The Strategy for Fabricating Wire-Structured Part Using Wire Arc Additive Manufacturing

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The Strategy for Fabricating Wire-Structured Part
Using Wire Arc Additive Manufacturing

By
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I, Ziping Yu, declare that this thesis, submitted in partial fulfilment of the requirement for the award of the degree of Master of Philosophy, in the Faculty of Engineering and Information Science, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This thesis has not been submitted for qualification at any other academic institution.

Ziping Yu

November 2019
ABSTRACT

Wire Arc Additive Manufacturing (WAAM) is an up-and-coming process for manufacturing complex metallic products due to its high deposition rate and rapid prototyping capabilities. To enhance the ability of the WAAM process to fabricate workpieces with high spatial complexity geometry, this thesis proposes the WAAM strategy that is particularly suitable to produce free-form wire-structured parts.

Contributions in this thesis mainly include a bead modelling study for finding the suitable welding parameter combination and establish optimal welding parameters range, and an innovative deposition strategy, which the main functions include an adaptive slicing methodology and height control system.

In this thesis, the effectiveness and reliability of this approach are demonstrated through the fabrication process of a honeycomb structure workpiece of the 2D plane, a cube structure workpiece in the 3D space, and various simple wire-structure part samples for demonstration. With the current results described in this thesis, the proposed strategy requires less processing time and rarely requires manual intervention to manufacture the wire-structured part, which dramatically reduces the difficulty of processing workpieces with these complex wire-structured geometries, and it will have broader application in the future.
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NOTATION

\(D_i, D_i(x,y), D_i(x,y,z)\)  
Deposition layer with coordinate \(x,y,z\), mm

\(\alpha, \alpha_i\)  
Inclination angle with the substrate or relative objects, °

\(h, h_i\)  
Layer height-increase of strut along the build direction, mm

\(d, d_i\)  
Layer diameter of struts, mm

\(\delta\)  
Offset distance, mm

\(v, \text{WFS, wfs}\)  
Wire feed speed, m/min

\(t, \text{WT, RT, wt, rt}\)  
Welding residence time, s

\(\text{Eo}\)  
Mean-square error

\(G, F_a, \sigma\)  
Welding forces, N

\(E_o\)  
Eotvos number for surface tension

\(\rho\)  
The density of the molten pool

\(\gamma\)  
Surface tension of the molten pool s

\(s_k\)  
Strut

\(W, S, S_*, S^*, S^{*}, N\)  
Set

\(B(t), P_*\)  
Bezier curve

\(\vec{h_i}, \vec{s_i}\)  
Vectorisation parameter \(hi, si\)
CHAPTER 1 INTRODUCTION

1.1 Overview

Additive manufacturing (AM) is an emerging manufacturing process which uses the powder material or wire material to be deposited layer by layer in the form of extrusion, sintering, melting, photocuring, spraying, etc. to fabricate the solid product [1]. This technology can quickly finish the deposition of the approximate shape of the products. Therefore, it is also called rapid prototyping technology [2], and the manufacturing method that can achieve the same function is also called rapid manufacturing [3].

With the deepening of research on additive manufacturing, the process of manufacturing products is gradually realised by the computer control with computer-aided design (CAD) to achieve higher precision simulation and manufacturing process [4]. The additive manufacturing technology, which is directly fabricated the product by using a digital 3D STL model or a CAD model, is also called 3D printing [5]. This processing method can effectively reduce material waste, thereby significantly reducing processing costs and production cycle [6].

Wire arc additive manufacturing (WAAM), as a novel and highly promising additive manufacturing technique, which uses the metal wire as a filler material and the electrical arc as the power source to deposit the sizeable metallic workpiece with medium-to-high geometrical complexity [7]. Although this method required more additional post-processing time to deal with lower resolution and poorer surface finish [8] for various reasons such as deformation or residual stress caused by interlayer overheating or multi-layer overlapping gaps [9], in the field of metallic additive manufacturing, its deposition rate is more efficient than other additive manufacturing, and it can significantly reduce expensive metal raw materials waste [10].
The WAAM process is not sensitive to the size of the workpiece to be fabricated, and the location where the process is performed can also be arbitrarily selected. Moreover, the arc energy source used is inexpensive and readily available so that it has low capital investment [8]. Therefore, the larger the workpiece needs to be processed, the more the advantages of WAAM can be demonstrated.

In the early days of WAAM process, the direction of material deposition was mostly vertical up, which means that the so-called 3D printing still cannot deposit materials in any direction in the space, and the growth direction of the workpiece cannot be changed throughout the whole manufacturing processing. This processing technology is often referred to as 2.5d printing, not an actual 3d printing [11]. However, in the past few decades, the WAAM process has evolved with the development of the industrial robot, whose high degree of freedom (DOF) and repeatability allow the material deposition process to be performed in multiple directions [12]. The high precision of the robot also significantly reduces manual intervention, thus improving the accuracy and stability of the whole manufacturing process [13]. The robotic WAAM can process large-scale frame structures or thin-walled structures with high buy-to-fly ratio [14]. Therefore, this manufacturing technology plays an irreplaceable role in various fields, especially in the aerospace industry [15].

As an extended application, robotic WAAM is also gradually becoming interested in the manufacturing strategies of metallic wire-structures, which are made of multi-struts, has been
widely used in many fields such as artwork, sculpture, architecture and geometric modelling to build everything from elegant decoration to home furniture to large-scale skeletal frame structure [16]. Some projects are already made by the Amsterdam MX3D company, as shown in Figure 1.1 [17], showing the unique artistic value of metal crafts. In everyday life, wire-structures are also gradually prevalent in the geometric design of buildings, as shown in Fig.1.2 [18]. This low-fidelity printing process allows the overall structure lightweight. Thus it is possible to realise the manufacturing of the parts with complex structures that cannot be fabricated by the solid structures, while maintains whole workpiece’s structural and physical stability [19].

![Figure 1.2 Buildings with wire-structures in everyday life](image)

Although the focus on the design of metallic wire-structured parts has increased day by day, and many ideas for processing wire-structure have been raised for a while. There is still a lack of strategies with high manufacturing efficiency for processing this structure through a fully automated robotic WAAM system. Therefore, this thesis makes an essential contribution to the strategy development of fabricating the wire-structured part using the point-to-point robotic wire arc additive manufacturing system. Its function includes bead modelling, height control of the depositing process, and the adaptive slicing and planning for processing sequence for each strut and the torch moving path. The proposed strategy aims to reduce the processing difficulty and improve the manufacturing efficiency of this structure. Its effectiveness is presented by two simple parts fabricated through the proposed methodology.
1.2 Aim and Objectives

The thesis work presented here provides essential investigations and development of the novel fabrication strategy for manufacturing the wire-structured parts using point-to-point robotic wire arc additive manufacturing. The objectives of the thesis mainly include:

- Preliminary study on the manufacture of wire-structure process
  
a) Use cold metal transfer mode (CMT) as the welding method to find process parameters related to strut geometry and an appropriate range of these process parameters.
  
b) Identify the geometric limitations of this approach during deposition processing.

- Establishment of single strut bead modelling
  
a) Select a suitable range of welding parameter combination for depositing strut.
  
b) Record and analyse the geometric data of the struts under different parameters based on the mathematical calculations.
  
c) Build the bead modelling to accurately predict the geometric shape of each strut under any combination of parameters in the given range.

- Programming and control strategy development
  
a) Establish a height control system to ensure wire-structure accuracy.
  
b) Propose an adaptive slicing algorithm to automatically slice each strut in the given workpiece along its growth direction.
  
c) Program an algorithm to control the robot and torch moving path to set up the optimal collision-free processing sequence for each strut.
  
d) Sample workpiece demonstration.

- Further process development and demonstration
a) Establish wire-structure processing strategies for a variety of materials, such as stainless steel, aluminium, nickel aluminium bronze, etc.

b) Enhance processing strategy compatibility and prototype software package for workpieces with solid structure and wire-structure based on either STL file.

c) Develop the potential defect detection function and avoidance algorithm through data analysis and deep machine learning

1.3 Research Scope

➢ Thesis scope

The strategy proposed in this thesis applies to workpieces with only wire-structures. The algorithm proposed in the strategy can manufacture arbitrary wire-structured part from the input CAD/STL to the final product. It can accurately find each welding position of the deposition point within the struts. However, in the current research and development, this strategy does not provide the function of preventing and solving defects in the welding process. The main challenges facing the thesis are also obvious. One is to establish an accurate bead modelling to control the geometry of every single strut. The other is to propose a robust algorithm to ensure that the welding torch has a reasonable processing sequence and does not collide with the built strut when depositing multiple struts.

➢ Deliverables

- Database of corresponding strut geometry value under different process parameters.

- Bead modelling for controlling and predicting the geometry (such as height-increase or average diameter) of each deposit in a single strut.

- Adaptive slicing algorithm to control and adjust the growth direction and position of the welding torch during the depositing process.
• Overall algorithm for the manufacture of the whole wire-structured part with the optimal non-collision processing sequence.

➢ Technical requirements and limitations

Wire-structure has been widely used in polymer 3d printing, especially in the fused deposition modelling (FDM) process using thermoplastic materials [20]. The processing is mostly depositing each strut in a single stroke by directly extruding the filament, which shows a much faster speed than the traditional layer-by-layer deposition [21]. However, when using the WAAM process to deposit metallic wire-structured part, although the strategy used is similar to the FDM, it is difficult to continuously deposit an entire strut because the higher interlayer temperature will cause the strut to collapse after the heat accumulation reaches a certain level. Therefore, the thesis uses point-to-point welding method to perform strut depositing process, as the skeleton arc additive manufacturing (SAAM) [22] or spot-welding WAAM process [23] mentioned in previous papers.

The focus of the manufacturing strategy mentioned in the thesis is to control the overall shaping of the wire-structured part. Therefore, the microstructure and mechanical properties of wire-structured part processed in this strategy have not been much studied. The defect that occurs during a layer of welding process is also considered as a correctable error, which can be fixed by changing the position of the torch and adjusting the process parameters in the next layer of welding. In the initial stage of the experiment, the materials that have better welding properties such as steel are first selected, thus reducing the control difficulty of the material itself to the whole fabrication process.

As mentioned in the thesis before, WAAM can only process approximately shaped workpieces. In order to give it some fault tolerance of the manufacturing process and to reserve materials for post-processing, the near-net shaped workpieces are deposited with a larger geometry size than the actual workpiece size, then through surface finish treatment or post-machining to get the final workpiece with the desired dimensional accuracy as shown in Figure 1.3 [24], [25].
However, for a wire-structured part, the struts within have small geometric dimensions and high spatial complexity, so that it is highly challenging to perform post-processing for this structure. Moreover, in a welding cycle, the start and end of the weld are not very stable. However, the welding time of each layer of the strut is short, so unstable time takes a high proportion of the whole welding period, which can affect the structural accuracy and surface finish of strut more frequently, as shown in Figure 1.4 [22], [23].

This phenomenon is difficult to avoid, even if all process parameters are set correctly. The thesis will use reasonable process parameters to reduce the occurrence of such defects as much as possible, but to solve these problems, further research is still needed, which is not included in the manufacturing strategy proposed by this thesis.
Other technical requirements are mentioned in thesis chapters where cover the experimental setup and methodology. The accuracy and reliability of the resulting manufacturing strategy and proposed algorithm depend on theoretical support and experimental research, which is demonstrated in the chapter on the manufacture of wire-structured parts.

- Research timelines

Research timelines are shown in Appendix A.

### 1.4 Chapter Summary

A brief summary of the contents of each chapter is given below:

Chapter one provides an overview of the metallic additive manufacturing, as well as the wire-structured part. Then the thesis discusses the research problem, aim and objectives, and the research scope.
Chapter two reviews the full contents of metallic additive manufacturing and the wire arc additive manufacturing. Then presents various literature on bead modelling, metal transfer mode, adaptive slicing and collision-free path planning strategies that are beneficial for this thesis experiments.

Chapter three gives all the hardware components and software system used in this experiment and the definition of the wire-structured part as well as the methodology.

Chapter four elaborates on the entire process of the experiment, which achieves that a wire-structured part can be manufactured automatically from the CAD model to finished part.

Chapter five demonstrates the reliability and precision of the proposed manufacturing strategy by fabricating two wire-structured parts.

Chapter six discusses the conclusion and recommendations for future works.
CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

In this chapter, the thesis elaborates in detail on the development of additive manufacturing, and systematically reviews the various existing studies on research and optimisation of wire arc additive manufacturing. The setup and methodology of the experiment mainly refer to the current experience and experimental results, which are commonly used in other papers. The proposed strategy draws on in-depth learning and innovation of previous research and ideas from various kinds of literature, which are summarised in the following sections.

2.2 Reviews of Metallic Additive Manufacturing

Additive manufacturing (also known as 3D printing) is a revolutionary approach to industrial production that can create lighter, sturdy, and more complex parts, which has been widely used in the production of various metallic products (steel, aluminium, titanium alloy, etc.) [26]. Additive manufacturing is often referred to by its more astounding description of 3D printing. However, this technology has existed and been researched for at least 30 years [5]. Over the past decade, metallic AM also has attracted much attention due to its inherent advantages, such as impeccable design freedom, no special fixture tool needs and short lead times [8].

The process of fabricating a product by metallic additive manufacturing typically involves sequentially adding materials layer by layer [27], unlike traditional subtractive manufacturing [28], such as machining, milling, forging, grinding or casting processes, which removes material from the raw solid blocks or pour it into a mold, and then applying external force to be
shaped through a die, press or hammer [29]. One of the main advantages of metallic additive manufacturing technology is that it can help significantly reduce the buy-to-fly (BTF) ratio compared to subtraction manufacturing [25]. The BTF ratio, which reflects the material usage efficiency of the parts being manufactured. It was first introduced in the aerospace industry to determine the amount of material that needs to be purchased, rather than fabricating the final flying product [30]. Briefly, the BTF ratio is the weight ratio between the weight of material used to fabricate the workpiece and the weight of the final workpiece itself [31]. Therefore, metallic AM has the ability to fabricate workpieces with very complex shapes or geometries, which is difficult to be processed with the condition of low-cost and low material waste using the conventional subtraction manufacturing in a short time [32], as an example shown in Figure 2.1 [10].

![Figure 2.1 An example of comparing AM and subtraction manufacturing BTF ratio.](image)

For a multi-thin-walled structure part weighing 250 pounds, 5,000 pounds of raw materials are required for machining it when using the subtraction manufacturing, which wasted 4,850 pounds of materials (97% difficult-to-recycle materials waste). However, when using additive manufacturing to deposit this part, it only needs a 200 pounds substrate, 75 pounds of filler wire. Then, the final part can be obtained after removing 25 pounds of material in the post-processing.
In this example, metallic AM reduces the BTF ratio by 90% compared to subtraction manufacturing, thus demonstrating its unmatched environmentally friendly and cost-effective advantages.

The AM system can be classified based on raw materials feedstock, energy type, manufacturing quantities, etc. [7]. According to the feedstock material types, AM can be divided into three categories, (1) powder-bed, (2) powder-feed, and (3) wire-feed processes [10]. Three different categories are illustrated in Table 2.1, in which various metal AM processes are grouped using different heat sources.

