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

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

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

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ABSTRACT

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

1. Introduction

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

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

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

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* Corresponding author.
E-mail address: florent.michel@cranfield.ac.uk (F. Michel).

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enabling a complete commercial solution. In fact, many studies have focused on this particular topic from which two mains approaches can be distinguished.

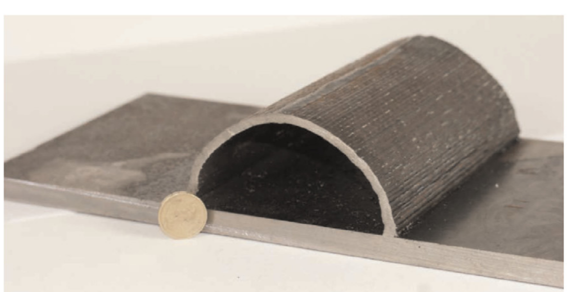
The first approach is to slice a geometry and to generate a path using the same path planning strategy, for each resulting layer. Although this solution has been successfully used on other AM process such as FDM [6], it is not directly applicable to WAAM, which has specific requirements inherent to arc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

The alternative approach is the feature-based design introduced by Kazanas et al. [11]. In their research, they demonstrated WAAM's ability to build complex parts like enclosed structures by designing a path strategy that fits the requirement of this particular targeted shape. This solution has been then followed by the development of cross structures [12], T-crossing features [13] and more recently, multi-directional pipe joints [14] (Fig. 1). Thus, this approach has shown that designing a path strategy ad hoc for a given topology guarantees the deposition quality; however, this solution requires a time-consuming path design research for each new part, which is incompatible with the purpose of AM.

Furthermore, one must bear in mind the fundamental differences between powder-bed AM and directed-energy deposition AM. In the former, the layer height is fixed by the downward movement of the build platform and the consistency between thickness of the sliced layers in pre-processing, and thickness of the layer built is somehow always ensured. The latter, instead, is closer to micro-casting, and numerous factors can influence the shape of the deposited bead (width and height). One of these factors is the local variation in the part geometry. This means that even if the same set of parameters is used, the resulting bead geometry can vary. Imagine a linear deposit; in such a case there is a balance between energy introduced, energy conducted away, energy used to melt the wire, and energy used to melt the underlying material. In this steady state, the resulting geometry does not change. However, when that linear structure changes into an intersection, the energy balance is disturbed; more heat is conducted away; the melt pool would shrink resulting in thinner wall width, and larger layer height, if no compensation is applied to the process parameters. Therefore it is absolutely essential that parameters are changed ad hoc to compensate for such variation and to ensure that the geometry obtained is the same as that expected per sliced CAD file, and no errors are accumulated throughout the build. This is also why simple reverse-machining strategies, which fill the sliced layers, cannot be applied.

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

The following Section presents the MPP concept and defines the rules and the decomposition process to guarantee the uniform



(a) Enclosed structure [11]

(b) Cross intersection [12]

(c) T intersection [13]

(d) Pipe joints [14]

Fig. 1. Structures examples build using a feature-based design approach.

deposition of a layer. Then, Section 3 describes the MPP implementation that reduces user inputs to basic CAD modelling operations. To describe the entire solution, an application example is presented in Section 4. Section 5 compares the MPP to a traditional path solution and shows its ability to build complex parts for industry. Finally, in Section 6, the benefits and limits of the presented solution are discussed, followed, in Section 7 by the conclusion and the presentation of future work.

2. Theoretical approach

2.1. Slicing

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

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

2.2. Segmentation

Segmentation is the fundamental idea of the MPP to integrate modularity into the path design process. Indeed, where a traditional approach would apply a single path planning on the entire layer, the MPP requires users to segment the given layer into sub-parts called sections (Fig. 3) to then generate individual paths.

The purpose of this segmentation step is to create a set of sections shaped into basic geometries, usually narrow rectangular shapes, to facilitate their deposition. However, the optimum segmentation is determined based on experience and is highly dependent on the part geometry. Nevertheless, some basic rules need to be followed. For example, if curved trajectories can be deposited, sharp turns should be avoided, and instead replaced by corner intersections (Fig. 4). Similarly, if a slight width variation does not alter the deposition (Fig. 5a), an abrupt width variation can create irregular paths (Fig. 5b) leading, layer after layer, to significant defects. Therefore, to avoid those irregularities, it is preferred to divide this part in multiple sections (Fig. 5c).

The sections shape is fundamental to provide a controlled deposition but, to assure uniform deposition of the entire layer, it is also crucial to provide particular attention to the topology of the intersections since poor junctions can create critical defects in the final part. As it can be seen in Fig. 6, many junction configurations are possible when using only parallel and oscillated paths. Some of these intersections can be more complicated to deposit than others as they are more likely to produce defects. In any case, an appropriate research study should be conducted on each intersection type to determine deposition parameters that will assure a defect-free junction.

2.3. Path planning

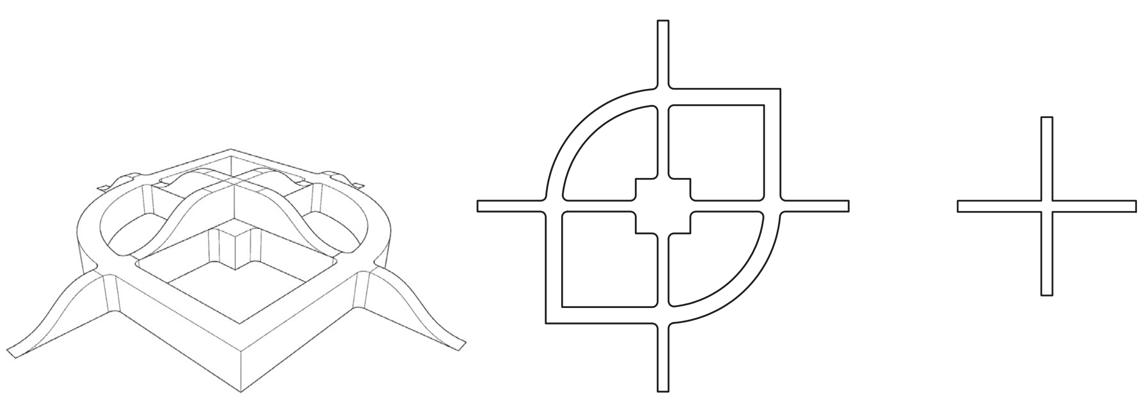
Once the layer has been segmented, a path can be generated in each section. An advantage of the segmentation is that, compared to the traditional approach, multiple path planning strategies can be used across a single layer to best fit the requirement of each section.

