

Enhanced-pixel strategy for wire arc additive manufacturing trajectory planning: operational efficiency and effectiveness analyses

Rafael Pereira Ferreira

Federal Institute of Education, Science and Technology of Maranhão (IFMA), Campus Barra do Corda, Barra do Corda, MA, Brazil

Louriel Oliveira Vilarinho

Department of Engenharia Mecânica, Universidade Federal de Uberlândia, Uberlândia, Brazil, and

Americo Scotti

Department of Engineering Science, University West, Trollhättan, Sweden and Department of Engenharia Mecânica, Universidade Federal de Uberlândia, Uberlândia, Brazil

Abstract

Purpose – This study aims to propose and evaluate the progress in the basic-pixel (a strategy to generate continuous trajectories that fill out the entire surface) algorithm towards performance gain. The objective is also to investigate the operational efficiency and effectiveness of an enhanced version compared with conventional strategies.

Design/methodology/approach – For the first objective, the proposed methodology is to apply the improvements proposed in the basic-pixel strategy, test it on three demonstrative parts and statistically evaluate the performance using the distance trajectory criterion. For the second objective, the enhanced-pixel strategy is compared with conventional strategies in terms of trajectory distance, build time and the number of arcs starts and stops (operational efficiency) and targeting the nominal geometry of a part (operational effectiveness).

Findings – The results showed that the improvements proposed to the basic-pixel strategy could generate continuous trajectories with shorter distances and comparable building times (operational efficiency). Regarding operational effectiveness, the parts built by the enhanced-pixel strategy presented lower dimensional deviation than the other strategies studied. Therefore, the enhanced-pixel strategy appears to be a good candidate for building more complex printable parts and delivering operational efficiency and effectiveness.

Originality/value – This paper presents an evolution of the basic-pixel strategy (a space-filling strategy) with the introduction of new elements in the algorithm and proves the improvement of the strategy's performance with this. An interesting comparison is also presented in terms of operational efficiency and effectiveness between the enhanced-pixel strategy and conventional strategies.

Keywords WAAM, Path planning, Space-filling strategies, Operational efficiency, Operational effectiveness

Paper type Research paper

1. Introduction

Through wire arc additive manufacturing (WAAM), components with thin and/or thick walls are built. However, the technology to make production efficient and effective is still not consolidated. Even the terminology for wall thicknesses is still fuzzy amongst users. From a practical point of view, thin walls, for the current paper authors, would be those built using a single track per layer, using or not torch oscillation. On the other hand, thick walls require multiple tracks per layer or a single track with wide-amplitude oscillation (known as zigzag). Confusion may also occur when using the torch oscillation in a single track (for example, using a rectangular profile) and the mentioned zigzag strategy. The current authors prefer to adopt the understanding of oscillation when the melting pool remains liquid for the entire oscillation

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amplitude. In the zigzag strategy, in turn, solidification occurs along with this transversal movement of the arc movement. Therefore, the zigzag strategy is not strictly a single track per layer, even though the layer is accomplished resembling it.

In manufacturing thick-walled parts, it is important to highlight that those deposition strategies commonly used for polymer building are not always applied satisfactorily in WAAM. This is due to the different nature of the track width obtained by these different technologies. In the case of WAAM, wide spaces between tracks are necessary due to the width of the beads and their spreading-out character obtained by different welding processes and techniques. For example, Cui *et al.* (2021), depositing a nickel-aluminium-bronze alloy, found layers (with a single pass, or track, deposition per layer) with dimensions ranging from 3.2 to 9.0 mm in width and from 2.6 to 4.5 mm in height, using the gas metal arc welding-cold metal transfer (GMAW-CMT) and GMAW-pulsed processes, respectively. Using carbon steel, Teixeira *et al.* (2022) elaborated a working envelope also with a single deposition pass per layer, covering layer dimensions ranging from 4.8 to 8.1 mm in width and 1.7 to 3.5 mm in height, using GMAW-CMT. Larger layer widths can be achieved with oscillation techniques, as presented in the study by Ma *et al.* (2019) or by the use of double wire, as presented in the studies by Martina *et al.* (2019) and Shi *et al.* (2019). In relation to polymers, the widths obtained can be smaller than 1 mm. However, with larger layer widths, conventional building strategies may evidence non-conformities (such as unfilled regions), which are often imperceptible in polymers because they have a narrower track width.

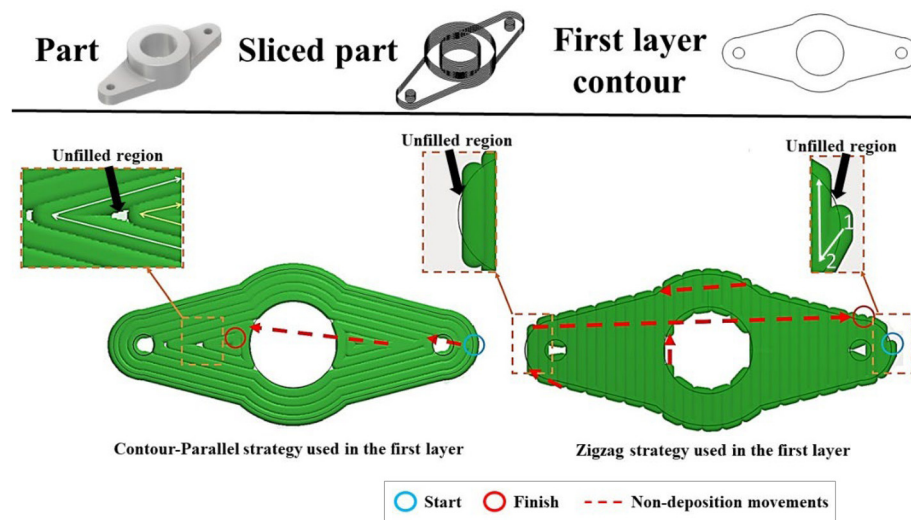
To illustrate this problem, Figure 1 presents two deposition simulations using contour-parallel strategy with wide tracks (commonly obtained by WAAM) and the other that used zigzag as the filling strategy of a thick wall. See the zoomed-in details in the drawings. In the contour-parallel strategy, unfilled regions can be noted (left frame). Liu *et al.* (2020) explained that this occurs because a trajectory with a direction change with an angle smaller than 58.65° will generate an offset trajectory at the direction change point. With this, the adjacent beads deposited following this

