uniform layer deposition but also with fewer defects than the state-of-the-art. Moreover, the production of a pylon bracket mount showed that the MPP solution could be applied to complex geometries while maintaining its deposition quality and fulfil industry requirements.

- The development of DeepWAAM has demonstrated that the newly proposed path planning solution can reach a fully automated level by integrating the power of deep learning technology within the path generation process itself. However, further work is required to integrate this into a path planning tool.

- This research work has produced successful algorithms and structures and enables the production of a commercial software solution currently under development.

8.2 Limitations of research

The Path Generator Framework for WAAM (PGFW) aims to become a crucial development tool in the prospect of investigating path planning solutions for WAAM, but frameworks are complex code libraries primarily designed for software developers, which can still be frightening for some users. Moreover, frameworks require continuous updates and evolutions to answer the users' needs over time. Such support requires, therefore, resources allocated to this task either inside a professional institute or as an online community, which are both technically challenging to put in place.

The feature library proved to be an essential software tool as both a research and commercial solution. However, the feature-based approach is inherently limited to a narrow range of geometries since each new feature requires a substantial amount of research and development. This solution will, therefore, be useful until a solution such as the MPP can outperform it on all its features.

The MPP solution proved to offer higher deposition quality than existing planning approaches. This performance is, however, based on the integration of the WAAM expert intervention into the path generation process to define the best segmentation pattern and the adequate deposition parameters, which increases, overall, the production time. If the resulting quality was for us a priority, in an industrial context, a faster and fully automated path planning method could be favoured over the quality. The MPP solution would not be able to impose itself as the standard path planning solution for WAAM as long as it does not offer similar speed and autonomy.

In fact, the developed DeepWAAM aims to fill the MPP limitations and has proved its ability to do so. Nevertheless, many improvements are still possible, mainly through the development of an instance segmentation solution and the use of adapted computing hardware to increase the pixel density of layer images. More importantly, the current DeepWAAM solution is, for now, only able to process four geometric topologies, which limits its deployment substantially. To have a real industrial impact, the DeepWAAM should be continuously trained with all the parts built through the MPP software.

8.3 Future work

Although this thesis has achieved its main objectives, it should also serve as a foundation for further research.

First of all, the PGFW developed in this research has mainly focused on the WAAM deposition process. However, post-deposition-treatments such as rolling or peening are also currently under development to increase some material characteristics. Therefore, these processes could also be implemented into the PGFW to facilitate the elaboration of paths, especially when these processes are mixed within the WAAM deposition. Since WAAM is a near-net-shape deposition process, traditional machining could also be integrated into the PGFW. Thus, a complete system combining deposition, post-treatment and milling would enable the automated production of end-use products. Moreover, adding those alternative processes could potentially have a more significant impact and help the framework to create a community capable of supporting it.

Additional features should be developed to increase the capability of the presented feature library. A more extensive library would, indeed, help researchers to study WAAM deposition on more complex geometries closer to the industry requirements. Future work should also focus on the establishment of a standard feature format that would help the deployment of features through a variety of CAM software and industries.

Regarding the MPP, the next step would undoubtedly be to concentrate on defining the deposition parameters automatically since this study mainly focused on a flexible and intuitive path generation. This new solution will have to combine information from the material characteristics, the welding technology, the geometrical shape and the thermal behaviour to determine the best parameters for each motion contained in the path. Such a solution would be crucial to reach, in the long term, a fully automated WAAM process.

Finally, the DeepWAAM study presented in this dissertation has demonstrated the feasibility of integrating deep learning solution into the MPP strategy. For this reason, most of the work still needs to be done before exploiting the full potential of DeepWAAM program. First and foremost, as discussed in Paper D, an instance segmentation solution should be developed. Another potential study would be to develop the DeepWAAM program so that it could learn directly from users operations and on a large variety of geometric topologies.

Appendix A

The industrial pylon project

A.1 Introduction

The pylon project is a program carried out in collaboration with a European aerospace company, which illustrates perfectly the interest of aerospace industries in the Wire + Arc Additive Manufacture (WAAM) technology. Indeed, in an aircraft, a pylon serves to connect an engine to the wing and is, therefore, a critical structural part of the plane. To support the substantial amount of force required by its function, the pylon elements are usually machined from a large titanium billet. Yet, machining titanium is a really slow and expensive process with a tremendous amount of wasted material. These characteristics justify, as a result, the pressing need for the aerospace industry to adopt new manufacturing technologies such as WAAM.