Any path planning strategies can be used to build those individual paths, however, the oscillated path (Fig. 13a) is the most recommended since it can handle width variation and slight curve very well, and therefore its deposition is easier to control. Nevertheless, the parallel path (Fig. 13b) can also be an adequate alternative, especially when used to build narrow shapes since it produces smoother surface waviness [16]. Still, interconnections can be more problematic when using parallel paths.

2.4. Zoning

As mentioned previously, although path design improves the deposition uniformity significantly, appropriate deposition parameters are essential to control the deposition. Deposition parameters depend on the geometry; on the location within a part; on the material being deposited and on the chosen WAAM sub-process (MIG, TIG, plasma, etc). For those reasons, the MPP adopts a concept of zones: where a zone, identified by a colour, contains a particular set of parameters (Fig. 7a) to be specified by the user after the path planning phase.

Thus, as it can be seen in Fig. 7a, a simple straight wall contains three zones to accommodate the different thermal conditions in the stages of deposition start, steady state, and end. This must be done whichever path is used: single bead, oscillated or parallel. Additionally, if a section contains a notable width variation requiring specific deposition parameters, a zone can be defined to account for that change in width, and to manually adapt the parameters locally (Fig. 7b). However, this situation could also be solved by using an algorithm that would calculate automatically the parameters needed to produce the desired layer width and height. Finally, because the heat dissipation is drastically different at the intersections, it is crucial to create zones at those locations (Fig. 7c), as explained in the Introduction Section.



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

Fig. 2. Example of topology variation.

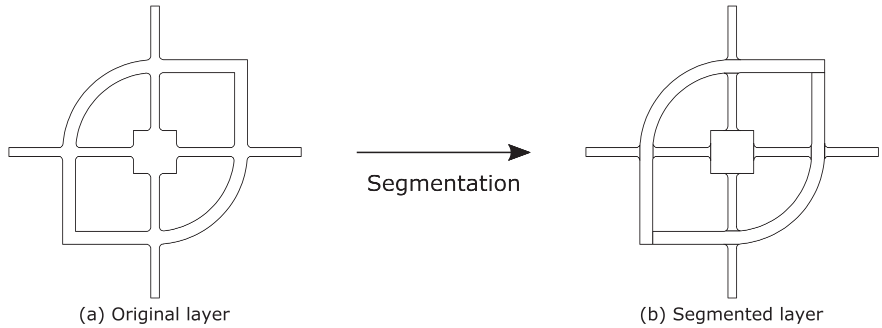


Fig. 3. Example of a layer segmentation.

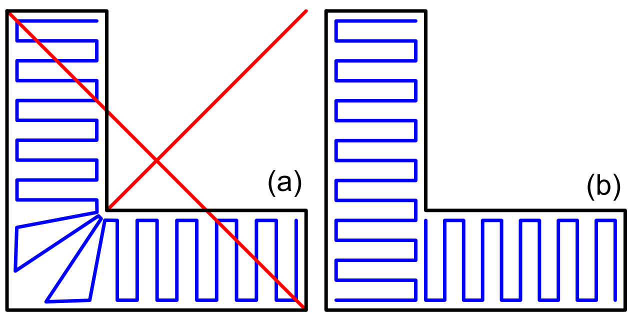


Fig. 4. Sharped turn (a) vs corner division (b).

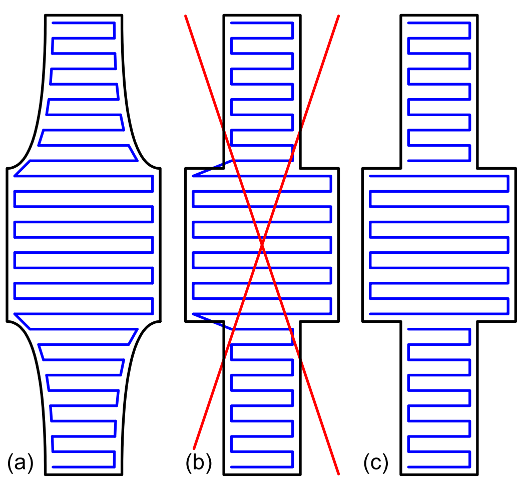


Fig. 5. Path generation through width variation.

2.5. Layer path

Once a path has been generated for all sections, they are combined into a single layer path. However, it is important to highlight that the deposition is not continuous along the entire layer. Instead, when reaching the end of a section, the deposition is stopped and the torch moves to the starting point of the following section with the arc off and without feeding any material (Fig. 8).

Sorting algorithms [17] can be used to reduce downtime by defining a better order of deposition. Yet, a particular deposition order can benefit some intersections. Indeed, in the case of the perpendicular intersection of oscillated paths (Fig. 6b), depositing section 2 after section 1 helps to melt the waving border at the junction reducing risk of voids. Moreover, the deposition sequence has a significant impact on distortion [18,19] and should, then, be taken into consideration to minimise buckling risk.