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Process</th>
<th>Feedstock types</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Beam Energy</td>
<td>Selective laser sintering (SLS) [33]</td>
<td>powder-bed</td>
<td>5kW high-power pulsed laser (e.g. carbon dioxide laser)</td>
</tr>
<tr>
<td></td>
<td>Stereolithography (SLA) [34]</td>
<td>powder-bed</td>
<td>Fast printing speed but requires expensive photopolymer</td>
</tr>
<tr>
<td></td>
<td>Laser engineered net shaping (LENS) [35]</td>
<td>powder-feed</td>
<td>high-power laser (400W to 3kW), equivalent to direct metal deposition</td>
</tr>
<tr>
<td></td>
<td>Laser metal deposition (LMD) [36]</td>
<td>powder-feed</td>
<td>one of directed energy deposition (DED), 1-6kW laser power</td>
</tr>
<tr>
<td></td>
<td>Selective laser melting (SLM) [33]</td>
<td>powder-feed</td>
<td>one of direct metal laser melting (DMLM), suitable for small parts</td>
</tr>
<tr>
<td></td>
<td>Direct laser deposition (DLD) [37]</td>
<td>powder-feed</td>
<td>one of directed energy deposition (DED), using 0.5-5kW laser power</td>
</tr>
<tr>
<td></td>
<td>Direct metal laser sintering (DMLS) [38]</td>
<td>powder-bed</td>
<td>does not melt the metal powder, so needs less energy</td>
</tr>
<tr>
<td></td>
<td>Direct metal deposition (DMD) [39]</td>
<td>powder-feed</td>
<td>one of directed energy deposition (DED), free work envelope</td>
</tr>
<tr>
<td>Electron Beam Power</td>
<td>Electron-beam melting (EBM) [40]</td>
<td>powder-bed/feed</td>
<td>takes place under vacuum room, commonly using 30 kW to 42 kW electron beams</td>
</tr>
<tr>
<td></td>
<td>Electron beam selective melting (EBSM) [41]</td>
<td>powder-bed</td>
<td>3kW electron beams power, needs high temperature and vacuum room</td>
</tr>
<tr>
<td></td>
<td>Electron Beam Freeform Fabrication (EBF) [42]</td>
<td>Wire-feed</td>
<td>creates a molten pool on the substrate takes place under vacuum.</td>
</tr>
</tbody>
</table>
Up to now, more than 20 kinds of metallic additive manufacturing technologies have been developed according to their different characteristics and use areas. In recent decades, with the aid of metallic additive manufacturing, communications, imaging, architecture and engineering have all experienced their own revolutions from analog to digital processes [7]. Today, metallic AM can bring digital flexibility and efficiency to manufacturing operations in many different fields [44], as summarised in Figure 2.1 by Yilmaz et al.

![Figure 2.2 Metallic AM applied in different industrial areas](image)

Figure 2.2 Metallic AM applied in different industrial areas [10].

As Frazier [7] mentioned, mechanical properties of metal material parts processed by metallic...
AM are comparable to conventionally fabricated metal parts. Furthermore, the metal parts through the post-processing and finished-machining can also show the same fatigue performance as the forged alloy.

Although the additive manufacturing has great innovations in the processing technology, whether the material technology is standardised and fully characterised or not is still a necessary criterion for whether it can be put into production [45]. Moreover, the verification of this standard usually takes a long time and a high cost [46]. Moreover, when mass production is performed, the recurring costs (such as raw materials) of traditional manufacturing is usually cheaper than AM. Thus, metal additive manufacturing can provide its value only if it can fabricate critical parts in just a few days. Otherwise, it shows less competitive than conventional manufacturing [47]. From the perspective of commercial use, additive manufacturing still needs more development to realise its benefits and expand its applications [7].

2.3 Details of Wire Arc Additive Manufacturing

In recent years, Wire arc additive manufacturing (WAAM), which is known as a novel and highly promising directed energy deposition (DED) additive manufacturing technique, is well developed [8]. Although this method required more additional post-processing time to deal with lower resolution and poorer surface finish [8] for various reasons such as deformation or residual stress caused by interlayer overheating or multi-layer overlapping gaps [9], in the field of metallic additive manufacturing, its deposition rate is more efficient, and it can significantly reduce expensive metal raw materials waste [10].

Wire arc additive manufacturing techniques, as briefly introduced in Table 2.1, use the metal wire as a filler material and the electrical arc as a power source to deposit the large metallic workpiece with medium-to-high geometrical complexity [7]. The schematic diagram of their working principle is shown in Figure 2.3 [9].
Gas tungsten arc welding (GTAW), also known as tungsten inert gas welding (TIG), is a welding method with a non-melting tungsten electrode. It obtains energy from a constant current welding power source, which is generated from the arc conducted by highly ionised gas and metal vapour [48]. This welding method has better weld bead formation and is beneficial to improve welding quality.

However, in GTAW, the wire and heat source are separated, and the position of the torch and wire needs to be adjusted at the same time during the entire welding process. Its operation method is extremely complicated, and most of them require experienced workers to perform [49]. Moreover, since it has a substantial heat input during the welding process, the welding speed is obviously slower than other welding methods [49]. Therefore, in the automation system, it is rarely used as a method of additive manufacturing [30].

Plasma arc welding (PAW), an arc welding process similar to gas tungsten arc welding (GTAW), is a process in which an arc is formed between sintered tungsten and a metal part [50]. It can produce a more focused welding arc, as shown in Figure 2.4, so it is often used in automated system [51] than GTAW. However, excessive heat (more than 28,000 °C) [50] still makes it less possible to be a highly efficient way of additive manufacturing.
Figure 2. 4 Different arc between PAW and GTAW. (left) PAW arc; (right) GTAW arc.

Gas metal arc welding (GMAW), also referred as metal active gas welding (MAG) or metal inert gas welding (MIG), whose arc forms between the metal wire that is the consumable electrode and the metal part. GMAW has a very high deposition rate, usually 2-3 times that of GTAW or PAW [52]. However, the GMAW-based WAAM is a little unstable compared with GTAW and PAW, since the current acts directly on the material wire, it generates more welding fumes and spatters due to the arc wandering [52]. This also led to the inability to process titanium alloys in this process [53].

Figure 2. 5 Multi-directional deposition WAAM process [30]. (a) Steel shelf; (b) Aluminum horizontal beam; (c) Horizontal welding parameter selection range [54].

Although GMAW has some certain drawbacks, it is still the best choice for automated WAAM systems. As GMAW is a welding-based additive manufacturing approach, horizontal structures
within the part can be fabricated without the need for a support structure relying on the surface
tension of the molten metal [54]. Therefore, with the aid of a six-degree-of-freedom industrial
robot, the WAAM can deposit workpieces at any angle within the suitable process parameters,
as shown in Figure 2.5 in the last page.

GMAW can be used in almost every application to process workpieces of every size. It does
not require harsh processing conditions such as vacuum chamber, high-temperature or high-
pressure environments [42]. The welding equipment used is inexpensive, and the assembly,
disassembly and handling of the equipment (such as robot, welder and computer) are simple
and take up less space. These advantages, combined with its high deposition rate, give GMAW
an unparalleled advantage in processing very large workpieces, as shown in Figure 2.6 [30].

Figure 2.6 Large Components made by robotic WAAM system; (a) 24 kg Ti–6Al–4V part. (b)
Wind tunnel testing part; (c) Hollow structure part. [30]

2.4 Review of Bead Modelling

Unlike polymer 3d printing, powder-bed or powder-feed processes, In WAAM, the metal-filled
deposits have a specific geometry during the welding process, which is referred to as a weld
bead [55]. Bead modelling plays a decisive role in both the welding process and the additive
manufacturing process. On the one hand, the forming of the weld bead determines the quality
of the workpiece and the performance of the welded materials. On the other hand, the slicing
thickness, robot path planning and process parameters setup of the manufacturing process all
depend on its geometric size [25].

The key to successfully implementing the WAAM process is to set up an accurate and reliable
bead modelling that can be used to control and predict the geometry formation of weld beads
and the final workpiece.

The current research shown in various literature on bead modelling is mainly based on stringer
bead, which is a single narrow bead with only a dragging motion from a single welding pass
[56]. In that case, these line-shaped weld beads can be continuously deposited on a solid surface
within a reasonable range of heat input. However, in the process of depositing strut, because
each dot-shaped weld bead is attached to the last deposit so that it cannot be successively
deposited due to its small welding surface as shown in Fig.2.7.

![Figure 2.7 Comparison of line-shaped weld bead and dot-shaped weld bead. (a) Line-shaped
bead [25]; (b) A strut deposited by multi-dot-shaped weld beads [23].](image)

The thesis regards the single strut (but not each dot-shaped weld bead) as a linear-liked weld
bead, to find its similarity and relationship with the usual weld bead modelling. The literature
reviewed in this section highlights the methods used in performing bead modelling, rather than
the conclusions and results obtained from them.
2.4.1 Bead empirical modelling

Since there are a lot of manipulated variables in the welding process, as well as many uncontrollable external factors, so it is complicated to create a mathematical model that contains all the process parameters that affect the formation of the weld bead [57]. Therefore, many studies tend to find a relationship between the critical process parameters of the welding and the weld bead geometry to establish the empirical model. As an example shown in Figure 2.8, which is proposed by Suryakumar et al. [58]. The empirical models they have established that contained relationships between wire diameter and speed, torch speed and weld bead cross-sectional profile are certified to have the high accuracy.

\[ y = h \left[ 1 - \left( \frac{16hv_t}{3\pi v_w d_w^2} x \right)^2 \right] \]

Figure 2.8 Weld bead Cross-sectional profile [58]

The setup of the weld bead model is mostly by describing its cross-sectional profile [59]. According to the shape of the profile, it can be fitted with a specific equation, as the symmetric parabola profile proposed by Suryakumar et al. [58], or parabola, sine, Gaussian and logistic functions profiles summarised by Cao et al. [60].

According to Xiong et al. [61] after extensive experimentation and comparison, they found the three most accurate weld bead models for the weld bead cross-sectional profile, as summarised in Table 2.2. The focus in these models is the bead height (h) and bead width (w). a, b, and c in models are constants and need to be calculated by measuring the accurate weld bead profile.
Table 2. 2 Bead models with three different models [61]

<table>
<thead>
<tr>
<th>Models</th>
<th>Model function</th>
<th>Bead width, w</th>
<th>Bead height, h</th>
<th>Bead area, A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabola model</td>
<td>$y = c + ax^2$</td>
<td>$2\sqrt{-\frac{c}{a}}$</td>
<td>$c$</td>
<td>$A_p = \frac{4c}{3}\sqrt{-\frac{c}{a}}$</td>
</tr>
<tr>
<td>Cosine model</td>
<td>$y = \acos(bx)$</td>
<td>$\frac{\pi}{b}$</td>
<td>$a$</td>
<td>$A_c = \frac{2a}{b}$</td>
</tr>
<tr>
<td>Arc model</td>
<td>$y = b + \sqrt{a^2 - x^2}$</td>
<td>$2\sqrt{(a^2 - b^2)}$</td>
<td>$a - b$</td>
<td>$A_a = \arccos\left(-\frac{b}{a}\right) - b\sqrt{a^2 - b^2}$</td>
</tr>
</tbody>
</table>

2.4.2 Bead geometry prediction

As mentioned in many kinds of literature, the geometry of a single weld bead highly depends on the wire feed speed (WFS) and travel speed (TS) [25], [59], [61]. When there are clear input and output, algorithms such as nonlinear regression equations, artificial neural networks (ANN), support vector machines or K-nearest neighbours (KNN) can accurately predict the weld bead geometry [62].

Nonlinear regression equations and artificial neural networks are two of the most typical control and prediction algorithms, which are often used alone or as a combination to predict the shape of the bead under various combinations of process parameters [58]. The nonlinear regression equation is a mathematical calculation method, and its commonly used second-order form can be expressed as

$$Y = \beta_0 + \beta_1 F + \beta_2 V + \beta_{11} F^2 + \beta_{22} V^2 + \beta_{12} F V \quad (2.1)$$

where $Y$ is regression equation model, $F$ is wire feed speed, $V$ is travel speed, $\beta_0, \beta_1, \beta_2, \beta_{11}, \beta_{22}, \beta_{12}$ are linear coefficients whose need to be calculated by multiple iterations through enormous $F$ and $V$ combinations.
When the amount of data is sufficient, and the variation between two adjacent parameters is small, the predicted value of this equation can almost achieve 99.9% accuracy with real data, as confirmed by Xiong et al. [62]. However, when the amount of data is small, the variation between adjacent data is considerable, or the value to be predicted is not within the given process parameter range, the regression equation reflects the extremely poor accuracy.

The artificial neural network is a mathematical/computational model that mimics the structure and function of a biological neural network for estimating or approximating functions [63]. This method only needs to give it a humongous number of associated input and input values, and then the machine can establish a reasonable mapping relationship to build the best prediction model. A schematic diagram of the artificial neural network architecture is shown in Figure 2.9 [24].

![Artificial neural network for weld bead geometry prediction](image)

When the amount of data learned by the machine is large enough, the predictions provided by the ANN within a given range are very accurate (more than 99.99% [62] ). However, in predicting bead geometry outside of the given range, fewer inputs can make the predictions very unreliable. Nevertheless, as the type of input given increases, the prediction accuracy and reliability under any combination of process parameters will also increase significantly.
2.4.3 Bead simulation model

In addition to establish the bead modelling that uses the wire feed speed, travel speed and other variables which can be easily observed, the use of current and voltage signals combined with finite element analysis (FEM) [64] or computational fluid dynamics (CFD) [65] to establish a bead simulation model can more intuitively control and predict the bead geometry.

As shown in Figure 2.10, Cho et al. [65] used the various arc images captured by the high-speed camera and the synchronised welding signals (current and voltage) in the CFD simulation model and analysed the molten pool by means of fluid mechanics.

![Figure 2.10 Weld bead simulation model based on CFD. (a) Cross-section view of temperature profile and the flow pattern; (b) Velocity; (c) Transverse cross-section view; (d) Simulation result with the experimental one.](image)

This method not only detailed elaborates the forming of the weld bead during the deposition
process, but also accurately simulates the geometry of the weld bead. Moreover, this method also dramatically reduces repetitive work in bead modelling, such as depositing a large number of weld beads with different process parameters.

However, as mentioned by Montevecchi et al. [64], the establishment of the model requires the same data as the actual material. If the data used are taken directly from the literature, the final simulation results may have large deviations. Because the establishment of this model is not based on empirical models obtained from a large number of experiments, once the theoretical formula and finite element calculation in the simulation model have problems, the bead modelling results will be completely unusable. Nonetheless, even if the material parameters in the model are correctly set, the external environmental factors can still primarily affect the accuracy of the boundary conditions setup.

So far, for now, the reliability of this approach is much lower than the results obtained by nonlinear regression or ANN analysis. Nevertheless, this approach still has great possibilities to become the mainstream trend in the future, from the initial simulation of the weld bead to the final simulation of the entire workpiece depositing process.

2.5 Cold Metal Transfer Mode

In particular, cold metal transfer (CMT) process that developed by Fronius [66], as a more advanced MIG process, can be virtually spatter-free with the smaller heat input [67]. This method can deliver weld beads with excellent quality and no need to apply for thermal protection so that it can significantly reduce the waiting time between each layer of depositing. Therefore, CMT is widely used in various industrial fields and research area, and until now, it is an irreplaceable cold welding process for high-quality welding and metallic additive manufacturing [66].
2.5.1 Characteristics in cold metal transfer deposition

Cold Metal Transfer (CMT) is a welding method that is usually performed by a welding robot. The CMT machine detects a short circuit that sends a signal to retract the filler wire material to cool down during the weld time and then place each droplet to the plate [68]. A schematic diagram of the Fronius CMT process operation is shown in Figure 2.11 [69].

![Figure 2.11 Fronius CMT process operation](image)

As indicated by Gungor et al. [70], (a) During the arc discharge, the filler metal moves toward the weld pool. (b) When the filler metal is immersed in the weld pool, the arc is extinguished, and the welding current is reduced. (c) The backward movement of the wire helps the droplet to fall off during the short circuit. (d) Eventually, the wire movement is reversed, and the process begins again.

This welding method makes the weld bead stronger and smoother. Because it has a smaller heat input during the welding time, so this approach is more efficient than other GMAW methods in welding thin metals that are easily deformed and burned through by the molten pool [71].

In the CMT process, the wire is fed through a computer-controlled system and then adjusted by a computer. This allows precise welding of materials such as steel and aluminium with virtually
no slag and splashes, resulting in cleaner welding [72].

Wang et al. [73] control the energy input in the process of aluminium by adjusting the characteristic parameters in the CMT, such as the speed of the wire feed motion, the current magnitude, etc., so that the welding properties can be designed and optimized easily, as shown in Figure 2.12 [73].

![Figure 2.12 Different weld appearance under different characteristic parameters](image)

This also means that the CMT process is very controllable, and the adjustments and improvements applied to it allow the CMT process to gain the high freedom to optimise and develop the performance and geometry of the workpiece.

### 2.5.2 Force analysis in cold metal transfer

The various forces in the welding process can have an adverse effect on the geometry formation of the weld pool, especially for thin-walled structures or inclined-angle structures. Excessive welding forces can cause the workpiece to fail to form [74].
For CMT, it can also be known as surface tension transfer (STT), which is developed by Lincoln Electric Company [75]. The term STT is more representative of how it works, which is to detach the droplets by surface tension. Unlike the traditional GMAW metal over-mode, CMT uses a short-circuiting transfer mode where the wire is in contact with the molten pool. Other transfer modes, such as globular, pulsed-spray, etc., are usually tiny molten droplets that are ejected along the arc [76]. The advantage of the short-circuiting transfer mode is that the droplet is attached directly to the plate, so there is no impact from the droplet drop. The simple force model under these two different metal transfer modes is shown in Figure 2.13 [77], [78].