trajectory cannot overlap with their neighbours, leading to the unfilled regions (this worsens as the width of the beads increases). To solve this, these authors proposed an extension of the displaced trajectory to fill the regions that would generate imperfections for angles less than 58.65° . Another situation observed in this strategy is the torch movements with non-deposition (represented by the red-dashed lines). In addition to increasing the building times (which can worsen with the high number of layers), non-deposition movements can cause problems of non-conformity in the bead due to the arc strikes and stops, as demonstrated by Hu *et al.* (2018).

Still, according to Figure 1, the zigzag strategy presents filling problems. The first one can occur when the dimensions of the part are not multiple of the distance between beads configured to generate the trajectory (a situation familiar in more complex parts), which causes unfilled regions, as illustrated in the central frame. In the second one, the part circular features can cause problems at the beginning of the trajectories. In these cases, the trajectory always starts at the most external points (represented by point 1 in the right frame). Then, its direction changes aside (represented by point 2 in the right frame), leaving the filling problem on the opposite side. In addition, non-deposition movements in this strategy can also be observed. That is, conventional strategies can lead to unfilled regions and a high number of non-deposition movements, which causes an increase in the building time and also non-conformities generated in the geometry of the deposited bead. The above-mentioned cause of filling problems can be aggravated by the increasing complexity of the parts.

These problems can be overcome by using the strategies called space-filling strategies. Cox *et al.* (1994) defined this family of strategies (or curves) as continuous trajectories in a unit square that passes through all the points that discretise this square. This type of strategy solves the filling problem because, as Sebastian *et al.* (2020) explained, fractals (mathematical space-filling curves) can well define a path to fill a given surface. Regarding the high number of non-deposition movements, Kapil *et al.* (2016) developed three space-filling strategies for additive manufacturing that can reduce and even zero the amount of non-deposition

Figure 1 Building simulations of a part with contour-parallel (left) and zigzag (right) strategies, focusing on non-conformities



Source: Figure by authors

movements to an arbitrary area. However, some of these strategies generate material accumulations, that is, an imperfection that subtractive processes must remove after building each layer. For polymer additive manufacturing, Lin *et al.* (2019) also developed a space-filling strategy called maze-like, which generates trajectories with non-deposition movements reduced for a more complex area. In addition to mitigating filling problems and many non-deposition movements, Catchpole-Smith *et al.* (2017) explained that space-filling strategies can potentially provide a more uniform temperature distribution than the cyclic heat input associated with one-way straight lines (characteristics of conventional strategies). This finding was updated to WAAM in studies conducted by Vishwanath and Suryakumar (2022), where it was evidenced that fractals generate higher temperature uniformity and, consequently, lower distortion in the built part when compared with conventional strategies.

To solve the problems of unfilled regions and the high number of non-deposition movements in WAAM, Ferreira and Scotti (2021) developed a strategy named *pixel*, which can be categorised as a space-filling strategy. In the pixel strategy, the layer to be filled is discretised at normally equidistant nodes that will be interconnected, thus generating a continuous trajectory. In this proposal, an adapted metaheuristic *greedy randomised adaptive search procedure* (GRASP) is used to find an acceptable trajectory for the deposition of the material. The metaheuristic begins with a random selection of a node (among those discretised in the layer) that will be the starting node for four competing and distinct heuristics (three of them developed by the authors for additive manufacturing). Each of the heuristics generates a trajectory, totalling four trajectories generated. Each of these generated trajectories is improved with an algorithm called *2-opt*, aiming to eliminate crossings between paths and thus obtain shorter courses. After that, the trajectory with the shortest distance is taken as the best result. These steps are repeated according to the number of user-defined iterations. In the end, a list of the best results is obtained from each iteration.

Like other space-filling strategies, the pixel strategy can perform a sound filling of bidimensional layers resulting from the slicing step. As the pixel strategy is based on an optimisation algorithm, one of its main features is the flexibility to impose modifications to achieve better performance. Considering the above, the main objectives of this work are: (a) to propose and evaluate improvements in the algorithm that may reflect on the performance gain of the original pixel strategy; and (b) to investigate the operational efficiency and effectiveness of the proposed enhanced-pixel strategy [the pixel strategy with the implementation of improvements achieved in objective (a), compared to conventional strategies].

The pixel strategy already described in a publication (Ferreira and Scotti, 2021) will hereafter be referred to as “basic-pixel” to facilitate the understanding of the work.

2. Improving the basic-pixel strategy

The improvement of the basic-pixel strategy is presented in the two following subsections: the proposals for improvements and their validation.

2.1 Proposal to improve the basic-pixel strategy

The improvements proposed for the basic-pixel strategy were achieved through four modifications, namely, the use of the 2-

opt closed-loop algorithm, the ordering direction of the nodes taking the *y*-axis as preferential, the introduction of a complementary trajectory planning heuristic and a choice of the heuristics' starting node.

2.1.1 Use of the 2-opt closed-loop algorithm

One non-conformity, not always mentioned in the WAAM literature, is caused by arc striking and extinguishing. Excessive volume of material is prone in regions where the arc starts. On the contrary, a material shortage occurs where the arc is stopped. Some authors have proposed solutions to solve this drawback. For example, Zhang *et al.* (2003) correlated a greater bead width at the arc start region to low penetration with the GMAW process. For this reason, they proposed that the current and welding speed should be increased at the beginning of the pass. Also, according to these authors, welding current and speed must be reduced to deposit more material at the end of the layer, thus compensating for the potential lack of material. Venturini *et al.* (2018) proposed that arc starts and stops should be done outside the useful part, to avoid non-conformities; so, the excess/shortage can be afterwards removed by machining.