Finally, once the path of the first layer is made, the same methodology can be applied to each following layer, generating a set of layers

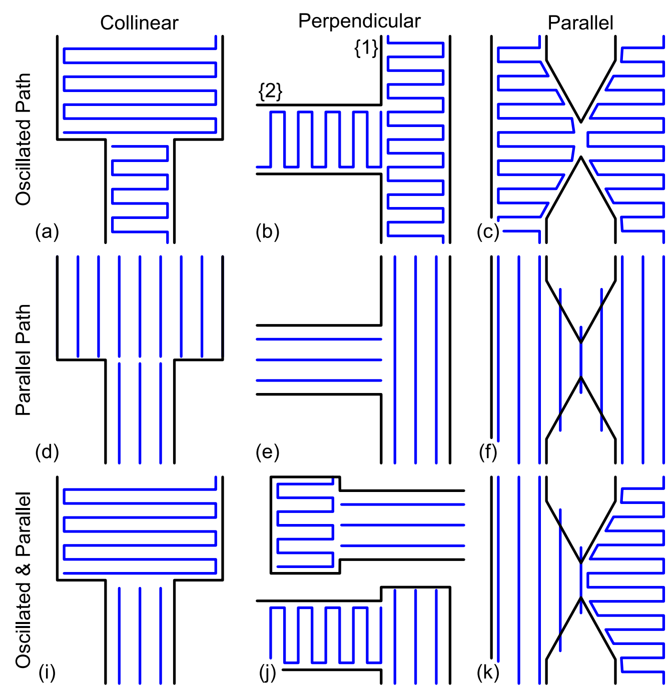


Fig. 6. Path intersection examples.

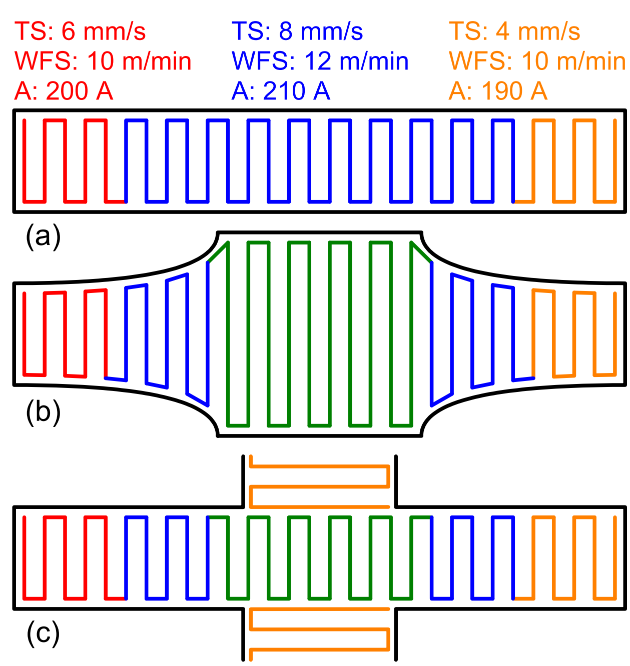


Fig. 7. Zones definition.

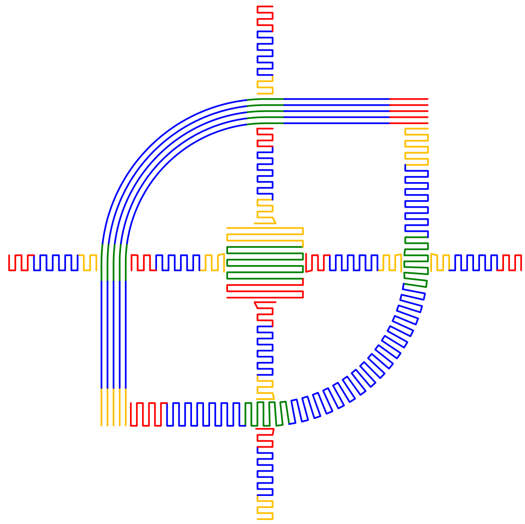


Fig. 8. Layer path.

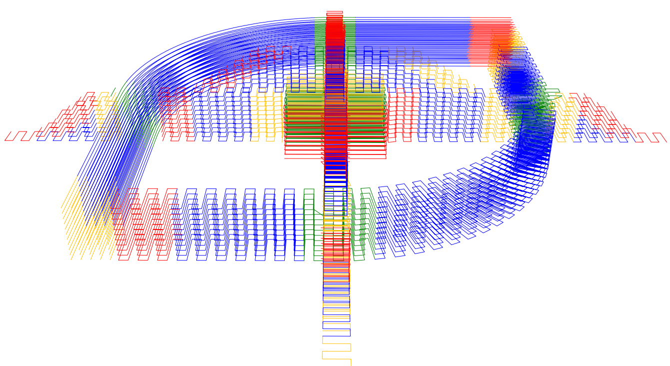


Fig. 9. Full part path.

that can be combined to build the entire part (Fig. 9).

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

3. Practical approach

3.1. Slicing

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

3.2. Building Strategy (BS)

The MPP solution aims to build a part by individually generating the path of each layer. However, as explained previously, the path planning of a layer can be laborious since it consists of partitioning the layer into simple sections (Segmentation); generating the appropriate paths for each section (Path planning) and integrating zones into each section (Zoning). Therefore, to avoid complex CAD modelling operations, the following Sections introduce a three-step process called Building Strategy (BS) (Fig. 10). This process offers users the ability to outline the desired layer path configuration with basic CAD inputs while, in the background, the application processes the technical CAD operations to generate the actual path.

3.2.1. Segmentation

For their first intervention, users are asked to identify each section of an extracted layer by following the rules defined in the theoretical approach (Section 2). Firstly, the active layer is shown in the background (Fig. 11a). Secondly, the user overlays planar closed-curves on the targeted sections (Fig. 11b). Thirdly, following the user's input, the software extracts automatically and instantaneously the sections (Fig. 11c) by applying a boolean intersection function (Fig. 12).

The result of this operation is multiple empty sections represented by their boundaries as planar closed curves (Fig. 10). However, no path can be generated yet since it requires an additional user intervention as described in the following Section.

