A Path Planning Method for Robotic Wire and Arc Additive Manufacturing of Thin-Walled Structures with Varying Thickness

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Abstract. Wire and arc additive manufacturing (WAAM) is a potential technology for manufacturing components with a shorter period of time and by a lower cost. Path planning is a key research interest in WAAM. This paper presents an adaptive path planning method for manufacturing thin-walled structures with varying thickness. Firstly, the straight skeleton, which represents the skeleton of a given geometry, is extracted to express the geometry. Then the deposition with weaving technology is applied to obtain required varied width of the geometry. The resulting adaptive paths are able to fill thin-walled structures with varying thickness less than twice of the single-bead width.

1. Introduction

Wire and arc additive manufacturing (WAAM), an additive manufacturing (AM) technology, has great prospects and potential due to its high deposition rate, high energy efficiency and low cost [1]. It is a deposition technology that employs either Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW) or Plasma Arc Welding (PAW) [1]. It has great advantages in manufacturing large scale components that are often seen in the fields of aviation and shipbuilding.

One of the essential steps in AM is the generation of paths, which determines the material accumulating process of the filling layers and has a dominating influence to the quality of the fabricated part. So far, many path patterns have been developed for AM to generate tool paths, such as raster, zigzag, contour, continuous, hybrid, etc. Generally, these path patterns are designed for universal applications with no considering structural speciality of the built part. As a result, it is often less satisfactory to apply these patterns in manufacturing thin-walled structures by WAAM because of its large width of the single bead [2]. Therefore, the path generation should be specially considered for manufacture of complex structures using WAAM.

To minimise the number of stopping-ending points in paths for WAAM, Ding D. etc. proposed a continuous path planning algorithm that can generate a closed tool path using a combination of zigzag and contour pattern strategies [3]. But it is not applicable for thin-walled structures. Based on medial axis transformation (MAT) which can represent the skeleton of a give geometry, Ding D. etc. proposed a practical path planning algorithm for WAAM to build thin-walled structures [2]. First, the skeleton is obtained through computing the bisector of each pair of segments. Then, branch loops are generated based on the skeleton considering the step-over distance. After that, each loop is offset from the inner part to the outer boundary of the geometry. The algorithm generates paths from inner to outside can avoid inner gaps that will occur using contour path patterns. However, this approach
generates too many discontinuous paths that are not desirable for WAAM. To solve this problem, an improved adaptive MAT algorithm [4] is proposed. The improved algorithm offsets the path loop with varying step-over distance. To fulfil the varying step-over distance, parameters need to be changed gradually to generate the desired bead width during the material accumulating process. Both of the above methods are designed for thin-walled structures having multi-bead width. However, when the thickness of the thin-walled structure is less than twice of the single-bead width, these methods are incapable of generating satisfactory paths.

This paper presents an adaptive path planning method for wire and arc additive manufacturing of thin-walled structures with varying thickness. The use of deposition with weaving technology in WAAM is explored. Based on the model of deposition with weaving, an adaptive path planning method for WAAM is proposed. Experiments validate the effectiveness of the method.

2. Deposition with weaving
Deposition with weaving is a technology used in welding applications to obtain wide weld beads. In related studies, it is proved to be of efficiency [5] and beneficial for the solute to diffuse [6]. To solve the problems in path planning of thin-walled structures with varying thickness, the deposition with weaving technology is studied in this paper.

2.1. Modeling of deposition with weaving
The applications of deposition with weaving is often carried out by industrial robots. In robot programs, there exists mainly three parameters to control the weaving movement of welding tools, namely, travel speed along a guiding line (\(v_t\)), amplitude (\(A\)) and weaving length (\(W_l\)), as shown in figure 1. Preliminary studies [4,7] show that the section profile of a weld bead without weaving can be fitted by a parabola curve. Thus, a simplified weaving bead model, mainly generated by scanning a parabola curve along the weaving trajectory, is presented, as shown in figure 2, to understand the bead generated by deposition with weaving. Given the travel speed (\(v_t\)) along the leading line, the nominal moving speed (\(v\)) along the weaving trajectory can be calculated as equation (1). Suppose the width of the bead generated with the calculated speed \(v\) is \(w_v\), then the width of the bead deposited with weaving is formed by equation (2). And the average bead height can be calculated as equation (3).

\[
v = \frac{4(A^2 + \left(\frac{W_l}{4}\right)^2)^{1/2}}{W_l} \cdot v_t
\]

(1)

\[
width = 2A + w_v
\]

(2)

\[
height = \frac{\pi \cdot r^2 \cdot v_w}{width \cdot v_t}
\]

(3)
where \( r \) is the radius of the wire material and \( v_w \) is the wire feed rate. Obviously, the amplitude has a great influence on the width of the weld bead.

![Weaving bead model](image)

Figure 2. Weaving bead model.