The solutions for arc starts and stops presented by Xiong *et al.* (2016) and Hu *et al.* (2018) are similar, being directed to both close and open paths. For open paths (where the multiple arc striking and extinguishing do not coincide in terms of position in the same layer), an opposite-direction movement must be adopted to deposit the following layer. Therefore, the arc strikes over the same point where the arc stopped in the previous layer, compensating for potentially generated non-conformities. In closed paths, on the other hand, the position in which the arc starts and stops already coincides. The idea of overlapping becomes interesting, as the compensation of an excess of material at the beginning of the deposition can be done by reducing the deposition of material at the end of the trajectory in the same region of the same layer.

However, these techniques become difficult for more complex geometries, generally requiring beads side by side to perform the building. This can be seen in the example illustrated in Figure 1, where the arc striking and extinguishing points (blue and red circles, respectively) in the same layer are never coincident – noticed mainly in bulky parts built up by the zigzag and contour-parallel strategies. It could even be argued that the mentioned drawback could be solved by building the next layer, which would follow a path opposite to that deposited in the previous layer. However, for more complex shapes, such as with holes, inversion of the deposition direction where paths without deposition will occur is not simple to implement computationally. Another argument would be in terms of productivity and print quality. For example, Jorge *et al.* (2022) stated that when starting a subsequent layer, it is necessary to wait for the interlayer temperature to become stable to guarantee the bead geometry. But as that point with undersupply of material is the last deposited, it will probably be hotter than the other regions of the part, which can lead to a longer temperature stabilisation time (at that point), thus increasing the dwell time between layers.

To solve the problem mentioned above (without changing parameters, a solution out of this work scope), the solution proposed in this work is to implement a closed-loop approach in the basic-pixel strategy. In the basic-pixel strategy (Ferreira and Scotti, 2021), a 2-opt algorithm is already used, yet acting in an

open loop, to improve the initial solutions proposed by the nearest neighbour heuristic (NNH), alternate heuristic (AH), biased heuristic (BH) and random contour heuristic (RCH). However, the open-cycle perspective does not form a Hamiltonian cycle (path where the start point coincides with the endpoint). Consequently, the 2-opt algorithm would find the shortest path, but the start point was not coinciding with the trajectory's endpoint. Then, it was thought of using the closed-loop 2-opt algorithm instead (attending the Hamiltonian cycle benefit). This algorithm seeks a shorter trajectory where the endpoint coincides with the start point (imposed constraint), as the classic Traveling Salesman Problem describes. In the next layer, another start point (which is not the same as the previous one) can be used to start the deposition at a point with a more stabilised interlayer/intertrack temperature. Because of this good performance, the version enhanced-pixel strategy adopted this solution.

2.1.2 Ordering direction of nodes taking the y-axis as preferential

By default, the basic-pixel strategy preferentially orders the inter-connectable nodes generated on the layer surface towards the x-axis (row-oriented). Figure 2(a) demonstrates the sorting process along the x-axis, where i_1 and i_n are the first and last nodes, respectively, of the first row of nodes (from bottom to top). The node i_{n+1} represents the first one of the second row of nodes. The algorithm organises such nodes in rows, indexing them to the values of y. The nodes are sorted in ascending order from left to right in each row.

However, a hypothesis raised is that other forms of ordering could favour the performance of the basic-pixel strategy, that is, generate shorter trajectories. An additional arrangement that uses the y as a preferential axis (columns oriented) is proposed in this context. In this case, the interconnectable nodes are organised in columns indexed to the x-values. For each column, there is a number of discrete nodes, which are sorted from bottom to top. As a preferential column, sorting starts on the column with the lowest x-value and moves to the column with the highest x-value (moving from left to right). Figure 2(b) demonstrates the sorting process in the y-axis direction, where i_1 and i_n are the first and last nodes of the first column of nodes (from left to right), respectively. The node i_{n+1} represents the first one of the second column of nodes.

With these two extra options for ordering the nodes, it is believed that a performance improvement of the basic-pixel strategy can emerge, allowing further exploration of the response space during optimisation.

2.1.3 Introduction of a complementary trajectory planning heuristic

The basic-pixel strategy has four heuristics, namely, NNH, AH, BH and RCH. These heuristics are applied to plan trajectories before going through the optimisation stage, through the 2-opt algorithm. The better the initial solution, the easier the local search efficiency (e.g. by 2-opt). Therefore, a new heuristic, continuous (CH), is proposed to boost the basic-pixel strategy.

Figure 3 shows the flowchart of how this planned heuristic works in the enhanced-pixel strategy. The process begins with selecting an initial node (the starting node of the trajectory), which will be considered the active node. Once the active node is defined, the heuristic will select the closest node among all the nodes not yet visited (not interconnected). With this selection performed, the active node links to the selected node to form a path and this last node becomes the active node again for the beginning of the process, until all nodes are linked. In the case of a tie in the selection step between unvisited nodes closest to the active node, the unvisited node with the highest sorting index will be chosen.