3.2.2. Path planning

Once the layer is divided into sections, a path planning strategy needs to be applied to each section to generate paths. As mentioned

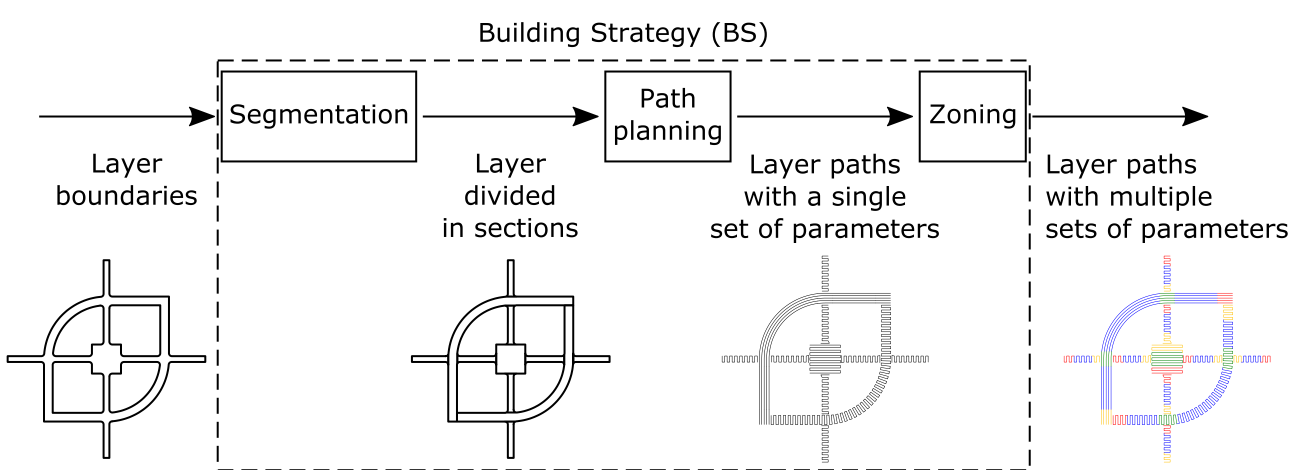


Fig. 10. Building Strategy flowchart.

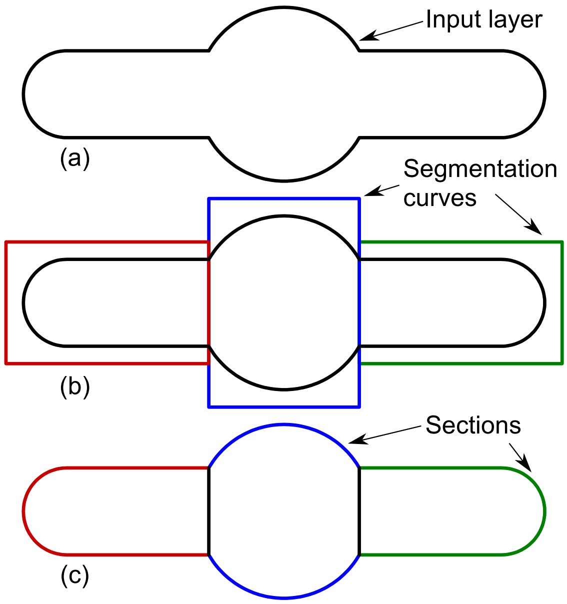


Fig. 11. Segmentation process.

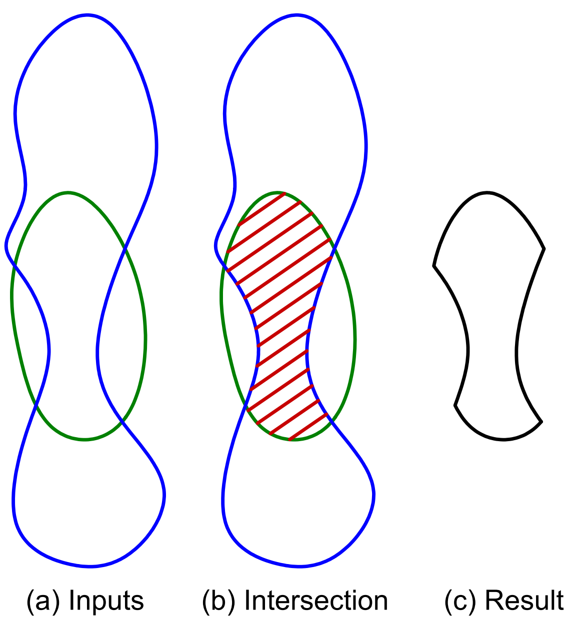


Fig. 12. Boolean intersection function.

previously, any path planning solution could potentially be implemented, however, in this paper only the oscillated and parallel deposition strategies are presented (Fig. 13). In general, at this point, users pick the best deposition strategies between those available, to best meet the requirements of the targeted geometry.

However, given that sections are mere planar closed surfaces, other information is needed. Firstly, the user must specify the direction of travel by drawing a guide. As can be seen in Fig. 13, a guide is a planar curve that specifies the deposition direction. If the oscillated path has been selected, it will be produced by generating an oscillation perpendicular to the guide-line, and with constant step-advancement. If the parallel path has been selected, a series of equidistant paths parallel to the guide will be produced. Moreover, intersections between the guide and the section boundary will represent the start and stop of the deposition. In fact, the guide must intersect the section's boundary exactly twice.

The result of this operation is an automatically generated path for each section (Fig. 10). It is essential to understand that these paths are not interconnected; meaning that during the deposition stage the manipulator will go from a path to another by stopping the deposition and retracting the end-effector.

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

3.2.3. Zoning

In the theorical approach (Section 2.4), a concept of zones has been presented to facilitate the integration of various deposition parameters across sections assuring a uniform deposition. The zoning method, presented here, allows users to define zones intuitively within a section.

By default, the path generated in a section is automatically associated with a zone (Fig. 14a), meaning that all movements in this newly generated path are sharing the same deposition parameters. From this state, the user can split the main zone in two by simply locating a point on the path (Fig. 14b). Thus, knowing the location of the point, the software regenerates a new path and changes the parameters dataset reference whenever it passes over a splitting point. This process can then be repeated to generate the necessary number of zones (Fig. 14c).