2.2. Regression model of process parameters

Practically, it is not easy to obtain the width of the bead \( (w_v) \) in figure 2. Therefore, a second degree regression model is adopted to establish the relationship between process parameters and bead geometry as equation (4),

\[
Y = CP
\]  

where \( Y \) is the bead width or height, \( P \) the combination of process parameters as shown in equation (5), and \( C \) the coefficient as shown in equation (6).

\[
P = \begin{bmatrix} 1 & v_w & v_r & W_l & A & v_w^2 & v_r^2 & W_l^2 & A^2 & v_w v_r & v_w W_l & v_r W_l & v_r A & W_l A \end{bmatrix}^T
\]  

\[
C = [c_0, c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8, c_9, c_{10}, c_{11}, c_{12}, c_{13}, c_{14}]
\]

![Deposited weld beads with different weaving parameters](image)

Figure 3. Deposited weld beads with different weaving parameters.

To determine these coefficients, totally 168 weld beads are deposited with different parameters (weave length from 2mm to 5mm and amplitude from 2mm to 8mm). Part of them are shown in figure 3. Then the widths of these beads are measured and the heights are calculated by equation (3). Part of the results are shown in table 1 (due to space limitations, only part of the data are listed). By using these data, the coefficients of the regression model are obtained as equation (7) and equation (8).
Table 1. Widths and heights of beads deposited with different parameters.

| No. | $v_u$(m/min) | $v_t$(m/min) | $W_l$(mm) | $A$(mm) | width(mm) | height(mm) |
|-----|--------------|--------------|-----------|--------|-----------|------------|
| 1   | 8            | 0.3          | 2         | 3      | 12.63     | 2.39       |
| 2   | 8            | 0.3          | 2         | 6      | 17.70     | 1.70       |
| 3   | 8            | 0.3          | 3         | 5      | 16.35     | 1.84       |
| 4   | 8            | 0.3          | 4         | 4      | 15.97     | 1.89       |
| 5   | 8            | 0.3          | 5         | 4      | 13.70     | 1.32       |
| 6   | 8            | 0.3          | 5         | 5      | 15.18     | 1.19       |
| 7   | 8            | 0.5          | 2         | 4      | 13.35     | 1.36       |
| 8   | 8            | 0.5          | 3         | 3      | 10.23     | 1.77       |
| 9   | 8            | 0.5          | 3         | 6      | 15.77     | 1.15       |
| 10  | 8            | 0.5          | 4         | 8      | 18.63     | 0.97       |
| 11  | 8            | 0.5          | 5         | 5      | 15.18     | 1.19       |
| 12  | 7            | 0.3          | 2         | 2      | 11.46     | 2.30       |
| 13  | 7            | 0.3          | 2         | 5      | 14.20     | 1.86       |
| 14  | 7            | 0.3          | 3         | 7      | 18.36     | 1.44       |
| 15  | 7            | 0.3          | 4         | 3      | 13.95     | 1.89       |
| 16  | 7            | 0.3          | 4         | 6      | 16.01     | 1.65       |
| 17  | 7            | 0.3          | 5         | 5      | 14.96     | 1.76       |
| 18  | 7            | 0.5          | 2         | 4      | 11.84     | 1.34       |
| 19  | 7            | 0.5          | 3         | 6      | 12.66     | 1.25       |
| 20  | 7            | 0.5          | 4         | 2      | 9.78      | 1.62       |
| 21  | 7            | 0.5          | 4         | 5      | 12.34     | 1.28       |
| 22  | 7            | 0.5          | 5         | 4      | 11.83     | 1.34       |
| 23  | 7            | 0.5          | 5         | 8      | 17.01     | 0.93       |
| 24  | 6            | 0.3          | 2         | 5      | 12.55     | 1.80       |
| 25  | 6            | 0.3          | 3         | 7      | 17.11     | 1.32       |
| 26  | 6            | 0.3          | 4         | 3      | 10.69     | 2.12       |
| 27  | 6            | 0.3          | 5         | 2      | 10.22     | 2.21       |
| 28  | 6            | 0.3          | 5         | 8      | 18.43     | 1.23       |
| 29  | 6            | 0.5          | 2         | 5      | 11.18     | 1.21       |
| 30  | 6            | 0.5          | 3         | 4      | 9.87      | 1.38       |
| 31  | 6            | 0.5          | 3         | 7      | 13.72     | 0.99       |
| 32  | 6            | 0.5          | 4         | 6      | 12.27     | 1.11       |
| 33  | 6            | 0.5          | 5         | 5      | 11.14     | 1.22       |
| 34  | 6            | 0.5          | 5         | 8      | 15.83     | 0.86       |
where $C_w$ and $C_h$ are calculated using the width and height data, respectively. The mean errors for the width and height model are 4.99% and 5.57%, respectively. By combination of equations (4) to (8), regression models for width and height can be obtained as equation (9) and equation (10). Using the regression models, the width and height of the weld bead can be predicted directly from process parameters.

$$\text{width} = C_w P$$  \hspace{1cm} (9)

$$\text{height} = C_h P$$  \hspace{1cm} (10)

3. Path planning method
Generally, in path generation for AM, CAD models in STL format are sliced, obtaining 2D polygons. Then within each polygon, paths are generated to fill the inner area of the polygon. The adaptive path planning method presented in this paper is based on straight skeleton and the deposition with weaving technology discussed above.