![Figure 2.13 Schematic representation of force model. (left) pulsed-spray [77]; (right) short-circuiting [78].](image)

In the pulsed-spray metal transfer mode, in addition to the inherent surface tension of the molten pool, its gravity $G$, arc force $F_a$, and droplet force $F_d$ all have the bad influence on the formation of the molten pool. In the short-circuit current transfer mode, the Lorentz force generated by the magnetic field and current can bring the pinch effect [78]. The cross-sectional area of the wire is gradually reduced under the increased pinch effect force $P$, and the surface tension between the wire and the droplet will finally become zero so that the droplet is drawn into the molten pool under the influence of the surface tension of it. The surface tension plays a dominant role in this metal transfer mode so that the welding process can be carried out at almost any welding angle as long as the surface tension of the molten pool can be maintained at a certain level [22].
2.5.3 Contact tip to work distance

Contact tip to work distance (CTWD) describes a distance from the contact tip of the torch to the metal substrate [79]. The concept is different from the electrical stickout (ESO or electrode extension, etc.), as shown in Figure 2.14 [80].

![Figure 2.14 Schematic diagram of CTWD.](image)

The GMAW process typically uses a constant voltage source (GMAWCV). For GMAWCV, the voltage is set by the welder via the selected wire feed speed (WFS). The power supply then automatically provides the proper amount of welding current required to maintain a stable arc [80]. The process variables of the GMAW current (I) and the WFS are interrelated, so it is not possible to independently adjust one variable without affecting the other by merely changing the welder settings [81].

A standard method of independently controlling the welding current from the WFS is to adjust the CTWD by applying Ohm's law $V = IR$ to the stickout of the wire [80], as shown in the Figure 2.14. The principle is that the constant voltage source will still maintain a constant arc length so that a CTWD change will increase the ESO, and as the electrode length increases, the resistance will also increase [79]. According to Ohm's law, since the voltage is constant, the current is inversely proportional to the resistance, so an increase in resistance will result in a
decrease in current. This method can also be used as a feedback control to detect the deposition results of the last welding process, thereby adjusting the deposition rate for the next welding process by changing the CTWD to achieve a stable manufacturing process.

2.6 Adaptive Slicing

Slicing is the most fundamental step in layer-by-layer-based polymer 3d printing and metallic additive manufacturing. It is worth noting that the slice algorithm is not included in the wire-structure-based polymer 3d printing. Because this method is not to fill the material layer by layer but to process a whole frame edge at one deposition time [21].

For the wire-structure processed in metallic additive manufacturing, as mentioned in the previous sections, it is impossible to deposit a complete strut continuously. Therefore, in metallic AM, especially in WAAM, manufacturing of any structure can be regarded as layer-by-layer processing. Thus, adaptive slicing algorithms are particularly important in these approaches.

The slicing algorithm is generally performed based on the STL model, which is a standardised file format that divides the imported model into several adjacent triangles and labels the coordinates of each vertex so that the model can be fully parameterised. An example of an STL section and 3D model is shown in Figure 2.15 [82].

![STL Model Example](image)

Figure 2.15 An example of the format and represent model of STL file.
This format container provides support for the most commonly used data structures, which allow specifying the data type of the elements in the container, simplifying many of repetitive and tedious tasks [83]. So, whether it is a model obtained with computer-aided design or obtained with a 3D scanner, it will eventually be converted to an STL file format. Then slicing algorithm slices these STL models into a set of layers.

### 2.6.1 Unidirectional slicing

The unidirectional slice cuts the STL model into several parallel layers with a certain thickness in a particular direction (usually the Z-axis direction), as shown in Figure 2.16 [83]. The accuracy of the slice depends on the thickness of each slice. The thinner the thickness, the higher the accuracy of the slicing model.

![Figure 2.16](image)

**Figure 2.16 (a) Unidirectional slicing of the STL model; (b) Obtained contour profiles**

One of the main challenges in the unidirectional slicing algorithm is how to find the correct layer boundary polygons. This problem arises because there may be multiple independent objects in the slicing process of a layer. If the proposed slicing algorithm cannot distinguish the boundary of each object, then the resulting sliced layer boundary polygons will be problematic. The second problem is how to ensure that the imported STL model does not miss details. For example, if the workpiece has a thin overhanging structure placed between two slice planes, it
will be lost in the final slice model. To solve these problems, Choi et al. [84] proposed a tolerance slicing algorithm, the flow chart of which is shown in Figure 2.17

![Figure 2.17 Flow-chart of the proposed slicing algorithm [84]](image)

In this algorithm, for each layer construction in a slice surface, this approach first scans the STL file to extract one of the facets at every single time and compares the z-coordinates of its three vertices with the z-height of the slice plane. By setting a small boundary tolerance value, the method can find the layer boundary polygons very accurately and has a specific fault tolerance to ignore unnecessary parts [84]. The algorithm proposed by Chio et al. has been proven to perform well when slicing complex models, whether it is a solid workpiece or a wire-structured part. Because this is a fault-tolerant algorithm, so its calculations are also very efficient. As
tested by Ding et al. [83], this slicing algorithm can have a total computing time less than 0.5 seconds when slicing an STL model with nearly 200,000 facets as shown in Figure 2.18 [83].

![Figure 2.18 The computing time of the efficient and fault-tolerant slicing algorithm.](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Facets</th>
<th>Computing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>1076</td>
<td>12 ms</td>
</tr>
<tr>
<td>Case II</td>
<td>1584</td>
<td>34 ms</td>
</tr>
<tr>
<td>Case III</td>
<td>172,122</td>
<td>352 ms</td>
</tr>
</tbody>
</table>

**2.6.2 Multidirectional slicing**

Although the unidirectional slicing algorithm is very efficient, in WAAM, if the workpiece build angle is processed in a constant direction, some structures may be difficult to process while some structures require a large number of support structures underneath, as shown in Figure 2.19 [85].
Figure 2.19 (a) Workpiece with the build direction $\vec{B}$; (b) The support structures (marked with orange) required with the designed build direction; (c) Multi-slicing the workpiece from different build direction $\vec{B}, \vec{B}_2, \vec{B}_3$, and the collision area (shown in red circle) between the torch and the overhanging structure.

The workpiece shown in Figure 2.19 has two overhanging structures, which require a large number of support structures if the manufacturing direction $\vec{B}$ of the workpiece is vertical up, as shown in Figure 2.19 (b). The use of the support structure not only leads to waste of materials and additional post-processing costs and time but also significantly affect the surface finish of the workpiece due to the large contact area between the surface of the support structure and the workpiece. Furthermore, as shown in Figure 2.19 (c), since the angle between the overhanging structure and the primary workpiece is small, the welding gun cannot deposit the overhanging structure by the build direction $\vec{B}$. One solution is to generate different build directions $\vec{B}_2, \vec{B}_3$ along the growth direction of overhanging structures themselves, which can reduce the usage of the support structure or even totally not use the support structure. This is also called as 3D or multi-directional slicing.

2.6.2.1 Silhouette edges projection [86]

The strategy uses the projected contour edges of the build direction of the input STL model to identify the non-constructible surface features of the model. The part is then broken down into subvolumes that can be built, known as $V_{proc-n}$ and not built, known as $V_{unproc-n}$. For subvolumes that cannot be built, Gaussian and Visibility maps are used to determine the new
appropriate build direction. For the new build direction, the unconfigurable subvolume will be further subdivided by repeating the same projection process until the smallest projected area is found, i.e. the support structure below it, as shown in Figure 2.20 [86].

![Figure 2.20 Silhouette edges projection. (a) Input model; (b) Gaussian and Visibility maps algorithm used; (c) Resulting support structures. [86]](image)

This method can effectively reduce the use of the support structure but cannot optimise the user-defined original construction direction. Therefore, if the construction direction of the workpiece is unreasonably adjusted, the algorithm will become very complicated and computationally inefficient.

**2.6.2.2 Transition wall [87]**

The critical steps of the strategy are straightforward and easy to understand, by identifying the difference between the current layer and the previous layer to identify the presence of an overhanging structure. As shown in Figure 2.21 [87], to construct the overhang structure, the welding torch is rotated to a specified angle (in this figure is 90°) to begin depositing a transition layer, i.e., a thin-walled overhanging structure. After the first layers are deposited, the processing of the walls is completed, and the subsequent overhanging structure can be deposited again in the vertical direction.
This method exhibits extremely high applicability when processing thin-walled overhanging structures, so it may have good performance when dealing with wire-structures who also have a small "thickness". However, if the overhanging structure is too complex or has a large thickness, this method shows its big limitations. Besides, in some cases, the deposition of the transition wall is difficult or impossible to achieve due to the collision of the deposition nozzle, such as the portion shown in Figure 2.19 (a) and (c).

### 2.6.2.3 Centroid axis extraction [88]

The first step in the strategy is to extract the model’s centroid axis, as shown in Figure 2.22, which provides a global perspective of its geometry formation, allowing the slicing process to be performed in the optimal order. By analysing the topology information from the centroid axis, the crack surface can be identified, and subsequent decomposition operations performed.

![Figure 2. 22 Schematic diagram of centroid axis extraction [88].](image)
In the centroid axis extraction method, the slicing process can automatically proceed along the growth direction of multiple axes, and it can detect the centroid changes of the pre-cut layer to decompose the components easily, which greatly simplifies the geometric analysis process. However, in some cases, if the geometry of the workpiece along the centroid axis direction is variable, but the center of mass does not change, this makes it difficult to decompose the workpiece and cause some errors in the slicing model.

For strut, the change in centroid is a good indication of the change in its growth direction, so this method is more suitable for slicing the wire-structured part. However, it is worth noticing that for struts with multiple central symmetry features, this method may not indicate whether they have their own centroid axes or share the same centroid axis. Therefore, some strut may be lost in the actual slicing operation.

2.6.2.4 Decomposition–regrouping method [85]

This method differs from the method used to find the optimal volume decomposition strategy, such as silhouette edges projection or centroid axis extraction. This approach introduces model simplification steps prior to CAD decomposition to significantly enhance the proposed multi-directional strategy. Then, a depth tree structure based on topology information is introduced and merged into an ordered group for slicing. The practise has proved that the proposed strategy is simple and effective on various test components. As shown in Figure 2.23 [85].

![Figure 2.23 Decomposition-regrouping method](image)

Figure 2.23 Decomposition-regrouping method. (a) Decomposition process; (b) Sub-volume regrouping process; (c) Final multi-directional slicing model. [85]
The part is broken down first and recombined, and then it will be sliced in multiple directions and filled with holes. However, for the wire-structured part, the struts that make up the whole workpiece are relatively independent, and it is difficult to define which strut is the base region. Therefore, although this method can accurately reorganise strut, with the increase of the number of struts, its tremendous amount of calculation may make this slicing strategy unacceptable.

In summary, the use of a single slicing algorithm mentioned in the literature review is not entirely reliable and effective when slicing wire-structured parts. Therefore, in order to find an adaptive slicing algorithm that is most suitable for a wire-structured part, it is still necessary to absorb the advantages of the various slicing algorithms mentioned in this section and further develop and optimise it.

2.7 Collision-free Path Planning

When processing the wire-structured part, the welding gun is kept stationary during each depositing process. Therefore, the planning of the robot travel path is not developed in this thesis, because collision can be avoided as long as the robot moves away from the workpiece in the opposite direction of the build direction that has been travelled before. The focus of the path planning outlined in the thesis is how the deposition tool avoids collision problems near the built-up part whilst has high processing efficiency.

2.7.1 Construction sequence of spatial structures

3D objects with complex spatial structures are more complex in construction than solid artifacts. This is because solid workpieces are mostly deposited layer-by-layer along the user-defined building direction. Depositing process can continue only if there is a support structure underneath the current processing layer. Otherwise, the current layer will be defined by various algorithms as an overhanging structure [87] or a volume that cannot be processed [86], etc.,
thereby a support structure needs to be added below it to continue processing. However, for the struts used to form the wire-structured part, since it itself plays a supporting role, there is almost no such unbuildable part within the wire-structured part. Therefore, when multiple struts support the same strut, if their processing order is not coordinated, then some strut cannot be deposited, as Hang et al. [16] proposed in Figure 2.24 (a).

![Figure 2.24](image)

**Figure 2.24** (a) Deposition tool collides with struts when it is printing blue strut if red struts are first printed; (b) Wire-structured part deformation.

When fabricating a wire-structured part, various geometric and physical constraints must be considered to ensure that no components are blocked by the existing structure during assembly. Also, the deformation generated during the deposition should be taken into consideration, so as to avoid a significant difference between the processed structure and the actual structure, as shown in Figure 2.24 (b) [16].

### 2.7.2 Path planning algorithm for wire-structured part

The idea of the wire-structured part was first proposed by Mueller et al. [21] in the polymer 3D printing. They use the zigzag path to quickly print the frame shape of a 3D object by scanning the outer contour of a model. This method allows the designer to quickly observe the
approximate shape of the object, and then fill the outer area of the whole object, as shown in Figure 2.25 [21].

Figure 2.25 (a) Frameshape of a 3D object; (b) Print the additional detail in the surface.

Wu et al. [89] used a 5-DOF printer to propose a strategy that can print arbitrary mesh shapes. The proposed algorithm can find a local minimum constraint set on the edge order to ensure that no collisions will occur. Then sort the edges so that the print runs smoothly. For most parts with complex spatial structures, it has excellent performance, as shown in Figure 2.26 [89].

Figure 2.26 Three parts with arbitrary mesh structures printed by a 5DOF printer
There are also many advanced algorithms for planning print paths. The topology optimisation algorithm proposed by Brackett et al. [90] can convert large solid workpieces into mesh workpieces with almost the same mechanical properties, thereby reducing material use and subsequent post-processing. The Alternating Direction Method of Multipliers (ADMM) algorithm proposed by Boyd et al. [91] is one of the most popular algorithms at present. In the algorithm, they discuss in detail the application of various statistical and machine learning problems, including lassos, basic tracking, covariance selection, sparse logistic regression (SLR), support vector machine (SVM), etc.

Although the manufacturing method of the wire-structured structure in metallic additive manufacturing is quite different from the polymer 3D printing, as mentioned before. These path planning methods are well worth learning in terms of optimising the processing sequence and preventing collision problems. The path planning developed in the experiment is based on these proposed collision-free path planning and has been further modified and adjusted to make it suitable for robotic WAAM system.
CHAPTER 3 EXPERIMENTAL SETUP AND METHODOLOGY

3.1 Introduction

This chapter mainly introduces the various hardware and software used in the experiment, as well as the hardware combination and software system built. The definition of the wire-structured part, and the method and theoretical analysis of the application of the part are also explained in this section.

3.2 Hardware Components

All the equipment used in the experiment is from the Material Research Laboratory (MRL) at the University of Wollongong. Some portable measurement and recording tools (e.g. vernier calliper, infrared thermometer, etc.) are also available in the MRL during the experiment.

The hardware equipment in the experiment mainly includes Fronius welder, worktable, ABB robot and various data acquisition tools attached to the welding tool head. Their specific details are explained in the following sections.

3.2.1 Industrial robot

The robot used in the experiment is 6DOF ABB IRB 2600 robot [92], as shown in Figure 3.1. It has a working load of up to 20kg and a working range of up to 1.85m. This robot has the
highest precision and acceleration in its field of welding, ensuring high throughput and low scrap rates for increased productivity. Its detailed technical data is attached to Appendix B.

Figure 3.1 ABB IRB 2600 industrial robot

The end-effector of the IRB 2600 can be highly customised. In addition to being able to load the welding tool, it can be attached to many devices, as shown in Figure 3.2. The introduction to them is also explained in this section.

Figure 3.2 (a) Right view of the robot end-effector, and (b) Left view of the robot end-effector. The equipment attached to the end-effector is: 1. The welding torch, 2. A laser scanner, 3. A high precision camera, 4. The CCD camera, and 5. An infrared temperature sensor
3.2.1.1 3D profile laser scanner

3D profile scanning has the unique advantages of high efficiency and high precision that traditional single point measurement methods cannot achieve. 3D laser scanning technology can provide 3D feature points on the surface of the scanned object, so it can be used to obtain high-precision and high-resolution digital models [24].