Alternatively, users can zone the path by defining a length at the beginning and/or at the end of this path (Fig. 14d). The benefits of this solution are detailed in Section 3.3 but are mainly related to the fact that arc-based deposition requires particular parameters at the ignition and termination stages for a limited length.

Finally, it is important to notice that both of these alternatives can be used simultaneously (Fig. 14f), giving substantially more flexibility to the user throughout the process.

At this stage, all required inputs for building a layer are completed, and the software can, therefore, combine all the generated section paths into a single layer path (Fig. 10). However, although this process is fast and straightforward to produce a single layer, repeating it over hundreds of layers can still be tedious.

3.3. Mask and 3D zoning

All the inputs needed to generate the path of a layer can be grouped into one entity, the mask (Fig. 15). The advantage of this approach is that the same mask can be used over multiple layers. In fact, as can be seen in Fig. 16, even when each extracted layer is slightly different (Fig. 16a), applying a unique mask to all layers (Fig. 16b) results in a path accommodating layer boundaries and users' instructions, for each

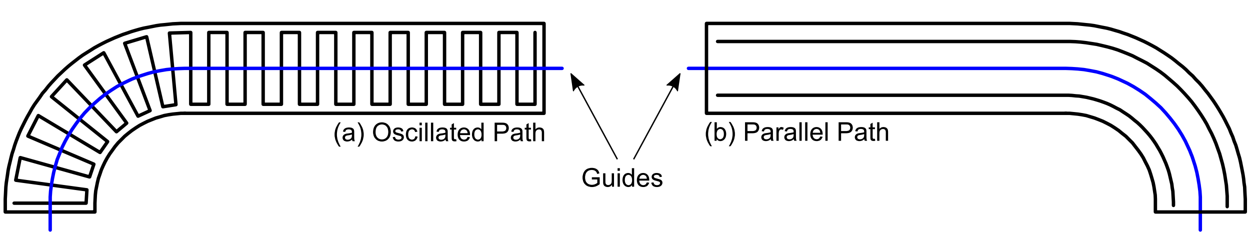


Fig. 13. Guides definition and path strategy examples.

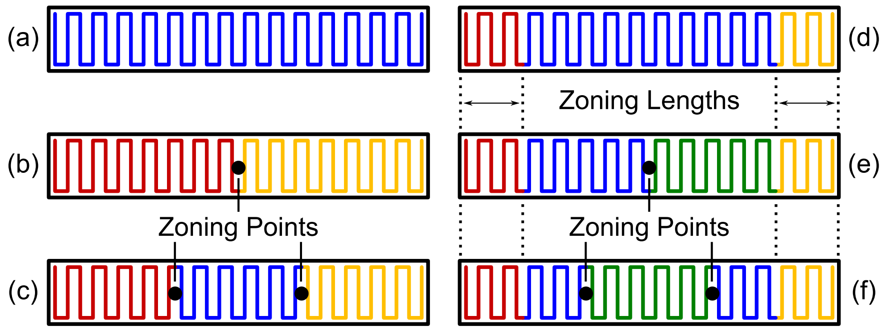


Fig. 14. Zoning.

layer (Fig. 16c).

In fact, this mask property is at the core of the MPP to reduce user's interventions. Indeed, once users have defined the first layer mask, the software solution can automatically apply this mask to the following layers. However, if the input geometry contains various layer topologies as can be seen in Fig. 17, the program may fail to generate a path: for instance, when a single segmentation curve would produce two independent closed sections. In this situation, the software raises an exception, stops the path generation and asks users to create a new Building Strategy (BS) mask for the failed layer. This new mask is then used to generate automatically the current and following layers until a new exception is raised or the last layer is reached. Please note that users have the opportunity to integrate a new BS mask at any layer. Indeed, in some situations, although the software correctly generates a path using the previous mask, users can consider having a better alternative for the current and following layers.

The mask concept also enables 3D zoning. Indeed, the zoning process described in Section 3.2.3 provides two alternatives to define a zone using zoning points or zoning lengths. If this can seem redundant in 2D, this combination gives the user better control over the zoning definition of a 3D CAD model. Indeed, having the ability to mix points and lengths enables the user to define which zones can vary when the boundaries are changing across layers. To clarify the 3D zoning control, a simple example is shown in Fig. 18. In this example, zoning lengths are applied to the section to accommodate the arc welding behaviour at the ignition and termination of the deposition (Green and Red). Additionally, zoning points are located in the middle of the section to define a particular zone (Yellow zone) as an intersection. The result of this combination is that the green, yellow and red zones keep a constant length over the different layers, while the blue and purple zones adapt their length. In such a way, users can easily control the zones configuration across multiple layers.

3.4. Deposition parameters

Deposition parameters are deliberately omitted throughout the MPP process, so the user can focus entirely on the path architecture. Indeed, users are only asked to describe when those parameters need to be changed using the zoning method (Section 2.4).

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

As shown in Fig. 19, the XML file is structured consistently to the MPP process. It contains a node for each layer; within each node, there are sections; within each section, there are the different zones, also identified by their colour; and inside the zones, the user then inputs the various deposition parameters (f.i. Current, Wire Feed Speed (WFS), Travel Speed (TS), etc).

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

4. Application

In this Section, a complete step-by-step example of the MPP solution is presented using the geometry seen in Fig. 2. To generate this example, the MPP method has been implemented into the Rhinoceros 3D software and its extension Grasshopper. This extension facilitates the development of innovative solutions thanks to its intuitive and powerful interface.