3.1. Straight skeleton
The straight skeleton is first defined for simple polygons by Aichholzer et al. [8,9] to describe a geometry by a topological skeleton which is defined by a continuous shrinking process in which the edges of the polygon are moved inwards parallel to themselves at a constant speed. As the edges move in this way, the vertices where pairs of edges meet also move. Finally, the straight skeleton is the set of straight lines traced out by the moving vertices. The computation of the straight skeleton can be performed by simultaneously parallel offset the polygon edges. In a planar polygon, as shown in figure 4a, each skeleton edge (the red line) is a bisector of two polygon edges. For each endpoint of a skeleton edge, the distance between the endpoint and one of the corresponding two polygon edges is computed. Then the width of the polygon at the endpoint position is twice the distance. The centerline of the polygon can be roughly defined by comprising all skeleton edges that are not incident to a vertex of the polygon. It is an approximation of the medial axis of the polygon. For each free-end edge in the centerline, it is extended to intersect with the polygon edge, as shown in figure 4b.

![Figure 4.](image)

**Figure 4.** Straight skeleton and centerline (a) straight skeleton (b) centerline of the polygon.

3.2. Parameter determination
In the process of WAAM, the welding torch moves along the centerline of the polygon. The task of the path generation process is to determine the parameters adopted in the torch movement process. To complete the task, first, the layer height is artificially specified in the slicing procedure. Then, for each
edge of the centerline, it is divided into several line segments. The number of the line segments, \( n \), is determined by equation (11)

\[
2 \leq W_i = \frac{L_e}{n} \leq 8
\]  

(11)

where \( L_e \) is the length of the edge. Suppose the endpoints of an edge are \( P_s \) and \( P_e \), and the widths of the polygon at the endpoints of the edge are \( w_s \) and \( w_e \). After division, there will be \( n-1 \) interpolation points on the edge, as shown in figure 5. The interpolation points and corresponding widths are calculated as equation (12) and equation (13). For each line segment, if the widths of the polygon at the two endpoints are not the same, the large one is selected as the width of the line segment. In this way, the polygon is approximated by a series of rectangles, as shown in figure 6.

\[
P_i = P_s + \frac{i}{n}(P_e - P_s)
\]

(12)

\[
w_i = w_s + \frac{i}{n}(w_e - w_s)
\]

(13)

Figure 5. Division of an edge.

Figure 6. Approximation of a polygon.

From an robot-moving viewpoint, if the nominal moving speed is constant during the movement of the torch, the robot runs much smoothly. Thus, another limitation can be obtained as equation (14)

\[
4(A^2 + \left(\frac{W_i}{4}\right)^2)^{1/2} = \frac{W_i}{V_i} \cdot v_i = const
\]

(14)

where \( const \) is a constant value which is artificially specified. According to the specified layer height and the computed width using equation (13), bringing equations (11) and (14) into equations (9) and (10), the parameters for each line segment can be calculated.

The line segments and corresponding process parameters form the adaptive paths for wire and arc additive manufacturing of thin-walled structures.
4. Experiments and discussions

To validate the effectiveness of the proposed path planning method, experiments are designed and executed by a robotic wire and arc additive manufacturing system as shown in figure 7. A KUKA robot controls the movement of a welding torch and a welding machine control cabinet controls the electrical arc and wire feeding process. A 2-axis tilt and rotatory positioning platform serves as the workbench.

Two structures are deposited to demonstrate the ability of the proposed method. One is a polygon structure with a gradually varying thickness from 10mm to 20mm as shown in figure 8. Though the polygon is approximated by a series of rectangles, no obvious staircase shapes, as shown in figure 6, are observed in the manufactured part. The other is a structure with a sharp changing thickness, from 9mm to 18mm, as shown in figure 9. It can be seen that the sharp change of the thickness is well reflected in the manufactured part. The experimental results show that the proposed method is an effective method for robotic wire and arc additive manufacturing of thin-walled structures with varying thickness.

![Figure 7. Robotic wire and arc additive manufacturing system.](image7)

![Figure 8. A polygon structure with a gradually varying thickness.](image8)
Figure 9. A structure with a sharp changing thickness.

5. Conclusion
This paper proposes a path planning method for building thin-walled structures with varying thickness by robotic WAAM. The deposition with weaving technology is detailed studied. A second degree regression model is established to describe the relationship between process parameters and bead geometry. The centerline of a polygon and varied process parameters generate the adaptive paths for robotic WAAM. Manufacturing examples demonstrate that the proposed method is an effective strategy for building thin-walled structures with varying thickness.

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6. References
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