The laser scanner used to scan the strut geometry in the experiment is scanCONTROL 2600-100 [93]. Its measurement range on the z-axis is 125 to 390mm, and on the x-axis is 58.5 to 143.5mm, as the schematic diagram shown in Figure 3.3. With its compact and lightweight design and high-profile frequency of up to 4,000 contours per second and high resolutions of over 0.02 mm, this scanner is ideal for measurement tasks in automation and robotics applications.

![Figure 3.3](image.png)

Figure 3.3 (left) Schematic diagram of scanCONTROL 2600-100; (right) X-axis and Z-axis measuring ranges of the scanner.

3.2.1.2 CCD camera

A CCD (Charge Coupled Device) is a semiconductor component that converts an image into an electrical signal composed of small pixels arranged in a checkerboard pattern, an example as shown in Figure 3.4 [94]. In digital camera applications, CCDs act as photoelectric conversion elements instead of film, and images are captured as digital information [94]. The camera's light efficiency is up to 70%, which is better than 2% of traditional film, so CCD has quickly gained
a lot of adoption in the industrial field.

![CCD camera](image)

**Figure 3. 4 CCD camera.**

The CCD camera used in the experiment is MER-502-79U3M [95] with megapixel resolution, high definition, extremely low noise, perfect colour conversion and compact design. With its extremely compact size (29mm x 29mm x 29mm), rugged metal housing and locking screw connector, MERCURY cameras ensure the reliability of cameras deployed in harsh environments such as welding.

### 3.2.1.3 High-speed cameras

The High-Speed video Cameras made by adept turnkey used in the experiment is used to take photos after each layer of processing to record the progress of the experiment.

### 3.2.1.4 Infrared temperature sensor

Initially, the purpose of using an infrared thermometer was to accurately monitor the temperature and residual heat of each layer of the welding process. However, the use of infrared radiation to measure temperature is also necessarily affected by external factors such as object emissivity (EMS), temperature measurement distance, soot and water vapour, and the measurement using infrared radiation is usually not a point, but an area (usually greater than 330m²). Therefore, for the workpiece with a small unit area and a complicated spatial structure, the result of the non-contact temperature measurement method can have a significant deviation.
However, in the experimental design, the interlayer temperature is not considered as a variable, which is mentioned in the next chapter, so an accurate measurement of the temperature is not necessary. Therefore, in addition to the infrared temperature sensor, the temperature measuring device used in the experiment also includes a thermal camera and a hand-held infrared thermometer, as shown in Figure 3.5. One of them can provide a global thermal field image while the other is very portable and easy to use.

![Figure 3.5 (left) Thermal camera; (right) hand-held infrared thermometer](image)

### 3.2.2 Welding equipment

The welding system used in the experiment is the PushPull System developed by Fronius [96]. This robotic welding system has a variety of welding application settings that can be used in almost all industrial areas. The main welding equipment used in the experiment is TransPuls Synergic 5000, which can realise a variety of materials (including but not limited to steel, aluminium, bronze, nickel, titanium alloy, etc.), different metal transfer modes (pulse, CMT, advanced CMT) welding process. In particular, the CMT process used in the experiments was confirmed to achieve a virtually sputter-free welding process with high welding speed and high-quality results. The other hardware used in the PushPull system is shown in Figure 3.6 below.
Figure 3. 6 Equipment in Fronius PushPull System. (a) VR 7000 CMT wire feeder, (b) Synchronised wirefeeders, (c) TransPuls Synergic 5000 CMT welder, (d) cooling equipment, (e) ROBACTA RA 5000 22G CMT torch, (f) RCU 5000 i welder controller, (g) Pro robot interface, and (h) Magnetic crashbox.

This set of welding system provided by Fronius, as the core hardware equipment of this experiment, reflects the robustness and reliability of its design from the beginning of the wire feeding process to the final welding process. The PushPull system is equipped with two (a) synchronised wire feeders to ensure extremely precise wire feeding. This is a prerequisite for achieving high process stability, especially in long wire feed distances and soft fill metals such as aluminium alloys. The highly dynamic (c) RA 5000 22G torch used by it supports all welding processes from standard welders to CMT. It can be used for both hollow arm robots and
conventional robots. The system also provides a variety of (g) external interfaces that can be connected to the robot to customise the connection and mapping of IO ports. The use of the (h) CrashBox minimises the forced shock of the load after the collision and reduces the damage caused by the collision of the torch with other built-up objects, thereby preventing damage to the torch body and the drive unit. Its extremely high reset accuracy allows the torch to recover quickly after it gets out of the collision position. As an automated welding system, a simple schematic diagram of its combination with the robot system is shown in Figure 3.7.

Figure 3.7 Assembly of Fronius CMT system and ABB robot.

3.2.3 Worktable

A 2DOF workpiece positioner is used in this experiment. The table is free to rotate in the XY plane (ranging from -359° to 359°) and can be rolled up to 90° around the base axis (ranging from 0° to 90°). Figure 3.8 shows the welding process at different angles of the worktable. However, since the workbench is not currently connected to the robot, the freedom of the workbench cannot be superimposed with the robot, and the final degree of freedom is still the maximum value that its individual components can provide.
For the experimental content in this thesis, the degree of freedom provided by the robot is sufficient to process a variety of wire-structures. So, the workbench will remain horizontal in the experiment. In the future, when processing a complicated wire-structured part, in order to simplify the walking path of the robot and improve the manufacturing efficiency, the table can be linked with the robot to provide a higher degree of freedom of up to 8.

### 3.2.4 Robotic WAAM system

The experimental set-up is already shown in Figure 3.1. Limited to the layout of the equipment
in the workplace, only the robot, the Fronius welder, and the workpiece positioner are shown in this figure. The schematic diagram of the robotic WAAM system is presented in Figure 3.9. Its black line indicates that the device is controlled by an external device, and the red line indicates that the two devices are internally connected.

### 3.3 Software system

Figure 3.10 shows the design of WAAM system, used for the research and development at the University of Wollongong (UOW) [52]. This Matlab-based manufacturing system has been proven to process thin-walled workpieces with high efficiency and fully automatically [24].

![Figure 3.10 Robotic WAAM software system at the University of Wollongong](image)

A variety of different devices were used in the experiment, and each of which was equipped with its own proprietary software, so operating the software separately would make the experiment process cumbersome. To simplify the operation, LabVIEW was used in the experiment to integrate these functions, as shown in Figure 3.11.
Figure 3.11 LabVIEW user-friendly interface.

It can record the current and voltage during the welding process, and call the various data acquisition devices to scan, measure, and take pictures of the built part according to the user's choice.

The programming of the robot motion, as well as the welding parameters setup and adjustment, are executed using ABB RobotStudio. Because all the IO ports in the Fronius welder can be written into RobotStudio, so once the user selected correct various material properties of the filling metal, the rest of the operations can be handled by RobotStudio.

It is worth mentioning that programming of bead modelling, slicing and path planning are all based on Matlab. Therefore, Matlab will write the Rapid for controlling the robot moving path, and export it in the .txt file, and then the file will be imported into the Rapid Editor of RobotStudio to finish the entire compilation process.

3.4 Wire-Structures Definition

Wire-structures, a kind of frame-shaped workpiece, whose overall structure is composed of various struts. All its structures contain only strut obtained by spot-welding, excluding solid
structures, thin-walled structures, or any structure that needs to be deposited layer-by-layer.

Struts as the only component of the wire-structure, A schematic diagram of its definition is shown in Figure 3.12, which mainly describes its build direction, torch direction and substrate.

![Figure 3.12](image)

**Figure 3.12 The schematic representation of the build direction, torch direction, mutation detected and substrate of the single strut.**

Strut is composed of deposits formed by multiple spot welding. Each layer of the deposit is denoted as $D_i$, where $i$ represents the sequence and number-of-time of spot welding. Its largest projected area shape on the plane is similar to the hemispherical shape, as summarised by Radel et al. [22] and Abe et al. [23]. Therefore, its characteristic parameters can be defined as layer height-increase, called $\Delta h$ or $h$, and layer diameter, called $d$ or $w$ (width).

From the cross-sectional perspective, the strut can still be regarded as the result of a multi short-time layer-by-layer welding process. Therefore, in order to unify the name, when referring to the geometry of the deposit, it represents the layer geometry deposited to the fabricating strut after each time of welding.

The build direction of the struts is the growth direction of the layers composed of struts, as
indicated by the red lines in Figure 3.12. Without particular emphasis, the torch direction as shown by the black line in the figure is parallel to the build direction, and the end of the torch has a constant distance from the deposition point, which equal to CTWD. For a strut that is not perpendicular to the ground, it will have a particular slope, defined as:

$$k_i = \frac{D_{iz} - D_{i-1z}}{D_{ix} - D_{i-1x}}$$

(3.1)

where $k_i$ is the slope between two layers $D_i$ and $D_{i-1}$.

Because torch is parallel to the build direction, when the build direction has a certain slope $k$, the torch direction will also have a certainly inclined angle $\alpha$, as defined as:

$$\alpha = \cos^{-1} \frac{h_i}{\delta} = \tan^{-1} \frac{D_{iz} - D_{i-1z}}{D_{ix} - D_{i-1x}}$$

(3.2)

where $h_i$ is layer height-increase, $\delta$ is the offset between the $D_i$ and $D_{i-1}$.

The function of the mutation point is to distinguish whether the strut’s build direction has changed so that the torch direction can be adjusted in time, that is, the values of $k_{i+1}$ and $k_i$ can be recorded and compared in real-time. For a strut whose build direction changes from time to time, if its path can be fitted to an arc, the coordinates of its deposition point can also be represented by the equation with center angle $\theta$, as shown by the green dotted line in the Figure 3.12. The idea proposed here will be used to build an adaptive slicing process, which will be explained in detail in later chapters.

In the manufacture of a strut, especially in the bead modelling, the geometric formation of the deposits is unstable during the welding process of the layers adjacent to the substrate. This is because the heat generated during the welding process can be quickly transmitted through the substrate, thereby greatly reducing the amount of heat that is transmitted through the air. This results in a faster cooling rate for the strut in the first few layers of welding, so the material properties and geometric parameters will be different from those in the subsequent welding process. In order to ensure the reliability of the experiment, especially the accuracy established
by the bead modelling, when manufacturing the strut, a strut-shaped substrate is deposited first, so that the thermal conductivity of the next layers of the strut can be the same.

### 3.5 Methodology

The research methodology of the experiment is to develop the manufacturing strategy from single bead models to final production. The entire manufacturing strategy process is shown in Figure 3.13.

![Figure 3.13 Experimental methodology](image)

A wire-structured part CAD/STL models are firstly sliced into a set of 2D layers. Then the path planning algorithm generates deposition paths for each of the sliced layers. For bead modelling,
on the one hand, controls the thickness of the sliced layers and path planning variables. On the other hand, it determines the optimum weld settings corresponding to the desired bead geometry. Then the deposition path, together with the selected welding process parameters, is transferred into an integrated robot code file through the code generation function. Then the final wire-structured part can be obtained. In this experiment, the multi-bead modelling, height control, adaptive slicing and collision-free path planning are the main focus of research.

The first step in the bead modelling experiment was to establish the relationship between the geometry of a single straight strut and various welding process parameters, such as current, voltage, heat input, wire feed speed, travel speed, waiting time, welding time etc. According to the results of Abe et al. [23], among the more commonly used welding process parameters, the welding time, wire feed speed, have the most significant relationship with the single strut formation, and heat input (i.e. welding current plus voltage) determines the range in which the sturts can be deposited appropriately.

In bead modelling, the overall formation of the strut and the geometric formation (height-increase and width) of each layer of the deposit are measured. The measurement of layer geometry determines the average diameter $d$ of the strut fabricated and the average height-increase $h$ that it can be obtained from each deposited layer under the given combination of process parameters. The measurement of the overall formation of the strut is to exclude some measurement results with large variance, as shown in Figure 3.14.
As shown in the middle strut of Figure 3.14, this is an ideal strut model. The geometry of each layer is almost the same, data from each layer can be used in the data processing so that its measured bead modelling is the most accurate. In the strut shown on the right side of the figure, some of the layer geometries are quite different from other layers, which has a high possibility happened in the actual depositing process, although it is not as exaggerated as the model shown in the figure. In this case, all data will be processed by residual analysis to exclude values with significant variances, and then the appropriate data will be used to establish the bead modelling.

The experiment is to consider adjusting the layer geometry in real-time during the welding process by controlling the current and voltage. However, in order to reduce the heat input and obtain a better geometric shape, the CMT process was used in the experiment. As mentioned in the previous chapter, CMT's characteristic parameters waveforms, and metal transfer behaviour during the welding process are complex. Although its amplitude and duration of arc ignition, arc boost, combustion start and end, current start and end can be adjusted. Nevertheless, these stages are usually completed within 0.02s. Currently, this data can be recorded, but there are still some difficulties in adjusting them in real-time. Furthermore, considering that there are too
many variables to be tested, it is now impossible to build a database with such a large amount of data. Therefore, these current and voltage data are recorded in the experiment instead of actively changing it. By observing the difference between the actual data and the analytical data with the corresponding layer geometry, hysteresis control is established to adjust the process parameters of the next layer to make up for the defect of the last layer.

The adaptive slicing algorithm and collision-free path planning will be based on the method of centroid axis extraction proposed by Ruan et al. [88], to avoid the occurrence of collision by determining the position of each strut and its characteristics with adjacent struts. It is worth noting that because the CTWD of the torch is adjustable, moving the torch away from the workpiece is also one of the crucial solutions to avoid collision problems.
CHAPTER 4 EXPERIMENT PROCESS AND DISCUSSIONS

4.1 Introduction

In this chapter, thesis mainly proposes to bead modelling to measure the approximate range of process parameters for manufacturing processable strut, and the layer geometry at various angles in the optimal range.

Then based on bead modelling, an adaptive slicing algorithm is established. Its function includes that detects the actual height-increase of a strut in the fabrication process by monitoring the change of current and voltage, which can be called the height control system.

The collision-free path planning is presented at the end of this chapter, which discusses in detail how to process multiple struts with reasonable deposition sequences and how to process the intersections and separation points of multiple struts.