The first step is to slice the input geometry into layers: to achieve it, users define the various layer heights (Section 2.1) and the slicing

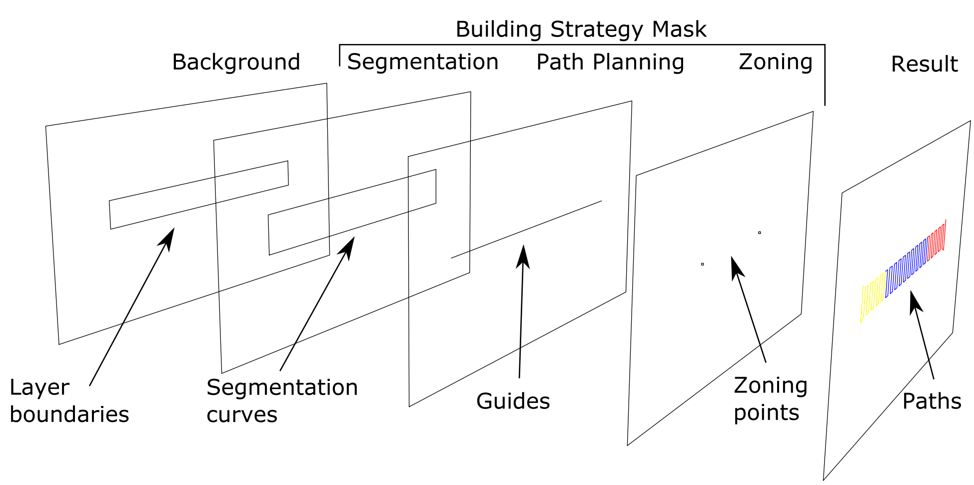
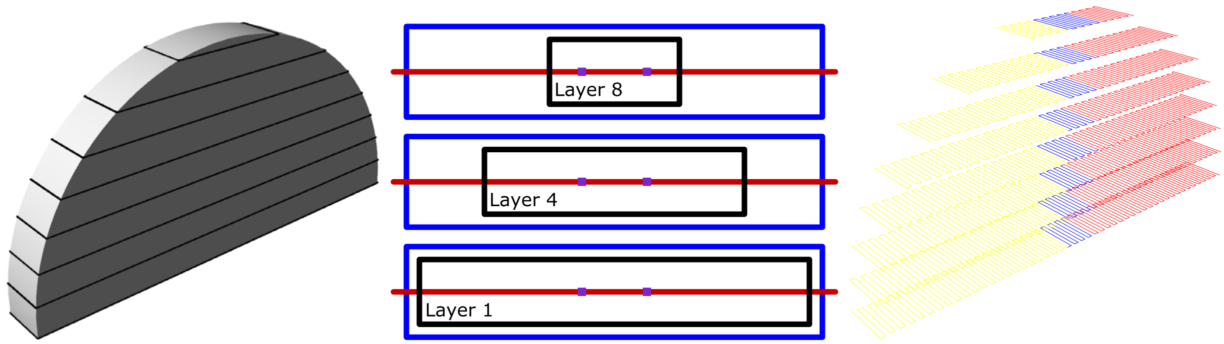


Fig. 15. Definition of the Building Strategy mask.



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

Fig. 16. Application of a single mask across multiple layers.

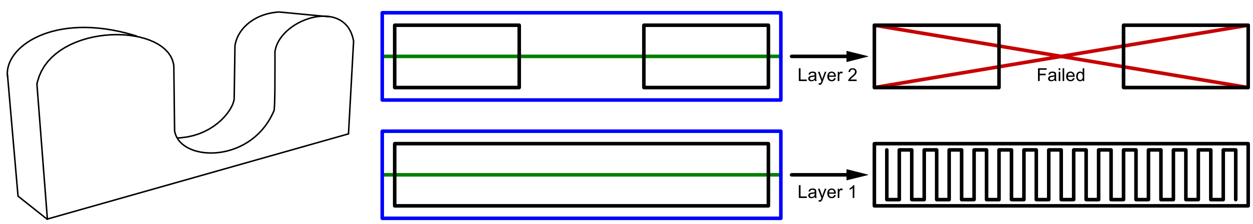


Fig. 17. Example of a failing mask application.

orientation. The resulting layers are then automatically aligned on the top view (Fig. 20), waiting for the user to start the next step.

From this stage, users are asked to define the mask of the first layer by following the three-step BS process described previously (Section 3.2). By drawing segmentation curves, guides and zoning points over the layer, the software generates the first path automatically (Fig. 20). Users can then verify the result and modify their inputs if required.

The first mask is applied automatically to the following layers until an exception is raised (Section 3.3). In this example, the program fails to generate the layer 25 since this layer topology is drastically different from layer 24. Therefore, users are asked to draw a second mask (BS 2) that fits the requirement of layer 25. Using the second mask, the program resumes the path generation from layer 25 until the last one.

When all layers are successfully processed, all the paths are automatically grouped into a single path as seen previously in Fig. 9 (Section 2.5). At this stage, users can inspect the resulting path of the entire geometry and, if needed, can modify an input mask. Any modification would then be applied to all the layers impacted by this mask.

Before starting the actual deposition process, users have to define the deposition parameters by filling the XML file generated automatically with the path (Section 3.4). Once all the parameters are set, the path can be processed by a robotic software solution to generate the appropriate machine code, which will be used to finally start manufacturing.

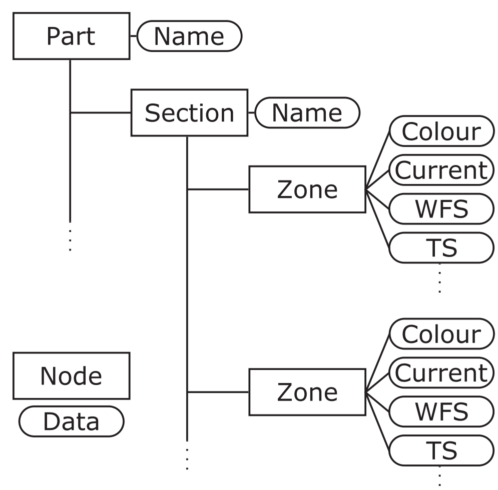


Fig. 19. XML structure of the deposition parameters.