This project also came as a perfect case study for the development of the Modular Path Planning (MPP) solution. The geometrical complexity of the pylon component exceeds, indeed, the features capabilities, and its size (73 layers) would require a substantial amount of time to design its path manually. Furthermore, this project integrates the use of high-pressure interpass rolling and requires for this reason, the use of a custom-made manipulator called the High Value Engineering (HiVE) Centre (Fig. A.1). The rolling process and the HiVE are therefore controlled and simulated through the Path Generator

Framework for WAAM (PGFW).

This appendix describes briefly the MPPs steps operated throughout the pylon project and presents the results achieved thanks to the MPPs and PGFW.

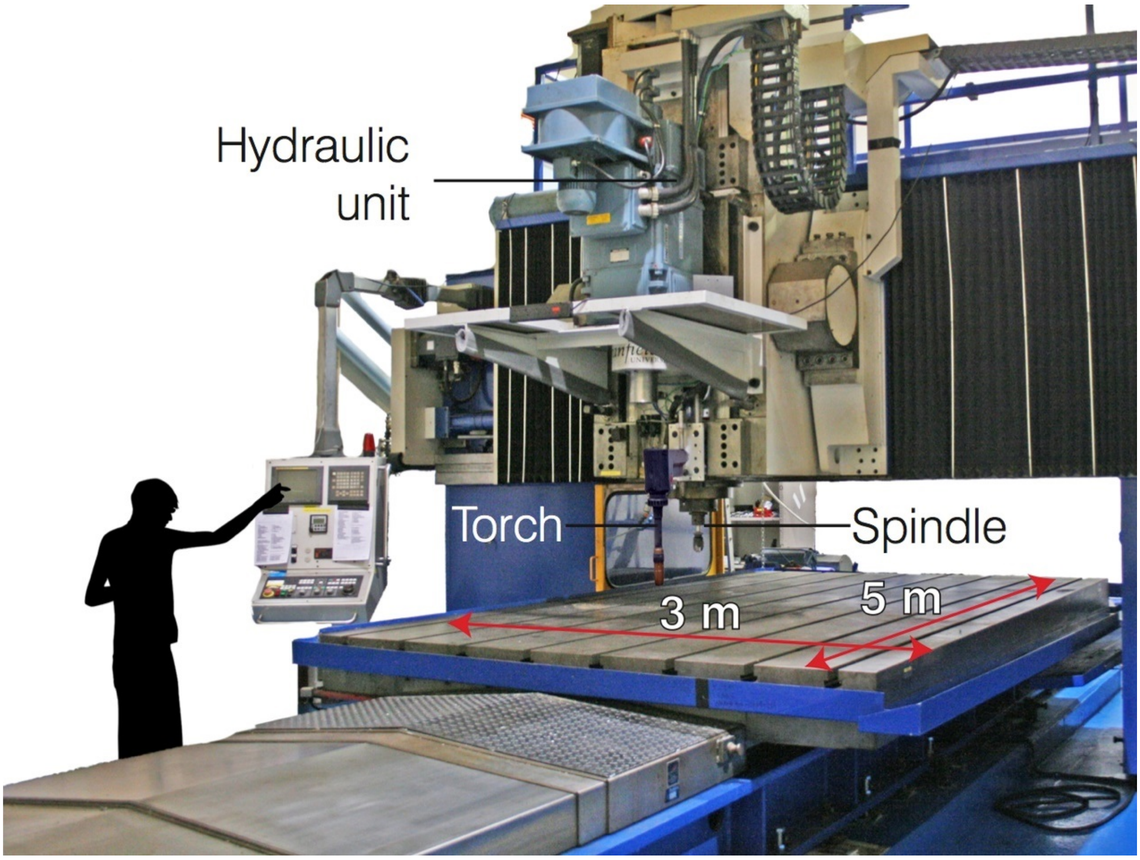


Figure A.1: Gantry based High Value Engineering (HiVE) machine

A.2 Modular Path Planning: An efficient solution

As it can be seen on Fig. A.2, the targeted pylon component is unsymmetrical geometry made of multiple levels and gradually growing walls, making path design particularly challenging. Yet, this project really highlights the full potential of the MPP solution. Indeed, although the input geometry contains many challenging features, the MPP software requests the path designer to intervene only three times, when two consecutive layers are considerably different and that the software failed to generate the path automatically.