4.2 Welding Materials and Shielding Gas Selection

The substrate used in the experiment is low carbon steel. The feedstock wire employed in the experiment is ER70S-6 carbon mild steel solid wire with a diameter of 0.9mm. Some of its chemical composition and properties are listed in Table 4.1. Specshield 15% CO2, Ar is chosen as the welding shielding gas for this experiment with a gas flux of 18 L/min., where the mixed gas composition is CO2 15 % and Ar 85 %.
### Table 4.1

**Chemical composition of as received ER70S-6 mild steel wire (wt.%)**

<table>
<thead>
<tr>
<th>Composition</th>
<th>C</th>
<th>Cu</th>
<th>Mn</th>
<th>P</th>
<th>Si</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER70S-6 Wire</td>
<td>0.08</td>
<td>0.18</td>
<td>1.53</td>
<td>0.009</td>
<td>0.88</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### Some properties of steel ER70S-6 in Ar 85%, CO2 15%

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($\rho$)</td>
<td>6500 kg/m³</td>
</tr>
<tr>
<td>Surface tension ($\gamma$)</td>
<td>1.3 N/m</td>
</tr>
<tr>
<td>Melt temperature</td>
<td>1700K</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>85-90,000 psi</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>70-75,000 psi</td>
</tr>
</tbody>
</table>

#### 4.3 Bead Modelling

According to the previous literature, the most influential process parameters for weld bead formation are wire feed speed (WFS, m/min) and travel speed, here in strut layer geometry modelling, travel speed is replaced by welding residence time (WT or RT, sec). Although current and voltage are also the more critical parameters in the process parameters, their changes are related to the setting of the wire feed speed. The current in the welding is kept constant under the control of the CMT machine, so the welding voltage is difficult to change with only one parameter changed. According to the selected WFS, the corresponding current and voltage required, and the heat input per second (power) are shown in Table 4.1.
Table 4. 2 Wire feed speed and the heat input per second that it brings

<table>
<thead>
<tr>
<th>Wire feed speed (WFS, m/min)</th>
<th>Welding current (A)</th>
<th>Welding voltage (V)</th>
<th>Heat input (power, J/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>12.1</td>
<td>423.5</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>13.2</td>
<td>792</td>
</tr>
<tr>
<td>3</td>
<td>77</td>
<td>13.6</td>
<td>1047.2</td>
</tr>
<tr>
<td>4</td>
<td>92</td>
<td>13.7</td>
<td>1260.4</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>13.8</td>
<td>1380</td>
</tr>
<tr>
<td>6</td>
<td>113</td>
<td>15.1</td>
<td>1706.3</td>
</tr>
<tr>
<td>7</td>
<td>123</td>
<td>15.1</td>
<td>1857.3</td>
</tr>
<tr>
<td>8</td>
<td>132</td>
<td>15.5</td>
<td>2046</td>
</tr>
<tr>
<td>9</td>
<td>152</td>
<td>15.7</td>
<td>2386.4</td>
</tr>
<tr>
<td>10</td>
<td>165</td>
<td>16.8</td>
<td>2772</td>
</tr>
<tr>
<td>11</td>
<td>175</td>
<td>17.4</td>
<td>3045</td>
</tr>
<tr>
<td>12</td>
<td>182</td>
<td>17.7</td>
<td>3221.4</td>
</tr>
<tr>
<td>13</td>
<td>201</td>
<td>18.1</td>
<td>3629.1</td>
</tr>
</tbody>
</table>

Other process parameters, such as contact tip to workpiece distance (CTWD, mm), interlayer temperature (T, ℃), etc., are considered constant values and are not changed in bead modelling. The change in CTWD will make the layer geometry in the depositing process unstable, which will be mentioned in the next section, so in the bead modelling, it will always maintain 10mm. For the interlayer temperature, the next layer of welding will not begin until it is lowered to near room temperature. Although there are no convincing experiments to verify the adverse effects of higher interlayer temperatures on the layer geometry, the experience obtained now is that if the interlayer temperature is too high, defects will occur more frequently during the deposition process as shown in Figure 1.4. Welding wait time (wt, sec), the duration of which is equal to the time from the end of the weld to the cooling of the interlayer temperature to room temperature, generally this time is less than 1 minute.
### 4.3.1 Acceptable WFS and RT range selection

The wire feed speed used in the experiment ranged from 1 m/min to 13 m/min with a variation of 1 m/min. The welding time ranges from 1 second to 7 seconds, with a variation of 0.5 seconds. There is a total of 169 combinations of WFS and WT available. According to their characteristics, their boundary conditions can be divided into four categories, namely: Low-Low boundary whose heat input is around 1000, its wire feed speed (about 2 m/min) and welding residence time (about 1 s) are relatively low; Low-High boundary whose heat input is around 5000, its wire feed speed is low (2 m/min), whilst welding residence time is long (>5s); High-High boundary whose heat input is over 18000, its wire feed speed (>9 m/min) and welding residence time (> 5s) are relatively high; High-Low boundary whose heat input is around 5500, its wire feed speed is fast (>10 m/min), but the welding residence time is short (< 2s). The selected range of the WFS and RT is shown in Figure 4.1

![Figure 4.1 Selected range of the WFS and RT and their heat input.](image)

Some figures are presented here to discuss in detail the strut shape formation on the four boundaries. According to the results of the deposition, the struts manufacturing on the High-
High boundary cannot be formed at all. Excessive heat input and excessive material accumulation make it impossible for the deposit to adhere to the previous layer. Therefore, some or all of its deposits will fall off the built object (even cannot be called as strut), as shown in Figure 4.2.

For struts that can be formed at the High-High boundary, as shown in Figure 4.3, their geometry is still unacceptable. It has a significant variance in the height and diameter of each layer geometry, and the deposit can be clearly seen to have a tendency to fall off the strut. Therefore, it is impossible to perform the bead modelling under the combination of process parameters with high values of both WFS and WT.

Figure 4.2 Deposition results near the High-High boundary.

Figure 4.3 Poor formation of the struts near the High-High boundary.
According to the results of the Low-High boundary, as shown in Figure 4.4, it can be observed that the formation of the strut is very poor, so the struts at this boundary cannot be used. The reason why the layer geometry is poorly formed is that the CMT has a small heat input, its arc extinction time in each arcing period can reach 0 heat input. Therefore, a smaller heat input, i.e. a smaller WFS, will result in insufficient penetration of each layer of welding.

![Figure 4.4 Deposition results near the Low-High boundary.](image)

The molten droplets during the welding process gradually merge into the molten pool under the influence of surface tension. However, because under this boundary condition, the heat input is insufficient to maintain a stable molten pool shape, and the cooling rate during the welding process may be higher than the molten pool formed by the molten strut part. Therefore, the molten pool may randomly change positions so that the layer geometry cannot be stably formed. The effect of heat input on strut geometry can be clearly seen in Figure 4.4, as the wire feed speed increases from 1 m/min to 3 m/min, the forming of the strut is also getting better.

The results of the deposition process at the Low-Low boundary are shown in Figure 4.5, and it can be seen that the formation of these struts is acceptable. Although the Low-Low boundary also has a lower wire feed speed, the deposition process can be completed before the melt pool cooling begins because of its short welding residence time. However, the problem with struts at this boundary is that they are relatively small in diameter, especially the strut made using a combination of process parameters of WFS=1 m/min and WT= 2s, which has a diameter of about 2 mm and only about two times the diameter of the feedstock wire. This type of strut is
challenging to find its use, except for its poor surface finish, the actual diameter that can be used may be less than 1mm. As the WFS increases, the formation of struts gradually becomes stable. As the strut shown at the rightmost in Figure 4.5, it has the very definite and entirely acceptable layer geometric shape.

![Figure 4. 5 Deposition results near the Low-Low boundary.](image)

According to the results of the Low-High boundary, as shown in Figure 4.6, it can be observed that the formation of the strut is acceptable. This means that the welding process can have high instantaneous power, i.e. a high wire feed speed, as long as the welding duration is short. However, in this case, some layers in the strut will collapse downward randomly. In the measurement, its average height-increase has significant variance, so it is impossible to establish a very accurate bead modelling to predict the height-increase of the layer geometry.

![Figure 4. 6 Deposition results near the High-Low boundary.](image)

According to the above measurement results of strut geometry formation in and around various boundaries, the final WFS and WT selection range are shown in Figure 4.7. In this figure, the acceptance and characteristics of the struts forming near the four boundaries are given, and
according to the layer geometry forming result under various process parameter combinations, the optimal combination of parameters to be used in the bead modelling is also shown in Figure 4.7

![Figure 4.7 WFS and WT range selection](image)

### 4.3.2 Layer geometry test and measurement

In the experiment, 25 groups of layer geometry tests were carried out, in which the wire feed speed \( (v; \text{ m/min}) \) ranged from 4 m/min to 8 m/min, and the amplitude change was 1 m/min (5 in total), and welding residence time \( (t; \text{ s}) \) ranged from 1s to 3s, and the amplitude change was 0.5s (5 in total). A 10-layer substrate will be fabricated under the process parameters combination of \( v=9\text{ m/min} \) and \( t=3\text{s} \) before the strut begins to deposit so that each layer of the strut has approximately the same thermal conductivity. Each strut will be deposited 20 layers without counting substrate and obtain the average values of the reliable parameters of each layer. Two same struts will be fabricated for each parameter combination so that more available parameters can be collected.

Some of the strut shapes under these 25 different parameters are shown in Figure 4.8, which
includes the average height growth \((h)\) and average diameter \((d)\) of each layer corresponding to the combination of WFS and WT parameters. It is worth noting that because of various external factors in the welding process, such as the airflow of the shielding gas or the bending of the feedstock wire itself, the strut cannot be wholly grown vertically. The solution has been mentioned in chapter 3.5. Nevertheless, this will make each strut have a different weighted average when calculating the height-increase and the diameter so that the accuracy of the geometry value of the strut with fewer data available will be slightly reduced.

Figure 4.8 The appearance of strut structures

Figure 4.9 illustrates the effect of wire feed speed \((v)\) and welding residence time \((t)\) on the diameter \((d)\) and height-increase \((h)\) of layer geometry. In the two graphs on the left side of the
figure, the change in wire feed speed is fixed to show the effect of weld residence time on the
diameter and height-increase of each layer. Similarly, in the two graphs on the right side of the
figure, the change in welding residence time is fixed to show the effect of wire feed speed on
the diameter and height-increase of each layer.

According to the fitting results, the effect of wire feed speed and welding residence time on
layer diameter and height-increase is nearly linear. The measured errors of the diameter of each
layer are small, but the measured error of the height-increase of each layer increases as the wire
feed speed and the welding residence time becomes larger.

This is because at the end of the welding, due to the solidification of the liquid and the reduced
surface tension, some small pits may appear randomly on the hemispherical surface of the

**Figure 4.9** The effect of process parameters on the layer geometry
deposit. As the volume of the deposit increases, the size of these pits also increases. The method for calculating the height-increase of each layer in the experiment is to collect all height values near the centre of the strut by a laser scanner. Therefore, once a small pit appears near the centre of the strut, this will bring some error to the actual height-increase of each layer. This error is difficult to rule out unless each layer is manually identified, but doing so may cause other errors due to human intervention.

Based on the measured values and the fitted image, a second-degree nonlinear regression equation was established to illustrate the height-increase \( h \) and diameter \( d \) of the layer, relative to the wire feed speed \( v \) and weld residence time \( t \), defined as:

\[
V = C_{00} + C_{10}v + C_{01}t + C_{20}v^2 + C_{11}vt + C_{02}t^2
\]  

(4.1)

where,

if \( h = V \),
\[
C_{00} = 0.5362, \quad C_{10} = 0.5408, \quad C_{01} = 0.001857, \quad C_{20} = -0.056, \quad C_{11} = -0.0056, \quad C_{02} = 0.004429.
\]

if \( d = V \),
\[
C_{00} = 4.566, \quad C_{10} = 0.4939, \quad C_{01} = -0.4138, \quad C_{20} = -0.05429, \quad C_{11} = 0.1766, \quad C_{02} = 0.04771.
\]

The relative errors \( E_d \) and \( E_h \) of the layer diameter and layer height-increase are defined as the percentage deviation between the regression equation predicted value and the measured geometry, as calculated by:

\[
E_d = \frac{|d_p - d_m|}{d_m} \times 100\%
\]  

(4.2)

\[
E_h = \frac{|h_p - h_m|}{h_m} \times 100\%
\]  

(4.3)

where \( d_p \) and \( h_p \) are the predicted values, and \( d_m \) and \( h_m \) are the measured geometry, also called \( d \) and \( h \). The measured results predicted results, and errors with the corresponding wire feed speed \( v \) and welding residence time \( t \) are shown in Table 4.3.
The error scatters plot shown on the left side of Figure 4.10 uses the heat input to represent the combination of various wire feed speeds and welding residence times, demonstrating the error value of predicted layer height-increase and layer diameter relative to the actual measured value. As can be seen from the figure, for the predicted layer diameter, the error is basically within 2%. For the predicted layer height-increase, the error is mostly less than 2.5%, and only a few of the predicted values have an error of more than 3%, and the overall error is less than 4%.
Figure 4.10 (left) The relative errors of layer height-increase and layer diameter; (right) The normalized comparison between predicted and measured.

The right side of Figure 4.10 uses a more intuitive approach, known as normalised analysis, to compare the difference between the actual measured value and the predicted value, rather than through error analysis. Firstly, all raw data will be normalised to $X_i$, calculated as:

$$X_i = \frac{2}{R_{\text{max}} - R_{\text{min}}} (R_i - R_{\text{min}}) - 1$$  \hspace{1cm} (4.4)

where $R_{\text{max}}$ and $R_{\text{min}}$ are the maximum and minimum data of the actual measured data, and $R_i$ is the value of height-increase or diameter from the raw data. This method scales all the data to the range of (-1,1), the characteristics of the data can be consistently weighted so that the difference between the input and the output value can be more intuitively compared.

In the normalised graph, the abscissa axis represents the normalised measured value of layer height-increase and diameter, and the ordinate axis represents the normalised predicted value of layer height-increase and diameter with the corresponding actual values. A solid line ($y = x$) indicates that the measured value is equal to the predicted value. It can be seen that most of the data points are located on or near the line, indicating that the bead modelling based on the nonlinear regression equation proposed in the experiment can predict the height-increase and diameter of each layer of strut within the given range with high reliable accuracy.
The surface pattern of the layer geometry used as a function of wire feed speed and welding residence time is shown in Figure 4.11. This model can give accurate layer geometry for any process parameter combinations of wire feed speed and welding residence time within the given range, where WFS from 4m/min to 8 m/min, and WT form 1s to 3s.

![Figure 4.11 Layer geometry of (a) diameter, and (b) Height-increase.](image)

### 4.3.3 Multi-directional bead modelling

In addition to the bead modelling in the vertical direction, the experiment also wants to know how the layer geometry changes when the strut has a certain inclined angle. In this case, the force applied on the deposit during the welding process and the path of the metal transfer may be complicated, so it is necessary to establish a force model to analyse it.

A force model for strut with the inclined angle is shown in Figure 4.2. This model assumes that during the process, no pending molten pool overflow, which means that the growth direction of the molten pool will always follow the build direction of the strut without being affected by gravity. To ensure this condition, the combination of process parameters that require for welding does not have a higher heat input and a more abundant material deposition volume. Another assumption is that for a strut with an arbitrary inclined direction, the layer height-increase is in the same direction as its build direction, and the layer diameter is perpendicular to its build direction. Therefore, the model gives the view that as long as the deposit can be stably deposited during the welding process, the strut can have the same layer geometry as the strut with the
same welding process parameters combination in the vertical direction, no matter how large the inclination angle it has.

Figure 4. Schematic representation of the force model for the inclined strut.

It is worth noting in the model that during the depositing process of the L2 and L3 layers, because the build direction has changed, but the height-increase and diameter of each layer have not changed. Therefore, there will be areas where the material is excessively depositing, and the material is missing. However, it can be seen in the model that the missing area of the material and the overlapping area of the material have the same volume, so here the model also assumes that the material of the overlapping area will shift to the area of the missing material when the first layer with an inclination angle is deposited.

The forces in the welding process proposed in the model are gravity $G$, arc force $F_a$, and surface tension $\sigma$. Since in the CMT process the feedstock wire is in contact with the workpiece, the droplets are attached to the molten pool by their surface tension, so that there is no impact force of the droplet falling into the weld pool comparison with other welding processes. Other external forces, such as the force generated by the shielding gas flow, which have less influence on the deposit, are not considered here.

When fabricating a strut with an inclined angle, the arc force and gravity can cause the molten
pool to collapse. Especially for gravity, it can be clearly inferred that the larger the inclination angle of the struts, the larger the volume of the molten pool, and the more severe the influence on the layer geometry. The force that can be used to counteract these two forces during welding is only surface tension, which is provided by the molten pool surface. Therefore, the analysis of the surface tension is vital to ensure that it can maintain the position and geometry of the deposit. For a fluid droplet, it can use Eotvos number $E_o$ to indicate the importance of gravity compared to surface tension, which is express as:

$$E_o = \frac{\Delta \rho g L^2}{4 \gamma}$$

where $\Delta \rho$ represents the difference in density between the two phases, that is, the difference in density between the molten pool and the air, where the density of air is negligible, as shown in Table 4.1, $\Delta \rho$ equals to 6500 kg/m³. $g$ is gravitational acceleration (m/s²). $L$ is the characteristic length, which is expressed here as the layer diameter $d$. $\gamma$ is the surface tension, which can be obtained from table 4.1 as 1.3 N/m.

Eotvos number is a dimensionless number used to measure the importance of gravity compared to surface tension. Higher values indicate that the system is relatively unaffected by surface tension effects. Lower values (usually less than 1) indicate surface tension dominates. Therefore, when the diameter of the strut is less than 9 mm, it can be satisfied that the deposit can be attached to the strut regardless of its build direction relative to gravity. This finding is in good agreement with the data collected during the strut bead modelling, in which most of the samples collected were below this limit diameter.

Another thing that needs to be discussed is that when the torch is manufacturing a strut with an inclined angle, its torch direction transitions parallel to the strut direction or remains in the vertical direction. The two are given in Figure 4.13, where (a) shows that the torch direction is the same as the build direction, and the torch direction in (b) maintains the vertical direction. The angles of the struts in the (a) from left to right with respect to the ground are 60°, 50° and 40°. The inclination angle of the strut in (b) is respectively 70°, 60°, 50°, 40°, 30° and 20° from
the upper left to the lower right. All struts are fabricated with the process parameter of WFS=4m/min and WT=2s.