5. Validation

A test-piece, shown in Fig. 21, was designed to validate the MPP approach. For comparison, the test-piece was also built using a path planning strategy available in the academic literature. The deposition parameters for the Ti-6Al-4V alloy were chosen based on the target

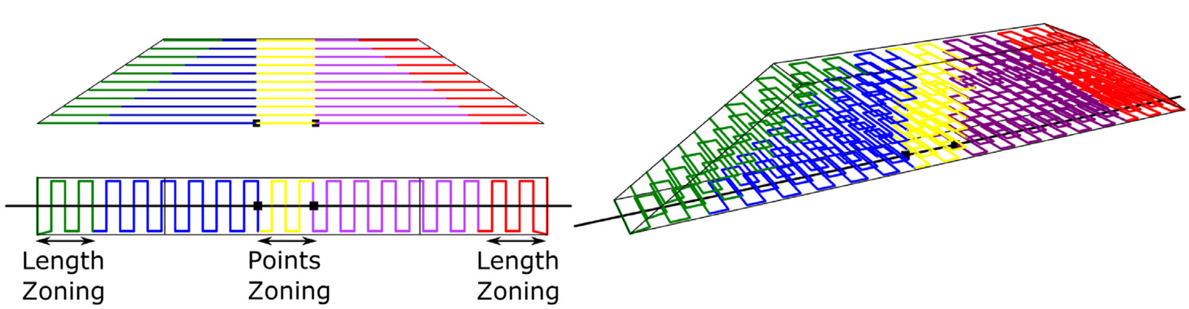


Fig. 18. Example of the 3D Zoning application.

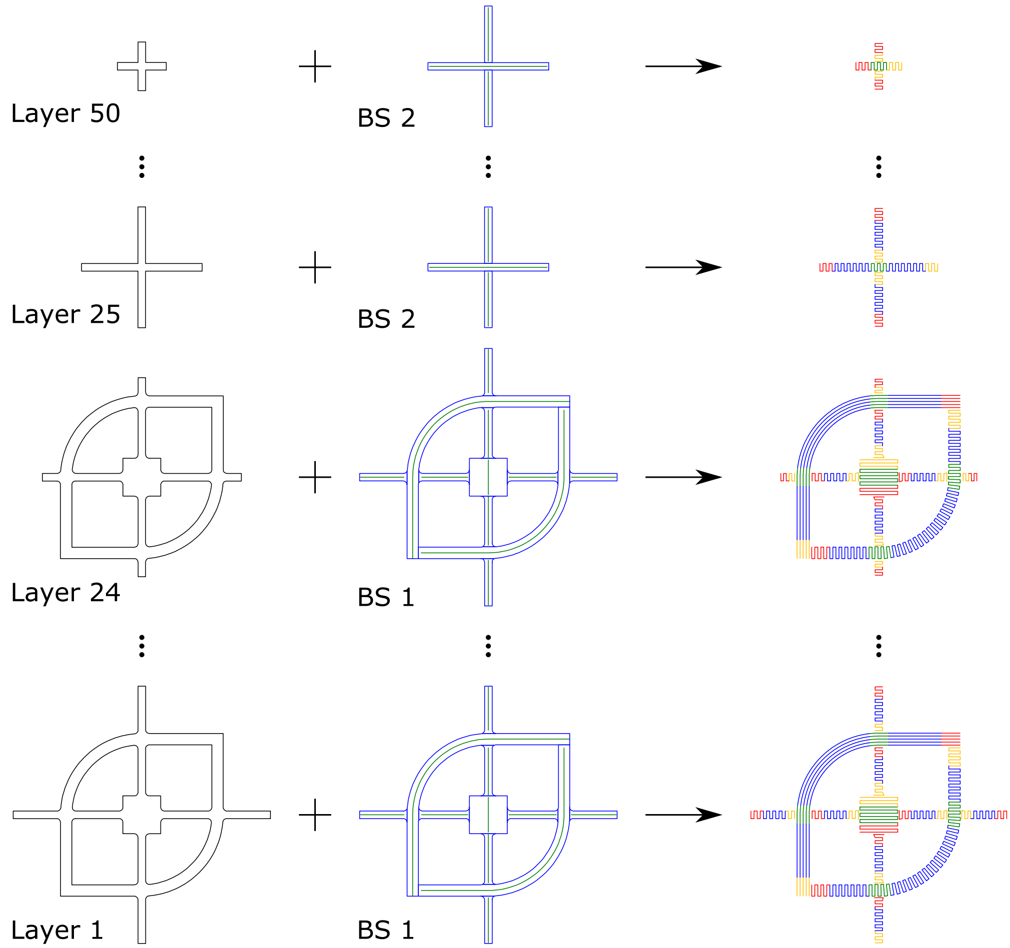


Fig. 20. Description of the Modular Path Planning process.

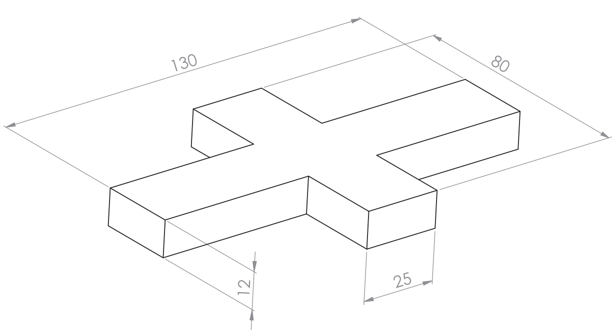


Fig. 21. Test piece designed to validate the MPP approach. All dimensions in mm.

baseline bead width and height of 6 mm and 1.5 mm, respectively. Regardless of the approach, eight layers were deposited to attempt reaching the desired height of 12 mm.

Four different tests were performed. The first test used the adaptive path planning method described by Ding et al. [9], which can be seen as a contour method when applied to this cross shape example (Fig. 22a). The process parameters were kept constant throughout the deposition. Fig. 22d shows the resulting component. Extensive presence of keyhole defects can be appreciated throughout. Fig. 22c shows a side view of the same component; the irregular height of the deposit can be seen.

The second test used the same method as the first attempt (Fig. 22a), although parameters were different from the baseline ones, to try and avoid the defects seen previously. Fig. 22d shows the resulting component. Keyhole defects could still be found, although the height of the deposit is certainly more stable (Fig. 22e).