2.1.4 Choice of the heuristics' starting node

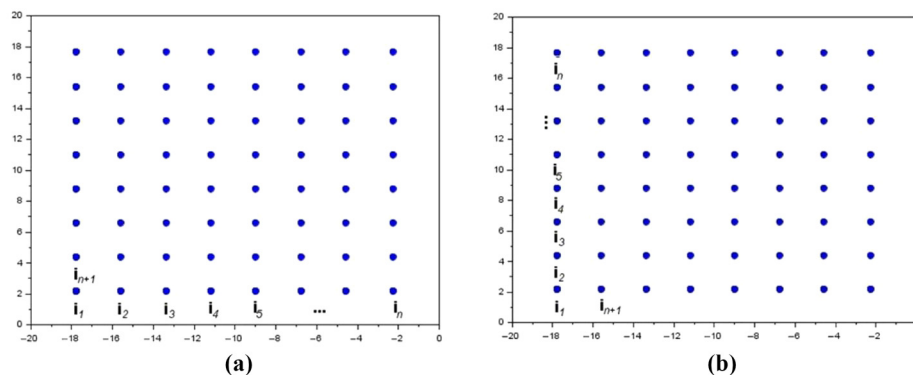
The self-selection of the initial node, which is the position where the trajectory planning heuristics will start the trajectory generation, was done randomly in the basic-pixel strategy. The same approach is planned to be used in the enhanced version. However, a relevant question would be whether the choice of any specific position of the initial node (starting node) could influence the performance (generate shorter trajectories) of the pixel family strategy. Therefore, it was also implemented a computation routine in the code to verify if the specific positioning of the initial node is relevant or not. By manually recognising the effect of the initial node position on the algorithm performance, the relevance of defining a starting node position could be assessed (this was carried out in Section 2.2.1).

2.2 Validation of the improvement proposals

2.2.1 Validation procedure

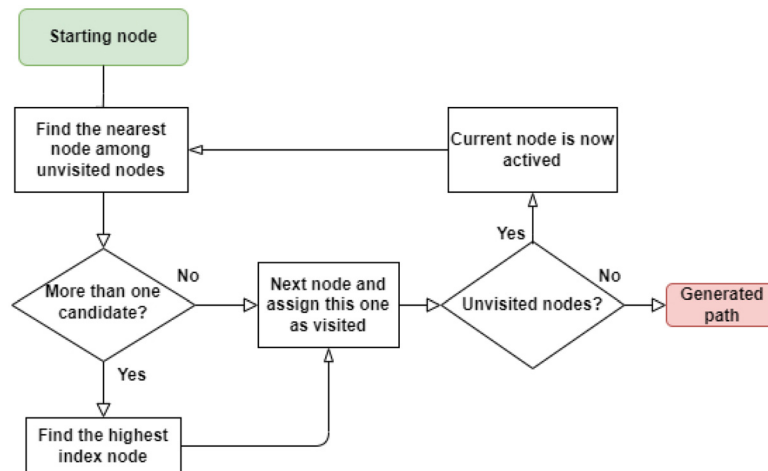
Figure 4 schematises the workflow of the novel algorithm proposed for the enhanced-pixel strategy. Initially, a random start

Figure 2 Ordering of discrete nodes on the layer



Notes: (a) Towards the x-axis (used in basic-pixel); (b) towards the y-axis (new ordering proposal used in the enhanced-pixel)

Source: Figure by authors

Figure 3 Flowchart of the continuous trajectory planning heuristic (CH)

Note: See Ferreira and Scotti (2021) for the NNH, AH, BH and RCH flowcharts

Source: Figure by authors

node is selected. The five trajectory planning heuristics (including the proposed CH) are performed for both ordering directions (row-oriented and the included column-oriented). This creates a total of ten combinations of node-ordering and trajectory-planning heuristics. The closed-loop 2-opt optimisation algorithm is then applied. This algorithm results in an array which stores the trajectory distance found for each of the generated solutions (“store values in a matrix” within Figure 4). This matrix is sorted in sequence, and the trajectory with the shortest distance out of these ten combinations is stored in a separate array (“best value matrix” within Figure 4).

It is important to note that two checking points are provisorily planned in the workflow, represented in the figure by cylinders (highlighted with dashed lines) on the right side. The first one is the “node classification”, which indicates the nodes drawn at each iteration to be the starting nodes of the heuristics. They are characterised as 0, for nodes belonging to the contour of the set of nodes, or 1, for the other nodes. The second checking point is referred to as “trajectory distance” after each combination of axis ordering and heuristic per iteration. The information from each provisory checking point made it possible to perform a statistical analysis relating the starting nodes’ location and the trajectory’s distance. Thus, the authors were able to study if there is any preferred position for the beginning of the trajectory in its initial phase.

Three printable parts (Figure 5) were studied to assess the feasibility of the enhanced-pixel strategy (with all improvement proposals implemented to the basic-pixel strategy). Note the differences in the designs of each part, highlighting a variety of complexities for the printing process (consequently, the trajectory planning) and a demand for different numbers of nodes. The distances between nodes were 4.87 mm, 5.5 mm and 4.10 mm for “Part 1”, “Part 2” and “Part 3”, respectively (not displayed in Figure 5).