Figure 4.13 Torch direction vs build direction. (a) Torch direction is parallel with the strut build direction, (b) torch direction always maintain a vertical downward direction, as a schematic diagram shown in (c).

When the torch direction is inconsistent with the build direction o, only one strut with a 70° tilt angle can be fabricated in Figure 4.13 (b), which results in a significantly reduced range of available process parameters for multi-directional deposition. Furthermore, a larger inclined angle will result in a larger offset $\delta$. When the offset $\delta$ exceeds the radius of the strut, the torch in the vertical direction may not even contact the strut, as shown in Figure 4.13 (c).

In summary, Figure 4.14 shows a part of the multi-direction bead modelling with the same torch direction as the strut build direction. Among them, five sets of parameter combinations are selected as examples, respectively (a) WFS=4m/min, WT=2s; (b) WFS=5m/min, WT=2s; (c) WFS=6m/min, WT=2s; (d) WFS=7m/min, WT=2s; (e) WFS=8m/min, WT=2s. The strut inclined angle changes from left to right in the figure are 70°, 60°, 50°, 40° and 30°.

The struts are shown in the Figure 4.14 all have suitable geometrical shapes, and the actually measured layer height-increase and layer diameter values among them are highly consistent with the values of the layer geometry under the same process parameters obtained from the vertical direction bead modelling. Its proper geometry formation and accurate material deposition angle ensure the reliability of the wire-structured part fabricating in multi-directional
4.4 Height Control System and Adaptive Slicing

As mentioned in the previous section, and as shown in Figure 4.9, the layer height-increase has
a large deviation during the strut depositing process. As the wire feed speed and welding residence time increase, the layer height-increase error can be as high as 20% in multiple measurements. This error can cause changes in the CTWD during welding, making the process unstable.

For example, when using WFS=6m/min, WT=2s, CTWD=10mm as the process parameter combination, it can be known from bead modelling that the height growth of each layer of strut should be 1.5mm. During the manufacturing process, the welding torch should move 1.5mm along the build direction each time when welding is finished. However, if a layer has the defect that causes the actual layer growth height to become 1.2 mm, then after the torch moves 1.5 mm, the CTWD of the next layer is increased by 0.3 mm. The accumulation of such errors can make the welding points in the manufacturing process challenging to locate, especially for strut with variable inclined angles, which may result in the inability to make welding point in contact with the strut.

One possible solution is to use the length of the CTWD represent by welding current so that the actual amount of deposition can be reflected by the length of the CTWD after the end of the weld. The input of energy is then changed during the next deposition to increase or decrease the volume of the deposit so that each layer can have approximately the same height increase. This section uses this method to build a height control system, and on this basis, the development of adaptive slicing algorithms and the discussion of some special-shaped wire-structures are also carried out.

4.4.1 Height control system

Based on the process parameter combination of WFS=4m/min and WT=2s, the corresponding current and voltage values at CTWD of 3mm, 6mm, 9mm, 12mm, 15mm, 18mm, 21mm, 24mm and 27mm heights are measured. As an example, the current and voltage waveforms selected under 2000hz sampling frequency at CTWD=3 and 12 are as shown in Figure 4.15. It is worth
noting that the current and voltage waveforms do not represent the actual waveforms of CMT. Because the data density of the sample is large, it cannot be displayed with enough resolution.

Figure 4.15 Recorded current and voltage value when WFS=4

At these given CTWD heights, the corresponding current (I) and voltage (V), as well as the layer height-increase (h) and layer diameter (d) of the strut, are presented in Table 4.4 below.

<table>
<thead>
<tr>
<th>CTWD (mm)</th>
<th>Welding process</th>
<th>Layer geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I (A)</td>
<td>V (V)</td>
</tr>
<tr>
<td>3</td>
<td>61.42</td>
<td>8.978</td>
</tr>
<tr>
<td>6</td>
<td>60.44</td>
<td>9.290</td>
</tr>
<tr>
<td>9</td>
<td>61.34</td>
<td>9.600</td>
</tr>
<tr>
<td>12</td>
<td>60.42</td>
<td>9.900</td>
</tr>
<tr>
<td>15</td>
<td>60.63</td>
<td>10.18</td>
</tr>
<tr>
<td>18</td>
<td>60.67</td>
<td>10.48</td>
</tr>
<tr>
<td>21</td>
<td>60.75</td>
<td>10.79</td>
</tr>
<tr>
<td>24</td>
<td>60.79</td>
<td>11.15</td>
</tr>
<tr>
<td>27</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
When the CTWD length reaches to 27mm, the strut has the extremely poor geometry formation due to the high resistance and insufficient shielding gas, so that welding cannot be continued in this case, as shown in Figure 4.16.

![Image of strut formed with very long CTWD](image1)

**Figure 4.16 Effect of very long CTWD on strut forming.**

Figure 4.17 shows the change in current and voltage with the CTWD change. With the increase of CTWD, the current is basically maintained at around 60A, but its variance is getting larger and larger, and the actual measurement has a maximum error of 14% with the average value. For the voltage in the welding, the accuracy of the measured data is very high, and it has a linear relationship with CTWD, which is represented as:

\[
V_i = 0.1017D_i + 8.673 \tag{4.6}
\]

where \( D_i \) is contact to work distance. Therefore, by reading the value of voltage \( V_i \), it can know the actual CTWD \( D_i \) after each layer welding process.

![Image of current and voltage change with CTWD](image2)

**Figure 4.17 Relationship between the CTWD with the current and voltage.**
After replacing CTWD $D_i$ with voltage $V_i$, its relationship with the layer height-increase and diameter of the strut is shown in Figure 4.18. Here, layer height-increase will be the focus of the control system.

![Figure 4.18 Relationship between the voltage with the layer geometry.](image)

The voltage in the graph and the corresponding layer geometry have a linear relationship, which is expressed as:

$$h_i = 1.31215 \times V_i - 6.629$$

$$d_i = 1.2489 \times V_i + 19.1429$$

where,

$$V_i = 0.6102 \times D_i + 52.038, \quad (4.6)$$

The height control system can be established through these several relationships, and its functions mainly want to achieve is that in the welding process, the system will ensure the stability of CTWD. For the actual movement distance of the welding torch, in addition to moving a distance equal to the theoretical value obtained from the bead modelling, the travel distance of the torch is also fine-tuned based on the voltage value. When there is a higher voltage value, indicating that the actual depositing layer height is a bit higher, so the torch needs to move an extra distance and vice versa.

One of the reverse applications of the system is to make each layer height-increase consistent.
by changing the CTWD. Its purpose is to target the traditional slicing algorithm, that is, for a strut, the slice height of each layer is constant, so if the deposit height in one layer is different from the slice height, this will cause the error accumulation of strut formation. Therefore, based on the voltage values presented by each layer of welding, it is possible to analyse what the actual layer height increase is. If it is lower, the torch will move to a higher CTWD in the next layer process, so that increase the growth height of the next layer by an unreached height of the previous layer. It can also be used in the adaptive slicing algorithm proposed in the next section so that it can automatically adjust the optimal each sliced layer height-increase of the strut.

4.4.2 Adaptive Slicing

The adaptive algorithm proposed in this chapter is mainly used for the following two points:

1. Find the build direction and the torch direction as well as the deposition point of each layer of the strut with simple or complex spatial geometry.

2. Quickly correct and adjust the next layer height-increase and deposition point when the actual layer growth height does not match the theoretical value, especially for struts with spatial complex geometry.

4.4.2.1 Robot pose adaptation

The pose of the robot is the position (x,y,z) of the robot in three-dimensional space, and the rotation of the robot Rx, Ry, Rz relative to a coordinate system. In this experiment, the adjustment of the robot pose will be limited to the adjustment of its tool center position (TCP, i.e. torch). The process and path for the robot to move the torch to the desired point are not of interest in the experiment. The pose of TCP is defined as

\[
R_o = [x_0 \ y_0 \ z_0]^T
\]  

(4.6)

It includes the position of x', y', z' of TPC in the dynamic coordinate system O'X'Y'Z' relative
to the original coordinate system OXYZ. It should be noted that the torch's TCP is based on the original tool coordinates of the robot, and its center point is the end of the feedstock wire, not the end of the torch, as shown in Figure 4.19.

![Figure 4.19 Location of weld torch TCP](image)

The positioning of the welding point in the experiment is effortless. The coordinates of each point on the strut can be directly read from the model and directly assigned to the coordinates of (x, y, z) of TCP. However, when strut has an inclined angle, especially when it has an inclined direction in three-dimensional space, the calculation of the rotation matrix is then applied to set the torch Orientation (Rx, Ry, Rz) to be the same as the strut build direction.

As defined in 3.12, in a strut, the build direction \( \vec{b} \) of each layer in 3D space is defined as:

\[
\vec{b}_i = D_{i,x,y,z} - D_{i-1,x,y,z} \tag{4.7}
\]

For the torch direction \( \text{tor}_{x_0,y_0,z_0} \), by \( \text{tor}_{x_0,y_0,z_0} \) through the rotation matrix R to \( \vec{b}_{i,x,y,z} \) is expressed as:
The matrix rotating around the x, y, and z axes are:

Rotate around the x-axis

\[ R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix} \]

Rotate around the y-axis

\[ R_y(\theta) = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \]

Rotate around the z-axis

\[ R_z(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

Here, defining whether the tool coordinate system or the workpiece coordinate system is rotated along with a fixed world coordinate system. In order to avoid the difference in the final rotation matrix caused by the different rotation axis order, we define that all objects rotate along the sequential z-axis, y-axis, and x-axis in rotation.

Let the Euler angles of the three axes x, y, and z be \( \theta_x, \theta_y, \theta_z \), and the sine and cosine values are \( s_x, c_x, s_y, c_y, s_z, c_z \) respectively, then the final rotation matrix is:

\[
R(\theta_x, \theta_y, \theta_z) = R_z(\theta_z)R_y(\theta_y)R_x(\theta_x)
\]

\[
= \begin{bmatrix} c_y c_z & c_z s_x s_y - c_x s_z & s_x s_z + c_x c_z s_y \\ c_y s_z & c_x c_z + s_x s_y s_z & c_x s_y s_z - c_z s_x \\ -s_y & c_y s_x & c_x c_y \end{bmatrix}
\]

\[
R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = \begin{bmatrix} c_y c_z & c_z s_x s_y - c_x s_z & s_x s_z + c_x c_z s_y \\ c_y s_z & c_x c_z + s_x s_y s_z & c_x s_y s_z - c_z s_x \\ -s_y & c_y s_x & c_x c_y \end{bmatrix}
\]

\[
(4.10)
\]
In robot programming, quaternions are used to define the orientation that their tool coordinates have, which can be expressed as:

\[ q = (\theta x y z)^T = q_1 + q_2i + q_3j + q_4k = [s, V] \]  

(4.12)

where \( \theta, x, y, z \) represents \( q_1, q_2, q_3, q_4 \) of the tool orientation, respectively. \( S \) represents \( q_1 \), \( V \) is a set of three elements, of which \( V(1) = q_2, \ V(2) = q_3, \ V(3) = q_4 \).

The rotation matrix \( R_q \) can be obtained from the quaternion using the Rodrigues formula:

\[
R_q = \begin{bmatrix}
1 - 2q_3^2 - 2q_4^2 & 2q_2q_3 - 2q_1q_4 & 2q_2q_4 + 2q_1q_3 \\
2q_2q_3 + 2q_1q_4 & 1 - 2q_2^2 - 2q_4^2 & 2q_3q_4 - 2q_1q_2 \\
2q_2q_4 - 2q_1q_3 & 2q_3q_4 + 2q_1q_2 & 1 - 2q_1^2 - 2q_3^2
\end{bmatrix}
\]  

(4.13)

It is worth noting that the quaternion represents the rotation of one coordinate system relative to another. For the torch tool coordinates, the relative coordinate is tool0, which is the robot flange. Since the robot base is used as the original coordinate system in the experiment, it is necessary to apply three rotation matrices calculation to find the orientation of the welding tool coordinate system relative to the workpiece coordinate system. To simplify the calculation, a new approach is used in the experiment, which assumes that both the tool coordinate system and the workpiece coordinate system are rotated with a unit vector \( \vec{v}_1 [0,0,1] \). By finding the relationship between the unit vector and the workpiece coordinate system, the tool coordinate system can be directly rotated through it to the workpiece coordinate system.

The principle of its realisation is that any quaternion can be regarded as a scalar part \( s \) and a
three-dimensional vector part \( \vec{v} \). Similarly, the vector of three-dimensional space can also be regarded as a quaternion with a scalar part of 0. Rotating a vector \( \vec{u} \) with a vector \( \vec{v} \) by \( \theta_{x,y,z} \), and the rotation equation is \( \vec{v}' = q\vec{v}q^{-1} \), where \( q = \cos \left( \frac{\theta}{2} \right) + \vec{u} \sin \left( \frac{\theta}{2} \right) \).

If the unit vector \( \vec{v}_1 \) is rotated to the orientation of the unit vector \( \vec{v}_2 \), pay attention to the angle, which is represented as \( \cos(\theta) = \vec{v}_1 \cdot \vec{v}_2 \), then,

\[
\cos \left( \frac{\theta}{2} \right) = \sqrt{\frac{\cos(\theta) + 1}{2}} = \frac{\vec{v}_1 \cdot \vec{v}_2 + 1}{2} \quad (4.14)
\]

The axis normal vector is \( \vec{u} \) then there is \( \vec{v}_1 \times \vec{v}_2 = \vec{u} \sin(\theta) \), so,

\[
\vec{u} \sin \left( \frac{\theta}{2} \right) = \frac{\vec{v}_1 \times \vec{v}_2}{\sin(\theta)} \sin \left( \frac{\theta}{2} \right) = \frac{\vec{v}_1 \times \vec{v}_2}{2\cos \left( \frac{\theta}{2} \right)} = \frac{\vec{v}_1 \times \vec{v}_2}{\sqrt{2(\vec{v}_1 \cdot \vec{v}_2) + 1}} \quad (4.15)
\]

So, the final quaternion of the rotation is expressed as:

\[
q = \left( \sqrt{\frac{\vec{v}_1 \cdot \vec{v}_2 + 1}{2}}, \frac{\vec{v}_1 \times \vec{v}_2}{\sqrt{2(\vec{v}_1 \cdot \vec{v}_2) + 1}} \right) \quad (4.16)
\]

In the experiment, the unit vector in the z-direction used is \( \vec{v}_1 \), and the unit vector \( \vec{v}_2 \) represented by the build direction \( \vec{b}_1 \) of the strut is:

\[
\vec{v}_2 = \left[ \frac{x}{\sqrt{x^2 + y^2 + z^2}}, \frac{y}{\sqrt{x^2 + y^2 + z^2}}, \frac{z}{\sqrt{x^2 + y^2 + z^2}} \right] \quad (4.17)
\]

Then the rotation matrix \( R_q \) can be obtained according to the formulas in (4.13) and (4.16). With this rotation matrix, the rotation angle of the workpiece coordinates on \([Rx, Ry, Rz]\) can be obtained by the formulas (4.11) and (4.9). The next step is to find the rotation matrix \( R_t \).
that the tool coordinate system has. The quaternion that is brought in can directly call the orient of its tool data from the robot program. Finally, after the tool coordinate system passes through the rotation matrix $R_f$, the same orientation as the workpiece coordinates can be obtained:

$$R_f = R_z(\theta)R_y(\theta)R_x(\theta)R_t$$  \hspace{1cm} (4.18)

where

$$|q_1| = \frac{1}{2} \sqrt{1 + R_f(1,1) + R_f(2,2) + R_f(3,3)}$$

$$|q_2| = \frac{1}{2} \sqrt{1 + R_f(1,1) - R_f(2,2) - R_f(3,3)}$$

$$|q_3| = \frac{1}{2} \sqrt{1 - R_f(1,1) + R_f(2,2) - R_f(3,3)}$$

$$|q_4| = \frac{1}{2} \sqrt{1 - R_f(1,1) - R_f(2,2) + R_f(3,3)}$$

The symbols of $q_1, q_2, q_3, q_4$ can be determined as follows:

$$\begin{align*}
\text{sign}(q_2) &= \text{sign}(q_1)\text{sign}(R_f(2,3) - R_f(3,2)) \\
\text{sign}(q_3) &= \text{sign}(q_1)\text{sign}(R_f(3,1) - R_f(1,3)) \\
\text{sign}(q_4) &= \text{sign}(q_1)\text{sign}(R_f(1,2) - R_f(2,1))
\end{align*}$$  \hspace{1cm} (4.19)

### 4.4.2.2 Adaptive slicing process

During the slicing process, although the slice direction and angle are changed, the general direction is increased along the $z$-direction, so there is no slice layer whose growth method is along the negative $z$-direction unless an error occurs during the slicing process.