The third test used the MPP approach, albeit with segmentation only, and no zoning (Fig. 22f). Fig. 22g shows the resulting component. A small keyhole defect could still be found, but the height of the deposit was very stable (Fig. 22h). However, please note the lower height at the ends of the part.

Finally, the fourth test used the MPP approach with both segmentation and zoning applied (Fig. 22i). Fig. 22j shows the resulting component. No defects can be seen, and the height of the deposit is stable (Fig. 22k); the part ends are less steep as well.

Taking the validation one step further, an Airbus A320 aft pylon bracket mount was built. The tool path plan is shown in Fig. 23a, while the resulting component is shown in Fig. 23b. Please note this part was also in-process cold-worked, as described by Martina et al. [20]; the tool-path-planning for the in-process cold-work was performed with the same MPP software used for the deposition. Unfortunately, the finish-machined component cannot be shown due to confidentiality issues. The machined component showed no defects.

6. Discussion

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

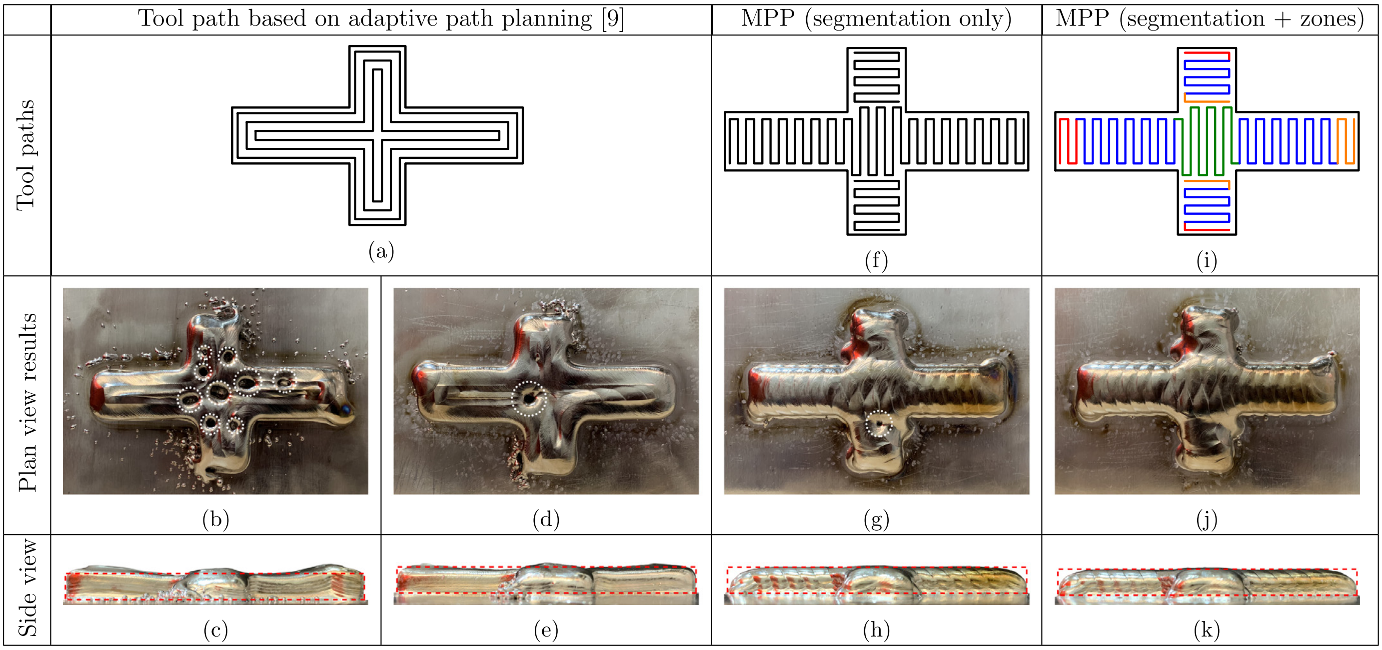


Fig. 22. Validation study. The circles indicate keyhole defects; the bounding boxes indicate the profile of the target geometry.

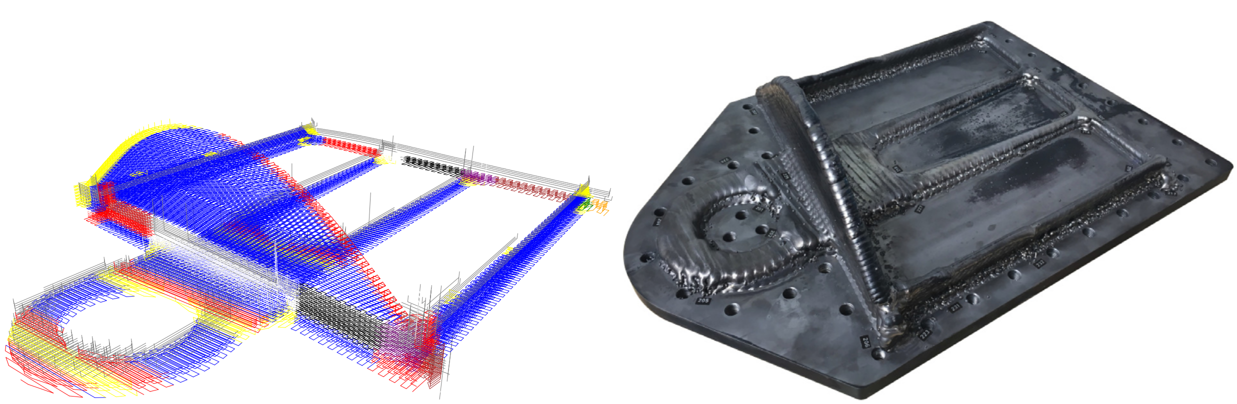
be adapted to new materials and processes.

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

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

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

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



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

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

Fig. 23. A320 aft pylon bracket mount built for Airbus.

7. Conclusion and future work

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

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

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

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