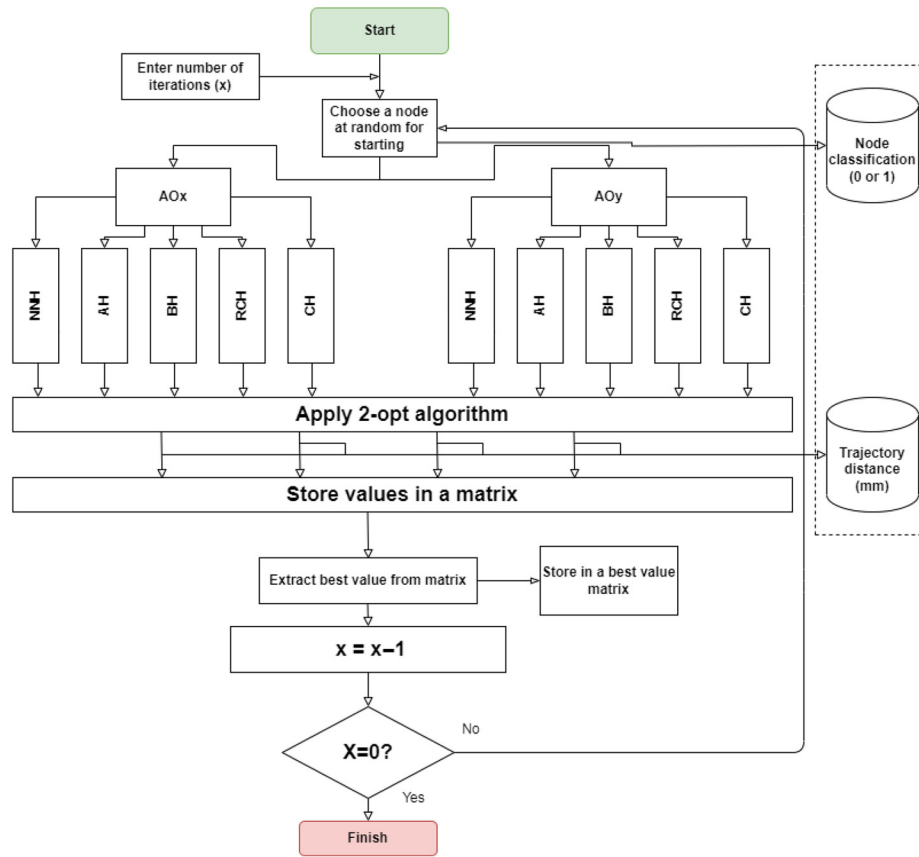
2.2.2 Validation results and discussions

A total of 40 iterations were arbitrarily defined to perform the trajectory simulation of each part, according to Figures 4 and 5.

Figure 6 shows the boxplots (a standardised way of displaying data distribution based on the minimum, first quartile, median, third quartile and maximum) of the resulting trajectory distances (in mm). Figure 6(a), (c) and (e) relate the trajectory distance with the heuristic used for a sorted axis. The symbology to indicate each heuristic used is coded as LL+N-xxx_e, where “LL” means the type of heuristic (NNH for Nearest Neighbour, AH for Alternate, BH for Biased and RCH for Random Contour), “N-xxx” that was optimised by the 2-opt algorithm and “_e” that the nodes were ordered in relation to the x- or y-axis (_x or _y, respectively) or that the trajectory generation node started at the contour (_IC) of the layer or started outside the contour (_OC). For example, the name AH + 2-opt_x, indicates that the AH was used, and the nodes were ordered in relation to the x-axis and optimised by the 2-opt algorithm. Figure 6(b), (d) and (f), in turn, relate the trajectory distance with the heuristic used for a given position of the starting node. For example, the acronym BH + 2-opt_NC, indicates that the trajectory generation node started at the contour (IC) of the layer and the BH was used to generate the trajectory, later optimised by the 2-opt algorithm. The opposite is true for the denomination BH + 2-opt_OC, where the trajectory generation node started outside the contour (OC).

The median (central line of the coloured box) was the only statistics used for the data analysis as a comparison parameter. In “Part 1”, the ordering of the axes significantly influences the distance of the trajectories in the BH and CH heuristics, as can be seen in Figure 6(a). For the other heuristics, the median results are very similar. The best result was with the CH and the nodes ordered on the x-axis. The worst result found was with the BH and the x-axis node ordering. Regarding the analysis of the position of the initial node, no significant differences were found (between the heuristics) in relation to the position of the initially chosen node, as seen in Figure 6(b). However, as will be seen later, the performance of each heuristic depends on the part geometry.

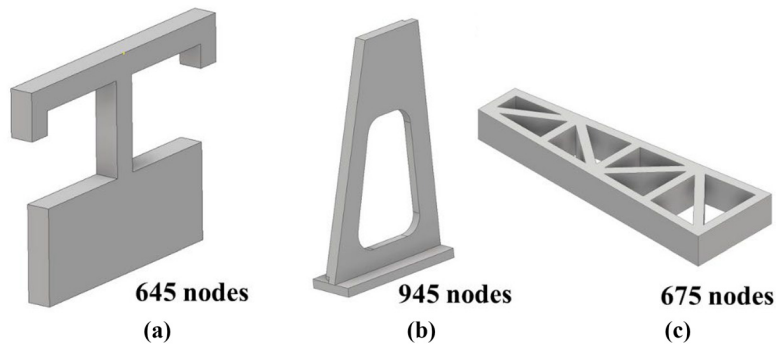
Figure 4 Flowchart of the GRASP metaheuristic representing the enhanced-pixel strategy, with the proposed improvements implemented to the basic-pixel



Note: NNH = nearest neighbour heuristic; AH = alternate heuristic; BH = biased heuristic; RCH = random contour heuristic; CH = continuous heuristic heuristics; AO = axis ordering, either in axis x or in axis y