During the slicing process, all the first few layers’ centroid axes of the wire-structured part are extracted, so that the part with a certain geometric volume can be transformed into points and lines for analysis. The next step in the process is to slice a plane with a wire-structured part height of 0 (also can be known as substrate plane), and the points on the sliced plane are defined as $D_{1,0_{x_0,y_0,z_0}}, D_{2,0_{x_0,y_0,z_0}}, D_{3,0_{x_0,y_0,z_0}}, \ldots, D_{n,0_{x_0,y_0,z_0}}$. 
where \( n \) represents the number of struts, and \( i \) (here is 0) represents the sliced layer number in the current strut point. For any individual strut, the total length is

\[
S_{\text{tot}} = \sum_{i=1}^{n} \sqrt{1 + (\Delta y_i / \Delta b_i)^2} \Delta x_i
\]  

(4.20)

The coordinates of all the points can be obtained directly from the STL/CAD model, and the highest precision is available up to \( \Delta x_i = 0.0001 \). The key step in slicing is to find each individual strut, which means that for \( D_i \) coordinates, only one \( D_{i+1} \) coordinates match it, as shown in Figure 4.20 (a). Here, its three-dimensional representation mode is displayed in a two-dimensional schematic.

Figure 4. 20 Schematic diagram of individual strut detection and slicing process.

For any individual strut, no matter how complex the spatial shape is in its growth path, its starting point \( D_{n,0} \) and ending point \( D_{n,i} \) will be the endpoint \( D_{m,j} \) and the starting point \( D_{m,0} \) of another strut. Here the strut that grows from the substrate is defined before. After completing this step, the next step is to slice a single strut with a total length of \( S_{\text{tot}} \), defined as:

\[
i_{\text{tot}} = \frac{S_{\text{tot}}}{hi}
\]  

(4.21)
wherein order to ensure that the deposit height can cover the entire strut height, \( i_{tot} \) remainder should be 0, defined as \( \text{mod}(S_{tot}, hi) = 0 \). Therefore, obtain a height-increase \( hi \) of each layer in the slicing process, besides obtaining the theoretical height-increase value of each layer from the bead modelling, there is also a fine adjustment of the CTWD.

It is worth noting that the strut with a total length of \( S_{tot} \) is not directly divided into \( i_{tot} \) parts during the slicing process. Because the height-increase of each layer is linear growth during the welding process. So, in fact, every linear-shaped single strut in the model has fitted to a polyline that each segment has a length of \( hi \). Thus, the location of each welding point on the strut is shown in Figure 4.20 (b).

First, a sphere \( S_{D_{1,0}} \) will be drawn with the radius of \( hi \) with the known starting point \( D_{1,0} \) as the centre of the sphere. This sphere surface \( S_{D_{1,0}} \) will create an intersection with the strut \( D_1 \), which is defined as the deposition point \( D_{1,1} \) of the next layer. Therefore, the deposition points of each layer \( D_{1,i+1} \) are determined by the intersection of the sphere surface produced by the previous layer \( D_{1,i} \) and the strut, defined as:

\[
D_{n,i+1,x,y,z} = S_{n,i} \cap S_{n,x,y,z} - D_{n,i-1,x,y,z}
\] (4.22)

here \( S_{n,i} \) is a set of all the elements \( \{4\pi hi^2\} \) on the surface of the sphere, where \( hi \) is a vector pointing in all directions. It is worth noting that the sphere surface will intersect with two points, one is the previous layer \( D_{n,i-1,x,y,z} \), which should be excluded. In terms of computational precision and speed, \( hi \) as a vector with uncertain direction will bring a lot of extra work to the calculation. To simplify the calculation, for all elements in the set \( S_{n,i} \), they are represented by spherical coordinates, as defined as:

\[
\{4\pi hi^2\} = \{M(x, y, z)|x = r\sin\phi\cos\theta, y = r\sin\phi\sin\theta, z = r\cos\phi\}
\] (4.23)
where \( 0 \leq r \leq \infty, \quad 0 \leq \varphi \leq 2\pi, \quad 0 \leq \theta \leq \pi, \) here \( r = |\vec{h}_i| \).

In general, a spherical surface has only two intersections with the strut. However, when three solutions or more solutions are calculated, this indicates that the current layer deposit has an overlapping area with another strut, as shown in Figure 4.21.

In this case, most of the time, it is stated that the structure is unprocessable. Since the layer height-increase is employed when slicing the wire-structured part, and its value is only 1/3 or less of the layer diameter, as shown by the bead modelling in Table 4.3. The slicing algorithm assumes that a deposit has the same diameter and height-increase. If the shape of the real deposit is placed in the model, the overlapping area will be larger. This situation often occurs at the intersection of multi-struts with the included angles. The overlapping area means that the deposit on one of the struts that were first manufactured may obstruct the torch moving path of the other strut deposit layer to be welded next, causing the loss of some layers, thereby affecting the geometric shape of the entire workpiece.

The rightmost diagram in Figure 4.21 shows a particular case that the proposed slicing algorithm misses some details of the strut. The growth direction of the strut shown in the figure has a large change, but this change occurs within the sphere surface, so the algorithm cannot recognise its actual growth direction. In the slice model, the final deposition path of the strut
changes from the path shown in the blue curve to the path shown in red polylines. This method can be modified to become an adaptive slicing algorithm with fault tolerance. When the sphere surface \( S_{n,i} \) has multiple intersections with its own strut \( S_{n,x,y,z} \), it will select the intersection with the highest z value as the welding point of the next layer \( D_{n+1,x,y,z} \). This algorithm part has not been added to the slicing algorithm already proposed in thesis, because the emergence of this situation is rare in the current experimental process, and in the model establishment of a wire-structured part, it will also artificially avoid the appearance of the strut with a large angle of change.

The height control system has also been employed to the adaptive slicing algorithm. The purpose is to change the remaining height \( S \) of the strut as a new strut, then re-slicing, and calculate the new \( h_i \) and weld points when the layer increase-height value has changed. It should be noted that the change of \( h_i \) will bring about the change of CTWD. The relationship, according to Figure 4.17, Figure 4.18, (4.6) can be expressed as:

\[
di = \frac{1}{k_1 k_2} h_i - \frac{b_2 + b_1 k_2}{k_1 k_2}
\]

(4.24)

where if the process parameter combination of WFS=4 and WT=2s, \( k_1 = 0.6102, k_2 = 1.31215, b_1 = 52.038, b_2 = 6.629 \). When the strut build direction changes only in a two-dimensional plane, the torch angle can be simplified to:

\[
\alpha_i = \tan^{-1}\left(\frac{D_{i+1z} - D_{iz}}{D_{i+1x} - D_{ix}}\right)
\]

(4.25)

Because the strut build direction of the welding process is the same as the torch direction, as previously defined, the CTWD effect on the TCP coordinate system is limited to the Z-axis direction, so the TCP coordinates will only be assigned a new position \([X^i, Y^i, Z^{new}]\) and the orient \([R_{xy}^i, R_{yx}^i, R_z^i]\).
A simple overview of the flow chart of the deposition strategy proposed in the paper is shown in Figure 4.22. Figure 4.23 highlights the effectiveness of this method, in which two arc-curved struts are placed. One is to use a constant sliced height mode, and the other is to use the adaptive method proposed based on real-time voltage measurement.

Figure 4.22 Flowchart of the adaptive slicing algorithm.
The importance of this adaptive approach can be clearly seen. The strut fabrication process which does not use the adaptive slicing algorithm accumulates positional errors more and more severe as the deposition process continues, thereby affecting the geometry of the final wire-structure. For curved strut that does not use the adaptive slicing algorithm, the feedstock wire and the strut are often staggered, so it must be artificially adjusted to the actual deposition point position, whilst the adaptive algorithm can detect automatically and adjust it autonomously, which shows that the adaptive slicing algorithm can provide a global perspective to observe the stability of the entire structure of the wire-structured part while ensuring the deposition accuracy of each strut.

Figure 4. 23 Curved strut fabrication process. (a) With adaptive slicing; (b) Without adaptive slicing; (c) Deposition point away from strut.
4.4.2.3 Discussion on the special-shaped strut

The strut shown in Figure 4.23 has the shape of a 1/4 circle on the plane. When layer height-increase is known, the coordinates of its welding point can be expressed in polar coordinates as:

\[(x,z)_{D_i} = [r\cos(i\theta), r\sin(i\theta)]\]  \hspace{1cm} (4.26)

where \(i\theta = 90^\circ\). When processing a workpiece with this type of geometry, the calculated welding point change could be directly used with the geometric relationship between the original torch TCP, the new torch TCP and the workpiece, as an example shown in Figure 4.24.

![Figure 4.24 The 1/4 arc-shaped strut welding position changes the by geometric analysis.](image)

As shown in middle diagram of Figure 4.24, when TCP does not change, that is, TCP = \(di\), the new welding point which is shown by the dotted line in the middle of the figure is:

\[(x,z)_{D_{i'}} = [r - r\cos(i'\theta), r\sin(i'\theta)]\]  \hspace{1cm} (4.27)

where
\[i'\theta = i\theta - 180^\circ \frac{di' - di}{\pi r}, \text{and} \ \theta = \frac{\pi r}{2h}.\]

However, in most cases, when the welding position changes, its CTWD will also change, as an
example shown in the rightmost diagram in Figure 4.24. If in this case TCP = \( di/2 \), Because the robot is centred on the welding point when moving and rotating, however, at this time the TCP has already moved to \( di/2 \), so the robot will go to a fake welding position. In this case, further calculations are needed to find the true welding position and robot pose, as shown by the orange line in the rightmost diagram in Figure 4.24. The new welding position is defined as:

\[
(x, z)_{D_{t'}} = \left[ r - r \cos(i' \theta) + di \times \sin\left(\frac{\theta(i' - i)}{2}\right)\cos \left(\frac{(i' + i)\theta}{2}\right) \right] \\
rsin(i' \theta) - di \times \sin\left(\frac{\theta(i' - i)}{2}\right)\sin \left(\frac{(i' + i)\theta}{2}\right)
\]

where

\[
i' \theta = i \theta - 180^\circ \frac{di' - di}{\pi r}, \text{ and } \theta = \frac{\pi r}{2h}.
\]

The slicing algorithm in this method is more convenient, and it is more accurate to find the welding position directly by finding the geometric relationship between the welding torch and the workpiece.

As a widespread application, the growth direction of the strut shown in Fig. 4.23 can be regarded as the trajectory formed by the points on the connection line \( P_0P_2 \) when \( P_0 \) moves on \( P_0P_1 \), and \( P_2 \) moves on \( P_1P_2 \), as shown in Figure 4.25.

![Figure 4.25 Schematic diagram of Bezier curve](image)

This curve, created by the four points on the control curve (starting point, ending point, and two intermediate points that are separated from each other), is also called a Bezier curve. Bezier curve is a very important parameter curve in computer graphics, and it is one of the most basic
lines used in graphic modeling. The continuous curves currently designed by computer software all can be represented by Bezier curves. In three-dimensional space, the Bezier curve is defined as,

\[
B(t) = \sum_{i=0}^{n} \binom{n}{i} P_i (1 - t)^{n-i} t^i, \quad t \in [0,1]
\] 

(4.29)

where the coordinates of each point on the curve are:

\[
P_i^k = \begin{cases} 
P_i & k = 0 \\
(1-t)P_i^{k-1} + tP_{i+1}^{k-1} & k = 1,2,\ldots,n, i = 0,1,\ldots,n-k
\end{cases}
\]

(4.30)

In this experiment, the growth path of all struts whose curvature does not occur is controlled by the Bezier curve. The use of Bezier curve is also a way to improve the accuracy of the slicing algorithm in the experiment, and the combination of the shape of the strut and the Bezier curve can make the proposed wire-structured part more practical use-value. However, for a single strut defined in the slicing algorithm, the linearity of its possible growth direction is a polyline, or multiple curves, or their combination. While Bezier curves can make slicing model accuracy higher, the use of its parametric equations makes the slicing algorithm more complicated. Therefore, this experiment does not add it to the proposed slicing algorithm. In the future plan, when processing a wire-structured part with a multi-segment Bezier curve set, it may come in handy.

### 4.5 Procedures for Branch Intersections

This section classifies the intersections of multiple struts in more detail mentioned in the section of the height control system and adaptive slicing and proposes different treatment methods for fabricating them. It is defined as, along the positive direction of the z-axis, when the struts
below the intersection is less than the upper struts, this intersection is defined as the divergence point, i.e. one or more struts split into two or more new struts; When the struts below the intersection is over the upper struts, this intersection is defined as the convergence point, i.e. two or more struts merge into one or less new struts.

4.5.1 Procedures for divergence point

There are two strategies for depositing struts near the divergence point, as shown in the example in Figure 4.26. The (a) strategy is to fabricate strut two first, after the deposition process is completed, then to fabricate the strut 3. The (b) strategy is to slice each of strut 2 and strut 3 at the divergence point and then deposit them layer by layer.

In contrast, the (b) strategy has higher processing efficiency. Although in these two strategies, the struts are processed in the same layer number, in (a) strategy a strut is continuously welded,
this results in higher heat accumulation, which makes the waiting time of each layer longer. Although the heat input can be dispersed in the (b) strategy, the other problem that may occur is that the welding arc is easily attracted to the already deposited material on the same layer in the different strut, under the influence of the magnetic force, thereby causing deformation of the structure. Furthermore, as the deposition process continues, this deformation will be gradually amplified. The comparison of the two processing methods for the same strut geometry is shown in Figure 4.27, where struts in Figure 4.27 (a) is used the second strategy shown in Figure 4.26, and struts in (b) are used the first process strategy. It is worth noting that when processing the first few layers of strut 2 as shown in Figure 4.27 (c), in order to avoid the collision between the welding torch and the built strut, it increases the length of CTWD. The strategy of adjusting the CTWD will be explained in the next section.

![Figure 4.27 Comparison of two different manufacturing strategies](image)

In addition to the influence of electromagnetic force, the reason for the struts with poor geometry using the layer-by-layer process strategy is that the struts near the divergence point have a small angle, so the layers of the two struts are very close. Because the deposit has a hemispherical shape, a gap is formed between the two deposits if they do not have enough distance. In addition to arc being attracted to the built-up strut, the molten pool will also move
into the gap, causing the layer to collapse. However, when two different struts have a long
distance between their weld points near the divergence point, this method can play its role, as
shown in Figure 4.28, using both of the (a) strategy and (b) strategy proposed in 4.26 will result
in a proper geometry formation of the struts.

![Figure 4.28 Both Strategies can be used to fabricate this wire-structured part.](image)

### 4.5.2 Procedures for convergence point

For the struts near the convergence point, because at least two struts are merged into one, it is
shown that there may be a collision problem in the path of the struts build directions, as shown
in Figure 4.29.

The size of the collision zone shown in Figure 4.29 is determined by the diameter of the torch
$d_t$, and the growth directions of the struts. Here $d_t = 20mm$ in the experiment.

The struts in the collision zone can only be deposited layer by layer according to their height in
the $z$-direction, instead of entirely depositing one strut first, then depositing another strut.
Furthermore, most of the time, the torch needs to be moved outside the collision zone, as shown
in Figure 4.30.
As shown in the flow (d), (e), (f) shown in Figure 4.30, the red dotted line indicates the minimum collision area lines of the two struts. When the height of the strut is lower than this line, it is feasible to continuously deposit the strut one-by-one or to process multiple struts layer-by-layer along the z-axis height growth direction. Nevertheless, once in the range above the
dotted line, the torch will have a high probability of colliding with the built-up struts. At this point, the CTWD of the torch needs to be adjusted to move the torch out of the collision zone. Up to now, this is the only solution that avoids collision problems while keeping the torch direction and the strut build direction unchanged. The algorithm for manufacturing strategy of convergence point is also shown in the next section.