Thus, at layer 1, 6 and 20 (Fig. A.3), the user was asked to follow the Building Strategy

Figure A.2: 3D model of the pylon component

(BS) process, which, as a reminder, consists of defining the individual sections using segmentation curves; the deposition directions using guides and finally individual deposition zones using points.

Once the path designer has completed the BS of each required layer, the software generated automatically the full deposition and rolling path of the part (Fig. A.4). In parallel, the MPP program produced a Extensible Markup Language (XML) file containing a tree structure of the deposition parameters so that the user could define the parameters along the deposition.

Before the actual production of the part, the entire deposition has been simulated thanks to the PGFW. This step was crucial to make sure that the HiVE, made of expensive custom parts, didn't encounter any issues such as collisions.

A.3 Results

The building of this part took several days since the rolling operation applied after each section deposition is a relatively slow process. The pylon component has however been successfully built and fulfilled the quality constraints imposed by the industrial partner. Thus, the Fig. A.6 presents the result of the deposition immediately after the deposition, and Fig. A.7 shows the resulting part after heat treatments. After this step, the pylon part will be machined to its final shape similarly to traditional manufacturing process but with a substantial reduction in waste material.

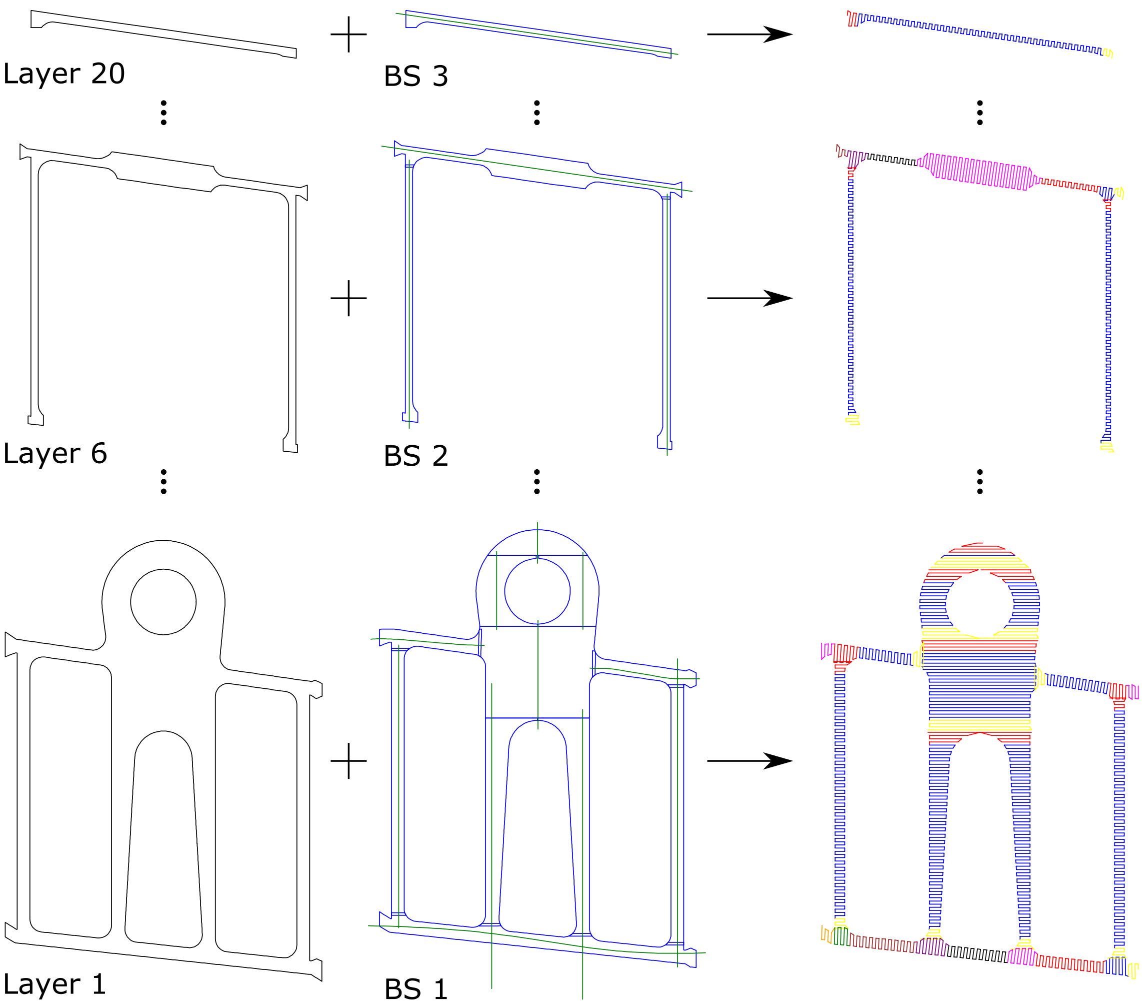


Figure A.3: Building Strategies required to build the pylon

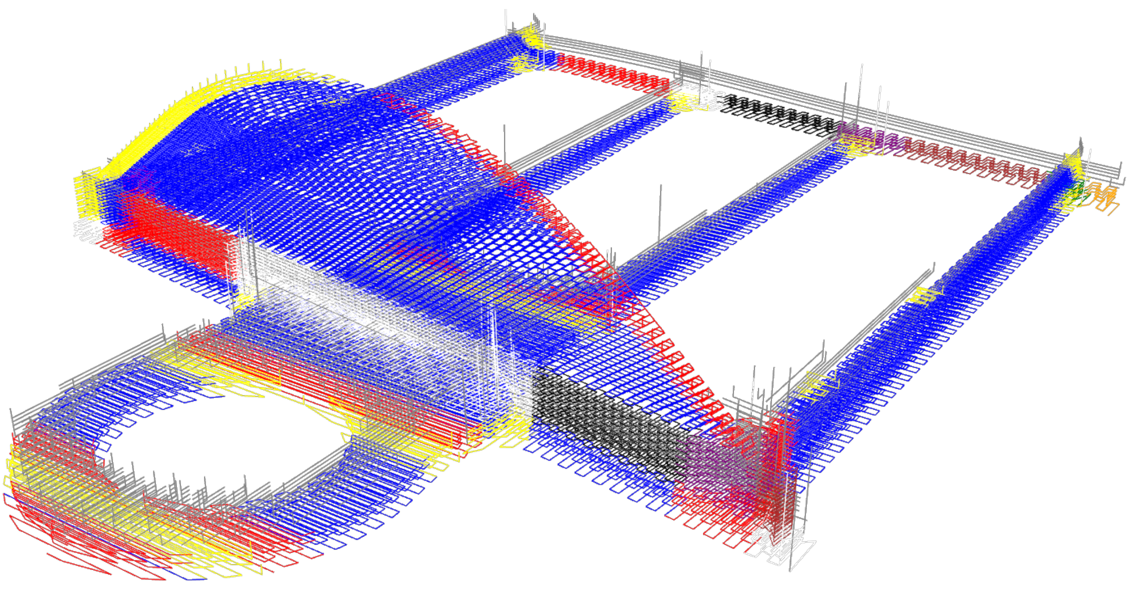


Figure A.4: Deposition and rolling path of the pylon

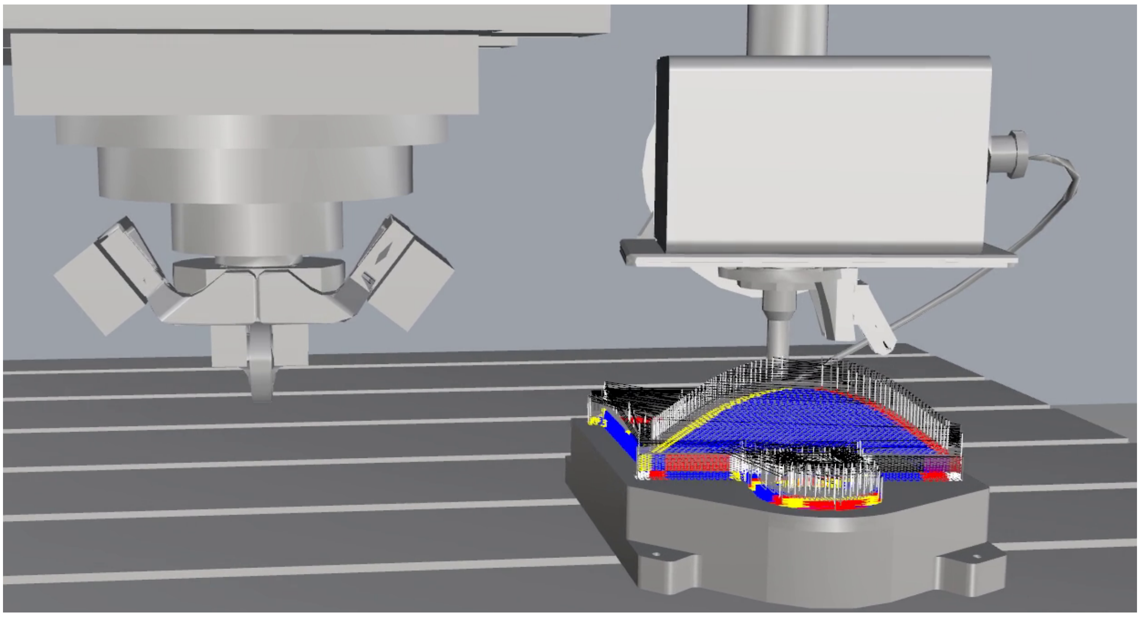


Figure A.5: Snapshot extracted from the deposition simulation

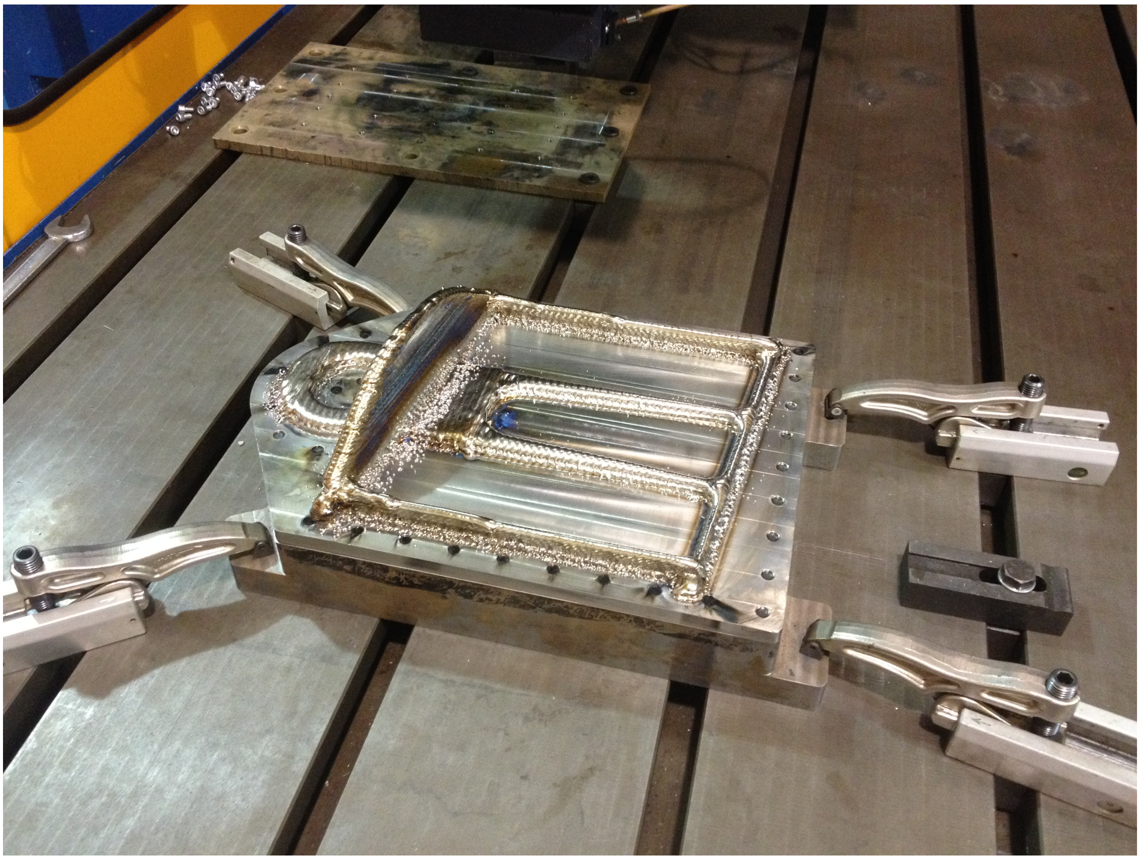


Figure A.6: Resulting pylon immediately after full deposition

Figure A.7: Resulting pylon component after heat treatment