Source: Figure by authors

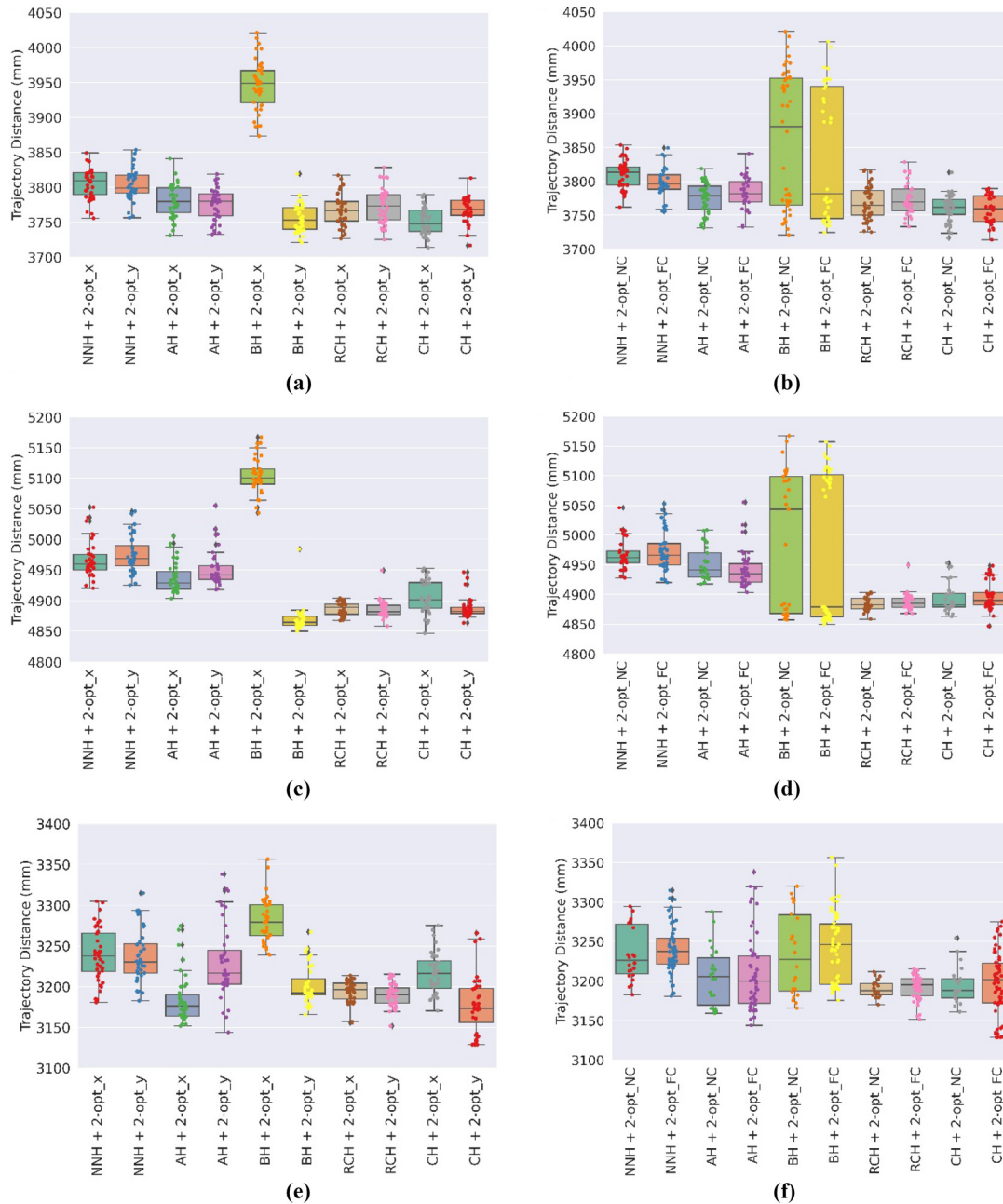
Figure 5 Selected printable parts with different complexities to validate the enhanced-pixel strategy



Notes: (a) “Part 1”, with narrow and bulky regions; (b) “Part 2”, not symmetrical with hole; (c) “Part 3”, in the form of a truss and composed of thin walls

Source: Figure by authors

Figure 6 Boxplots of path distances obtained by the heuristics by axis ordering (plots on the left) and by starting node positioning (plots on the right), where



Source: Figure by authors

Regarding “Part 2”, one can see in Figure 6(c) that the order of the axes significantly influenced the performance of the enhanced-pixel strategy when using the BH and CH. For the other heuristics, the median results are very similar. The best result found for “Part 2” (at the given number of iterations) was with the CH with the nodes ordered on the x -axis. The worst result found was the BH with an ordering in relation to the x -axis. In the initial node’s position analysis, according to Figure 6(d), no significant differences (between the heuristics) were found in the position of the node initially chosen.

Figure 6(e), in turn, indicates that for processing “Part 3”, the ordering of the axes presents significant differences in the AH, BH and CH heuristics. For the other heuristics, the median results are very similar. The best result found was with the CH with the nodes ordered on the y -axis. The worst result found was the BH with the ordering in relation to the x -axis. In the analysis of the initial node position for “Part 3”, according to Figure 6(f), no significant differences (between the heuristics) in the position of the node initially chosen were also found.

In view of the above, it is noted that for all three different parts shapes under study, the NNH has a median that is further away from the others; their minimum values can still be considered acceptable, as they are below the median of other heuristics-sorted axis combinations. Notwithstanding, there is no evidence that this outcome would repeat with a different part geometry and/or a higher number of iterations. This reinforces the need for the presence of all heuristics, including the continuous one introduced in this work. It can also be inferred that both axis ordering (x and y) can generate satisfactory results, depending on the layer geometry type. However, regarding the location of the initial node (belonging or not to the contour), the case study indicated that it does not influence the performance of the enhanced-pixel strategy, and both methods can be used (for safety's sake, better to keep this option). Therefore, the enhanced-pixel strategy benefited from all the improvements proposed in Section 2.1.

With this basic visual analysis done by boxplot, it can be inferred that the insertion of the CH and the y -axis ordering can increase the performance of the basic-pixel strategy. However, it is worth mentioning that more advanced statistical analyses would not be feasible for this study, as the objective is not to say which is the best combination between axis ordering and trajectory planning heuristics. One must remember that the number of nodes and the part topology may lead to either one or the other combinations as the better (as seen in the results). That said, a more straightforward method for the best combination selection between axis ordering and trajectory planning heuristics seemed to be that one of the optimisation processing.

3. Operational efficiency

In this paper, the operational efficiency of the trajectory planning (not of the printed parts) was used to define the WAAM processing qualification (assessment criterion) in terms of trajectory distance, building time and number of non-deposition paths. The trajectory planning is operationally more efficient if it provides a shorter movement distance of the torch, faster and minimal non-deposition paths.

