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Towards an automated robotic arc-welding-based additive manufacturing system from CAD to finished part

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ABSTRACT

Arc welding has been widely explored for additive manufacturing of large metal components over the last three decades due to its lower capital cost, an unlimited build envelope, and higher deposition rates. Although significant improvements have been made, an arc welding process has yet to be incorporated in a commercially available additive manufacturing system. The next step in exploiting "true" arc-welding-based additive manufacturing is to develop the automation software required to produce CAD-to-part capability. This study focuses on developing a fully automated system using robotic gas metal arc welding to additively manufacture metal components. The system contains several modules, including bead modelling, slicing, deposition path planning, weld setting, and post-process machining. Among these modules, bead modelling provides the essential database for process control, and an innovative path planning strategy fulfils the requirements of the automated system. A user friendly interface has been developed for non-experts to operate the developed system. Finally, a thin-walled aluminium structure has been fabricated automatically using only a CAD model as the informational input to the system. This exercise demonstrates that the developed system is a significant contribution towards the ultimate goal of producing a practical and highly automated arc-welding-based additive manufacturing system for industrial application.

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1. Introduction

Additive manufacturing (AM) has been used successfully for single-unit production in various sectors, owing to the paradigm shift that the process provides over conventional manufacturing. When it comes to metal AM, aerospace appears to be leading the way, seeing opportunities to produce light-weight components, reduce manufacturing lead-times, and improve the buy-to-fly ratios [1–5]. While much development is focused on powder-based processes for fine detail in small parts, commercially available equipment is limited in terms of part build envelope and build rate, especially in aerospace applications [6]. As a consequence, robotic wire-feed AM processes have attracted extensive research interest due to their ability to produce large parts (up to 5.8 m × 1.2 m × 1.2 m was reported) with high deposition rate (ranges from 3 to 9 kg/h) [7].

Arc-welding-based additive manufacturing is one of the wire-feed AM technologies, and uses either the gas metal arc welding process (GMAW) or the gas tungsten arc welding process (GTAW) [8]. The advantages of such a system over existing additive manufacturing systems include lower capital cost, a much larger build envelop, higher production rates, and a strong supply chain capability in industry [9]. A large amount of work has been done over the previous three decades to develop the ability to produce parts from weld deposits using a layer-by-layer approach. Early studies exploring arc welding for AM have been reported by European researchers [10–12]. The ability of arc welding to produce high quality near-net shapes has been confirmed. A preliminary automated system for welding-based AM was developed by Zhang et al. [13]. The deposition parameters, including the travel speed, welding current, and arc voltage were discussed in detail. Hybrid approaches to "3D welding and milling" have been established to fabricate parts with a high quality surface finish [14,15]. The effects of bead modelling and process optimisation in arc-welding-based AM were also investigated [16–18]. Recently, vision-sensing systems have been designed to on-line monitor and control the robotic arc welding process to

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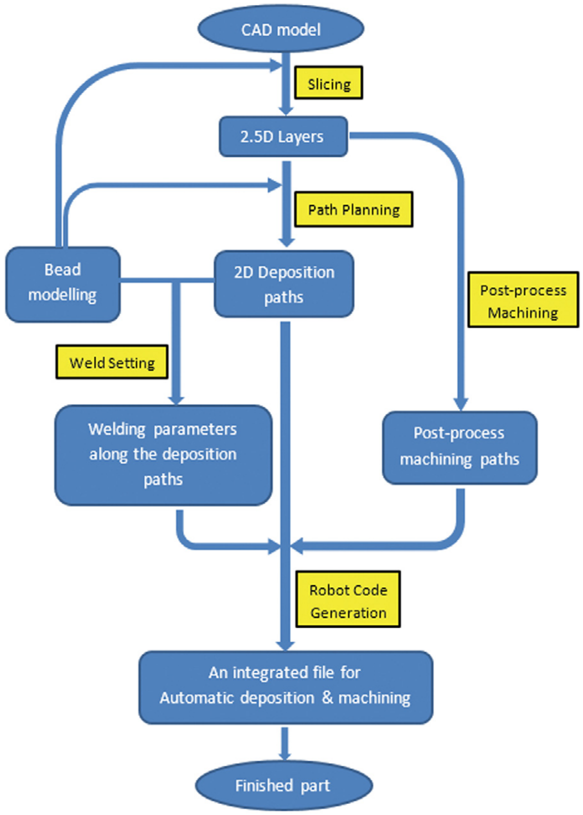

Fig. 1. A schematic diagram of the automated process planning algorithm of an arc-welding-based additive manufacturing system.

deposit the desired geometry [19–21]. Several other organisations throughout the world continue to work in this exciting field of arc-welding-based AM [22–27].