### 4.6 Overall Collision-Free Path Planning

This section integrates the strategy from bead modelling to adaptive slicing to the processing strategy of the intersections of the struts, so that a wire-structured part can be manufactured automatically from the CAD model to finished part. The algorithm is as follows:

For a wire-structured part \( W = \{S, N\} \), it can be represented as a set of all the intersection \( N = \{n_i \mid i = 1, 2, 3, \ldots, |N|\} \), and a set of all individual struts \( S = \{s_i \mid i = 1, 2, 3, \ldots, |S|\} \). Each strut has two feature points. One is the starting point, defined as \( n_{i_1} \), and the other is the ending point, defined as \( n_{i_2} \), where characteristic parameter matrix of \( s_i = [n_{i_1}, n_{i_2}] \). The set \( S \) has already been proposed in the section of adaptive slicing, and the feature matrix that each element \( s_i \) within \( S \) is also mentioned in that section.

The essential step in path planning is to find all individual struts with the same convergence point or divergence point. For a wire-structured part, any of the independent strut within (not including the strut in contact with the substrate), it must have a convergence point and a divergence point, as defined in Section 4.4. Thus, for all struts \( s_1, s_2, s_3, \ldots, s_i \), whose having the same starting point are placed in the set \( S_{p_m}^{div} \), defined as:

\[
S_{p_m}^{div} = \left\{ s_i \mid n_{i_1} = n_{j_1}, \ i \in (1, |N|), \ j \in (1, |N|) \right\} \tag{4.31}
\]

where

\[
P_m = \left\{ i \mid n_{i_1} = n_{j_1}, \ i \in (1, |N|), \ j \in (1, |N|) \right\}
\]
Therefore, all struts in $S^{div}$ have the same start point will be labelled as $P_m$. The reason for using a set as a label instead of using a number is that this method can compress the number of sets, thereby reducing the time of duplicate indexes. For example, when struts $s_1, s_3, s_5, s_7$ have the same starting point, if the number $m$ is used as the mark, then 4 sets will appear, which are $S^{div}_1 = \{s_1, s_3, s_5, s_7\}$, $S^{div}_3 = \{s_1, s_3, s_5, s_7\}$, $S^{div}_5 = \{s_1, s_3, s_5, s_7\}$, $S^{div}_7 = \{s_1, s_3, s_5, s_7\}$ respectively. If the $P_m$ is used as a label, then only one set will appear, which is $S^{div}_{\{1,3,5,7\}} = \{s_1, s_3, s_5, s_7\}$. In contrast, this approach requires less storage space and has higher computational efficiency. Correspondingly, for all struts with the same endpoint (convergence point), the expression is,

$$S^{cov}_{P_m} = \left\{ s_i \left| n_{i_2} = n_{j_2}, \ i \in (1, |\mathcal{N}|), \ j \in (1, |\mathcal{N}|) \right. \right\}$$ (4.32)

where $$P_m = \left\{ i \left| n_{i_2} = n_{j_2}, \ i \in (1, |\mathcal{N}|), \ j \in (1, |\mathcal{N}|) \right. \right\}$$.

The next step is to build the correct deposition sequence. Anyone of the struts should have at least two additional struts underneath it to support (if there is only one extra strut, it should be supposed as an individual strut). This means that the endpoint in each strut should be the starting point in another strut. Here, the struts that have been deposited is put into the set $S^{P}_k = \{s^P, \ldots, s^P_k\}$. Therefore, struts that are not deposited or are about to be deposited are defined as,

$$S^{u}_k = S \setminus S^{P}_k$$ (4.33)

When building the deposition sequence, the experiment uses convergence points as the basis for the analysis. First, find all the struts with the same endpoint at the convergence point, then find all the struts whose endpoints are consistent with its starting point, is expressed as,
For a strut $s_i$ in $\mathcal{S}_{p_m}^\text{con}$, it calls all the struts with the same endpoint value in this set. The role of $\mathcal{N}_{i_1}$ is that for any strut in the set $\mathcal{S}_{p_m}^\text{con}$, it will index all the struts with the same endpoint value $n_{j_2}$ as its start point $n_{i_1}$. The element in the set is then compared one by one with the element in $\mathcal{S}_k^p$. Only when $\mathcal{S}_k^p$ contains all the same elements as in $\mathcal{N}_{i_1}$, a reasonable processing sequence can be established. An example simply illustrates its principle, as shown in Figure 4.31.

Other strategies to be implemented are the adjustment of CTWD to achieve a collision-free deposition path. For the struts in the set $\mathcal{S}_{p_m}^\text{div}$, if their angle is less than 90°, then in the welding of the first layer, it is only necessary to increase the distance in the z-axis of the welding torch TCP by $|h_i|$ to avoid a collision. When they are at an angle of more than 90° to each other,
there are no collision problems.

For the struts in the set $\mathcal{SP}_m^{cov}$, as mentioned earlier, they create a collision zone as they continually approach. More precisely, if a strut $s_i$ is treated as a vector, it will not collide during the deposition process in the range $\lambda s_i$, and then enter the range $(1 - \lambda) s_i$, it may collide with other struts. Here, the determination of the value of $\lambda$ is the determination of the collision area. Firstly, in the case where the distance between the welding torch and the strut $s_i$ is known (that is, the radius of the torch), it is necessary to find the intersection with the other strut $s_k$, which is defined as:

$$
R = \sqrt{|s_i|^2 - \left(\frac{s_k}{|m|} \cdot \overrightarrow{m}\right)^2}
$$

(4.35)

where $R$ is the torch radius, $\overrightarrow{m}$ is an arbitrary vector parallel to $s_k$. $s_i$ represents both the strut build direction and torch direction, because the torch has the same direction of the strut growth direction. Therefore, the collision area $\lambda$ can be defined as:

$$
\text{max} (\lambda) = \text{max} \left( \bigcup_{p=1}^{n} \frac{R|s_v|}{\sqrt{|s_u|^2|s_v|^2 - (s_u \cdot s_v)^2}} \right)
$$

(4.36)

Each of the multiple struts with the same convergence point must be compared to each other to find the largest collision area $\lambda_{max}$. When the torch enters the range of $(1 - \lambda_{max})s_i$, the CTWD should be increased by a distance of $\left(\sqrt{(1 - \lambda_{max})s_i}^2\right)$ to move the torch out of the collision zone. The final flow chart is attached to Appendix D.
5.1 Proposed Strategy for Two-dimensional Structure

The definition of the two-dimensional wire-structured part is that the growth direction of all the strut exists in one plane (x-z or y-z). A honeycomb structure workpiece is fabricated using the manufacturing strategy proposed in the thesis and is shown in Figure 5.1.

Figure 5.1 (a) The centroid axis of all struts, (b) Theoretical model, (c) Slicing model, (d) Final honeycomb structure.
For the workpiece shown in the figure, the process parameters used are $WFS = 4 \, m / \, min, WT = 2 \, s$. The length of each strut within is 30mm. This honeycomb structure has a total of 640 layers. Its processing time is about 10 hours. Its good geometrical shape shows that the manufacturing strategy proposed in the thesis has satisfying reliability and accuracy.

5.2 Proposed Strategy for Three-dimensional Structure

Figure 5.2 shows a cube structure fabricated by the manufacturing strategy presented in the thesis. The process parameters used to fabricate this workpiece are: $WFS = 4 \, m / \, min, WT = 2 \, s$. Each side (strut) of the cube is 30mm long. This cube structure has a total of 260 layers. Its processing time is about 7.5 hours. It can be seen from the processing of this cubic structure that the manufacturing strategy proposed in this paper has the ability to process wire-structured part with high spatial structure complexity. At the same time, it ensures high processing efficiency while ensuring that the wire-structured part can obtain acceptable geometric forming quality.

Figure 5. 2 (a) Theoretical model, (b) slicing model, (c) Final workpiece.
6.1 Conclusion

In this thesis, the following results have been achieved well, including:

- The manufacturing strategy for fabricating wire-structure parts through robotic wire arc additive manufacturing.

- A bead modelling process was developed to select various combinations of welding process parameters that can accurately predict the strut geometry of the layer height-increase and layer diameter.

- A novel adaptive slicing algorithm and height control system were also presented. These algorithm and control system are used in combination to improve the processing efficiency and manufacturing precision.

- The effectiveness of this approach was demonstrated via the manufacture of two complicated wire-structure part.

In the booming development of the manufacturing system based on robotic point-to-point wire arc additive manufacturing, the fabrication strategy proposed by thesis will be widely used to make lightweight frame shapes in the future.
6.2 Recommendations for Future Work

Further research aims to:

- Integrate topology optimisation procedures to make the proposed manufacturing strategy more suitable for fabricating components with more complex features, such as spherical frameworks, or parts whose have both wire-structures and solid-structures in the workpiece in 3D space, as shown in Fig 6.1.

- Develop advanced bead modelling with a variety of process parameters and optimise strut geometry to reduce surface waviness.

- Evolve the control strategy to control and adjust CTWD in real-time with any combination of process parameters selected.

- Use local optimisation and other algorithms to increase the calculation speed of the overall fabrication strategy to improve manufacturing efficiency.

- Work will also focus on developing algorithms to transform solid artifacts into stable skeleton-type structures robustly.

Figure 6.1 Metallic artwork and crafts
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**Conference:** The 9th IEEE International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (IEEE-CYBER 2019)  
**Date:** 29 July – 2 August 2019,  
**Location:** Jinke Grand Hotel, Suzhou, China
REFERENCES


[41] C. Guo, W. Ge, and F. Lin, “Dual-Material Electron Beam Selective Melting:


[68] K. Kaori, K. Kenta, and F. Jun, “Investigation of metal transfer of ER70S-6 filler metal


[75] T. Lincoln Electric Company, “Surface Tension Transfer ® (STT ® ) Ideal for welding on joints with open root, gaps, or on thin material with no burnthrough.”


## APPENDIX A RESEARCH TIMELINES

<table>
<thead>
<tr>
<th>Time</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/2018</td>
<td>Coursework study, Literature review, Experimental setup</td>
</tr>
<tr>
<td>07/2018</td>
<td>Initial test</td>
</tr>
<tr>
<td>08/2018</td>
<td>Simple wire-structure test, Study at local level</td>
</tr>
<tr>
<td>09/2018</td>
<td>Case modeling, multiazonation, multi-modeling, Setup the program for reading voltage</td>
</tr>
<tr>
<td>10/2018</td>
<td>Height control system setup, Developing adaptive slicing algorithm</td>
</tr>
<tr>
<td>11/2018</td>
<td>Algorithm test, Procedures for branch intersections, Developing overall SMAM algorithm, Developing the multi theoretical look models, Developing the CFD code, Developing the CFD code, Developing the CFD code, Overall algorithm in 3D space, Overall algorithm in 3D space, Final automated system for wire-structures, Master dissertation</td>
</tr>
</tbody>
</table>
APPENDIX B TECHNICAL DATA FOR IRB 2600 INDUSTRIAL ROBOT

<table>
<thead>
<tr>
<th>Specification</th>
<th>Reach (m)</th>
<th>Handling capacity (kg)</th>
<th>Wrist torque (Nm)</th>
<th>Axis 4 &amp; 5</th>
<th>Axis 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot version IRB 2600-20/1.65</td>
<td>1.65</td>
<td>20</td>
<td>6.3</td>
<td>16.7</td>
<td></td>
</tr>
<tr>
<td>IRB 2600-12/1.65</td>
<td>1.65</td>
<td>12</td>
<td>1.8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>IRB 2600-12/1.85</td>
<td>1.85</td>
<td>12</td>
<td>1.8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Number of axes</td>
<td>6+3 external (up to 36 with MultiMove)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protection</td>
<td>Standard IP67; optional FoundryPlus 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mounting</td>
<td>Floor, wall, shelf, tilted, inverted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controller</td>
<td>IRC5 Single Cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Performance (according to ISO 9283)**

<table>
<thead>
<tr>
<th></th>
<th>Position repeatability</th>
<th>Path repeatability</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRB 2600-20/1.65</td>
<td>0.04 mm</td>
<td>0.13 mm</td>
</tr>
<tr>
<td>IRB 2600-12/1.65</td>
<td>0.04 mm</td>
<td>0.14 mm</td>
</tr>
<tr>
<td>IRB 2600-12/1.85</td>
<td>0.04 mm</td>
<td>0.16 mm</td>
</tr>
</tbody>
</table>

---

**Technical Information**

**Electrical Connections**

- Supply voltage: 200-600 V, 50/60 Hz
- Energy consumption: 3.4 kW

**Physical**

- Robot base: 676 x 511 mm
- Robot height:
  - IRB 2600-20/1.65: 1382 mm
  - IRB 2600-12/1.65: 1382 mm
  - IRB 2600-12/1.85: 1582 mm
- Robot weight:
  - IRB 2600-20/1.65: 272 kg
  - IRB 2600-12/1.65: 272 kg
  - IRB 2600-12/1.85: 284 kg

**Environment**

- Ambient temperature for mechanical unit: +5°C (41°F) up to +50°C (122°F)
- During transportation and storage: −25°C (13°F) up to +55°C (131°F)
- During short periods (max. 24 h): up to +70°C (158°F)
- Relative humidity: Max. 95%
- Noise level: Max. 69 dB (A)
- Safety: Double circuits with supervision, emergency stops and safety functions, 3-positions enable device.
- Emission: EMC/EMI-shielded
- Options: Foundry Plus 2

A supervision function prevents overheating in applications with intensive and frequent movements.

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Working range, IRB 2600-20/1.65, IRB 2600-12/1.65

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Working range, IRB 2600-12/1.85

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Data and dimensions may be changed without notice.
## APPENDIX C TECHNICAL DATA FOR TRANSPELS SYNERGIC 5000 (TPS5000)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mains voltage</td>
<td>3 x 400 V</td>
</tr>
<tr>
<td>Mains voltage tolerance</td>
<td>+/- 15 %</td>
</tr>
<tr>
<td>Mains frequency</td>
<td>50 / 60 Hz</td>
</tr>
<tr>
<td>Mains fuse protection</td>
<td>35 A slow-blow</td>
</tr>
<tr>
<td>Mains connection ¹)</td>
<td>Restrictions possible</td>
</tr>
<tr>
<td>Primary continuous current</td>
<td>100% d.c. ²)</td>
</tr>
<tr>
<td>Primary continuous power</td>
<td>13.1 kVA</td>
</tr>
<tr>
<td>Cos phi</td>
<td>0.99</td>
</tr>
<tr>
<td>Efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Welding current range</td>
<td></td>
</tr>
<tr>
<td>MIG/MAG</td>
<td>3 - 500 A</td>
</tr>
<tr>
<td>Rod electrode</td>
<td>10 - 500 A</td>
</tr>
<tr>
<td>TIG</td>
<td>3 - 500 A</td>
</tr>
<tr>
<td>Welding current at</td>
<td></td>
</tr>
<tr>
<td>10 min / 40 °C (104 °F)</td>
<td></td>
</tr>
<tr>
<td>40% d.c. ²)</td>
<td>500 A</td>
</tr>
<tr>
<td>60% d.c. ²)</td>
<td>450 A</td>
</tr>
<tr>
<td>100% d.c. ²)</td>
<td>360 A</td>
</tr>
<tr>
<td>Welding voltage range according to standard characteristic</td>
<td></td>
</tr>
<tr>
<td>MIG/MAG</td>
<td>14.2 - 39.0 V</td>
</tr>
<tr>
<td>Rod electrode</td>
<td>20.4 - 40.0 V</td>
</tr>
<tr>
<td>TIG</td>
<td>10.1 - 30.0 V</td>
</tr>
<tr>
<td>Max. welding voltage</td>
<td>49.2 V</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>70 V</td>
</tr>
<tr>
<td>Degree of protection</td>
<td>IP 23</td>
</tr>
<tr>
<td>Type of cooling</td>
<td>AF</td>
</tr>
<tr>
<td>Insulation class</td>
<td>F</td>
</tr>
<tr>
<td>EMC emission class</td>
<td>A</td>
</tr>
<tr>
<td>Marks of conformity</td>
<td>CE, CSA</td>
</tr>
<tr>
<td>Safety symbol</td>
<td>S</td>
</tr>
<tr>
<td>Dimensions l x w x h</td>
<td>626 x 287 x 477 mm</td>
</tr>
<tr>
<td></td>
<td>24.65 x 11.30 x 18.78 in.</td>
</tr>
<tr>
<td>Weight</td>
<td>35.6 kg</td>
</tr>
<tr>
<td></td>
<td>78.5 lb</td>
</tr>
</tbody>
</table>

¹) connected to public grid at 230/400 V and 50 Hz  
²) d.c. = Duty cycle