3.1 Methodology

The three parts presented in Figure 5 were used again as case study to assess the operational efficiency of the trajectory planning programme. In addition to enhanced-pixel, the contour-parallel and zigzag strategies were used to generate simulated trajectories, using an upgraded of the in-house software described in Ferreira and Scotti (2021). Particularities of the trajectory generation were adopted for all printable parts. Using the zigzag strategy, the scanning angles of 0° and 90° (in relation to the x -axis) were alternately used in the deposition of the layers. With the strategy of contour-parallel, the inside-out and outside-in build approaches were used alternately in the deposition of the layers (naturally, they have the same trajectory, inverting only the sense of the movement). And finally, in the enhanced-pixel strategy, the two best trajectories were selected to alternate during layer deposition, one applied to the odder layers and the second to the even layer. It is noteworthy that, regardless of the strategy, only two alternating trajectories between layers were used arbitrarily.

The input parameters to run the programme, which includes the stepover distance (distance between two consecutive bead

centres) are presented in Table 1; 40 iterations were applied. The operational efficiency criterion was evaluated through offline simulations of the building process performed in the SprutCAM software.

3.2 Results and discussions

Figure 7 shows the result of the offline simulations with their respective operational efficiency parameters for the strategies applied to generate trajectories for “Part 1”. It is noted that the enhanced-pixel strategy presented the shortest trajectory distances, but it does not mean the shortest building time. To explain this apparent contradiction, enhanced-pixel produced a greater number of direction changes than the zigzag strategy, in which the torch performs decelerations and accelerations that increase the building time. However, when analysing together the trajectories used to build the even and odd layers, the total building time performed with the enhanced-pixel strategy [Figure 7(d) and (e)] exceeds in one second the building time performed with the zigzag strategy [Figure 7(a) and (b)], i.e. 1,000 s against 1,001 s (see Table 2). It is important to mention that this building time difference is not significant. The contour-parallel strategy, in turn, presents the longest building time. Regarding the number of non-deposition paths, contour-parallel and enhanced-pixel strategies surpassed the others.

When the offline simulation was applied to “Part 2”, Figure 8 shows that the zigzag strategy reached the lowest building time and presented one non-deposition path at each layer. The contour-parallel strategy did not appear suitable for building this part because of the voids left inside, besides offering the longest trajectory distance and two non-depositions paths. The enhanced-pixel strategy generated shorter trajectories distance [Figure 8(e) and (f)] and with no arc interruptions, but with slightly higher building time.

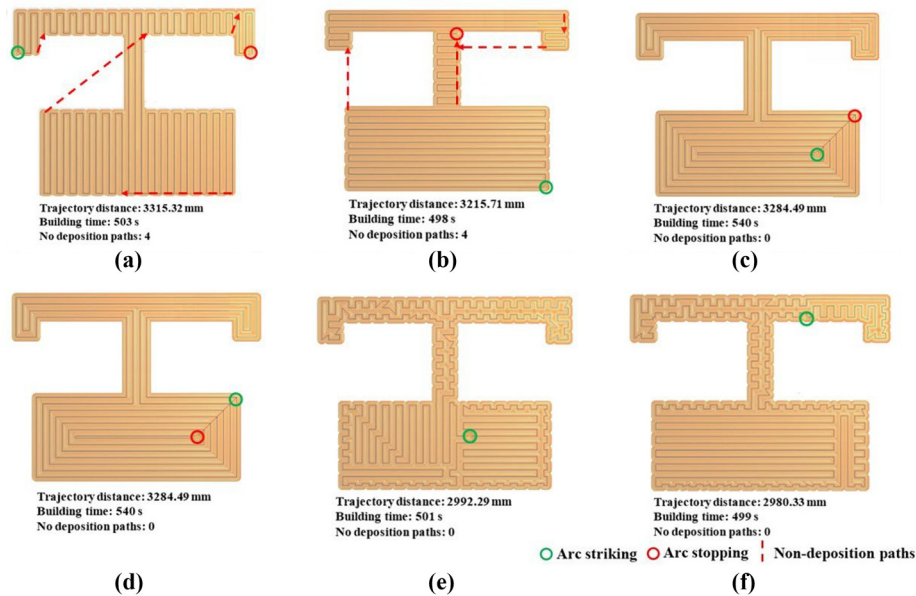
Concerning “Part 3”, data from Figure 9 suggests that the zigzag strategy obtained the shortest trajectory distance [Figure 9(b)] and the least building time, but presented several non-deposition paths (above ten). The contour-parallel strategy was not suitable for building this part due to the voids left at the intersections of the truss bars (a common problem reported in the literature), but it presented the shortest trajectory distance and building time, although totalled seven non-deposition paths. The enhanced-pixel strategy generated continuous trajectories, but with slightly longer building time.

Gathering all printable part results together, shown in the Table 2, in general, the zigzag strategy presented good performance concerning the trajectory distance and building time, superior to the other strategies when printing Parts 2 and 3. However, it should be noted that the zigzag strategy, used in more complex parts, can leave unfilled regions (the built part does not correspond to the measurements of the three-

Table 1 Input parameter for offline simulation of case-study parts

Input parameter	“Part 1”	“Part 2”	“Part 3”
Bead height (mm)	2.49	2.30	2.42
Bead width (mm)	6.60	7.45	5.55
Deposition speed (cm/min)	40	40	40
Stepover distance (mm)	4.87	5.5	4.10

Source: Table by authors

Figure 7 Offline simulations of trajectories for “Part 1” using the strategies

Notes: (a) zigzag 0°; (b) zigzag 90°; (c) contour-parallel inside-out; (d) contour-parallel outside-in; (e) enhanced-pixel for odd layers; (f) enhanced-pixel for even layers