Although several advancements have been made, an arc welding process has yet to be incorporated in a commercially available additive manufacturing system. This is due to the lack of an automated process planning strategy that is able to set all of the process parameters [7]. Process parameters such as deposition path, wire-feed rate, and travel speed, as far as we know, are mainly set by an experienced AM technologist depending upon part geometry, energy source, and the material selected. Accordingly, the next step towards a "true" wire-feed additive manufacturing system is to develop the automation software needed to produce seamless CAD-to-part capability.

This study aims at the development of a fully automated arc-welding-based AM system, which reads only the CAD model as an input and produces the finished part without human intervention. Section 2 introduces briefly the developed automated arc-welding-based AM system. Section 3 establishes bead modelling, followed by the MAT-based path planning in Section 4. Section 5 describes the experiments that validate the system and discusses the result.

2. Automated arc-welding-based additive manufacturing system

An automated process planning algorithm for an arc-welding-based additive manufacturing system from CAD model inputs to finished parts is shown in Fig. 1. Several modules are essential including slicing, path planning, welding parameter setting, post-process machining, and the robot code generation module.

The 3D CAD model in STL format is firstly sliced into a set of 2.5D layers through the slicing module. Slicing algorithm of 3D STL model has been widely reported [28]. In this paper, a tolerant slicing algorithm was used and detailed information could be found elsewhere [29].

Then the path planning module generates deposition paths for each of the sliced layers. After the paths are generated, the desired bead geometries along the path are determined accordingly.

Bead modelling controls two of the key slicing and path planning variables, namely layer thickness and step-over distance (to be defined in Section 4), respectively. In addition, it determines the optimum welding parameters corresponding to the desired bead geometry. Welding parameters are mainly wire-feed rate, travel speed, and stick-out length for the GMAW process in this study.

The post-process machining module generates machining tool paths for the post-weld machining process. With the geometries of the sliced layers, the machining paths are easily generated by outside offsetting the boundaries of the layers with the half of the machining tool diameter.

Subsequently, the welding deposition paths together with the automatically-selected welding parameters and the machining tool paths are transformed into an integrated robot code file through the robot code generation module.

Finally, a near-net shape deposit is produced automatically by the robotic arc welding system and the finished component with the desired dimensional tolerances is obtained through robotic machining.

For arc-welding-based processes, the bead geometry is highly dependent on both material and processing parameters. Therefore, accurate bead models are required to be established through experiments. In this study, aluminium material and the GMAW process are chosen as the experimental example. The automated process planning strategy in its current form can be applied to other materials (mainly steels) and also the GTAW deposition process.

In the operation of this automated system, automatic path planning required special attention to accommodate the geometrical complexity of parts that need to be manufactured in practice. Therefore, the bead modelling and path planning modules are selectively presented in the following Sections 3 and 4, respectively.

Table 1
Input process parameters.

Parameters	Factor levels			
	Level 1	Level 2	Level 3	Level 4
Wire-feed rate, F (m/min)	5.0	5.7	6.4	7.0
Travel speed, S (m/min)	0.35	0.46	0.58	0.7
Stick-out, L (mm)	9	11	13	15

3. Bead modelling

3.1. Inputs and responses

Fig. 2 shows the typical weld bead geometry with bead height (h) and bead width (w). Through adjusting process parameters such as wire-feed rate and travel speed, different bead profiles can be obtained. Based on the effect on weld bead geometry of aluminium material, the chosen input factors for this study are wire-feed rate (F), travel speed (S), and stick-out length (L); the responses are bead height (h) and bead width (w). The values of the chosen process variables at various levels are presented in Table 1.

3.2. Artificial neural network (ANN)

The artificial neural network has been demonstrated to be a powerful tool for representing complex relations between multiple

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