Source: Figure by authors

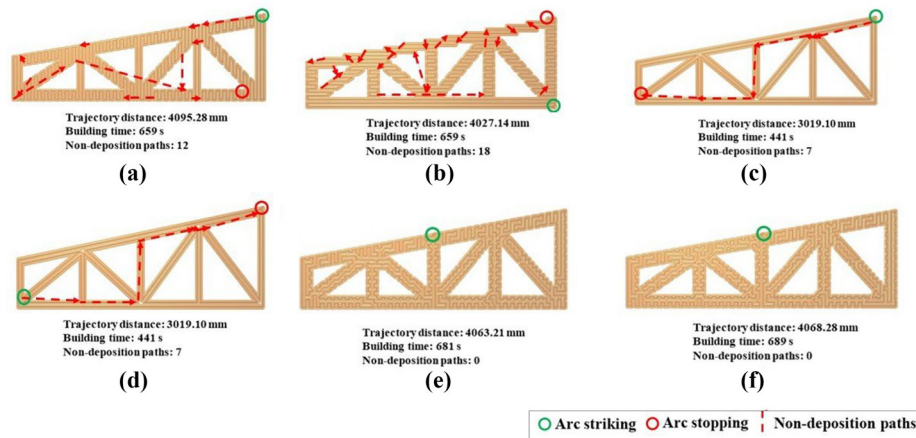
Table 2 Criteria data for all parts

Parts	Strategies	Criteria			Sum of criteria for two layers		
		Trajectory distance (mm)	Building time (s)	Non-deposition paths	Trajectory distance (mm)	Building time (s)	Non-deposition paths
"Part 1"	Zigzag 0°	3,315.32	503	4	6,531.03	1,001	8
	Zigzag 90°	3,215.71	498	4			
	Contour inside-out	3,284.49	540	0	6,568.98	1,080	0
	Contour out-inside	3,284.49	540	0			
	Enhanced-pixel odd layers	2,992.29	501	0	5,972.62	1,000	0
	Enhanced-pixel even layers	2,980.33	499	0			
'Part 2'	Zigzag 0°	4,231.92	676	1	8,425.82	1,349	2
	Zigzag 90°	4,193.90	673	1			
	Contour inside-out	4,322.95	700	2	8,645.90	1,400	4
	Contour out-inside	4,322.95	700	2			
	Enhanced-pixel odd layers	4,191.02	700	0	8,409.18	1,406	0
	Enhanced-Pixel even layers	4,218.16	706	0			
'Part 3'	Zigzag 0°	4,095.28	659	12	8,122.82	1,318	30
	Zigzag 90°	4,027.14	659	18			
	Contour inside-out	3,019.10	441	7	6,038.20	882	14
	Contour out-inside	3,019.10	441	7			
	Enhanced-pixel odd layers	4,063.21	681	0	8,131.49	1,370	0
	Enhanced-pixel even layers	4,068.28	689	0			

Source: Table by authors

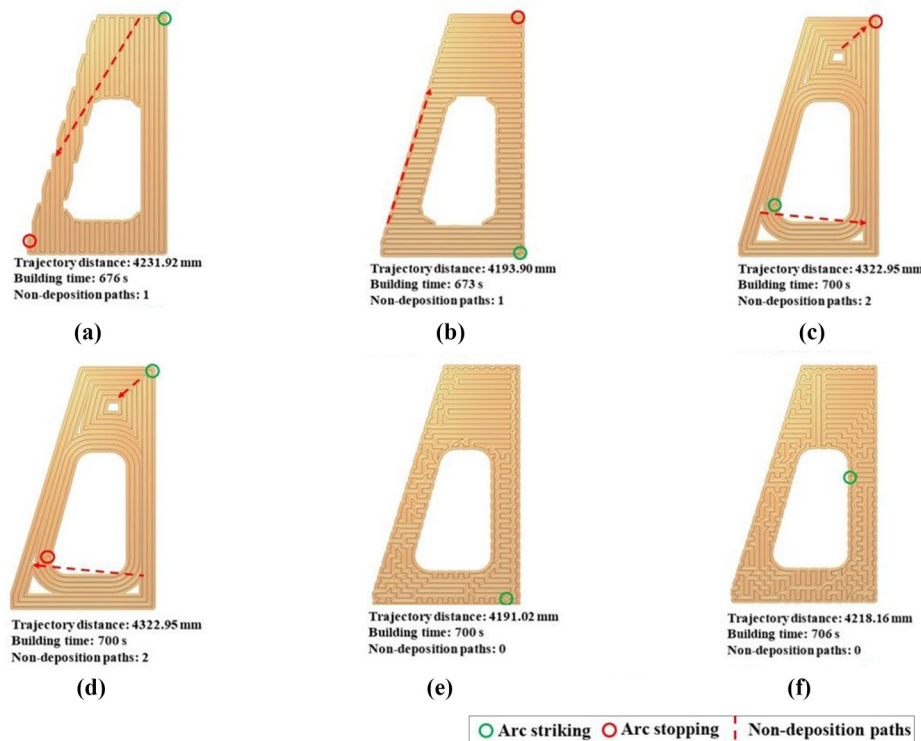
dimensional [3D] model). According to [Xiong et al. \(2019\)](#), the reason for this is the distance between the scan vectors, which may not be multiple of the part's regions to be filled with. This setback worsens when this strategy is used as a segment of the hybrid contour strategy, as shown in [Figure 10](#); the unfilled regions are clearly left inside the part. One solution would be to manufacture the parts with an adequately calculated over

metal. However, one should be aware that this will increase material usage and building time. Concerning non-deposition paths, non-conformities in geometry may occur in the arc striking and stopping regions, as cited by [Hu et al. \(2018\)](#). In the case of "Part 3" trusses, this can be an aggravating factor due to the high number of non-deposition paths (see [Table 2](#)).

Figure 8 Offline simulations of trajectories for “Part 2”, using the strategies

Notes: (a) zigzag 0°; (b) zigzag 90°; (c) contour-parallel inside-out; (d) contour-parallel outside-in; (e) enhanced-pixel for odd layers; and (f) enhanced-pixel for even layers

Source: Figure by authors

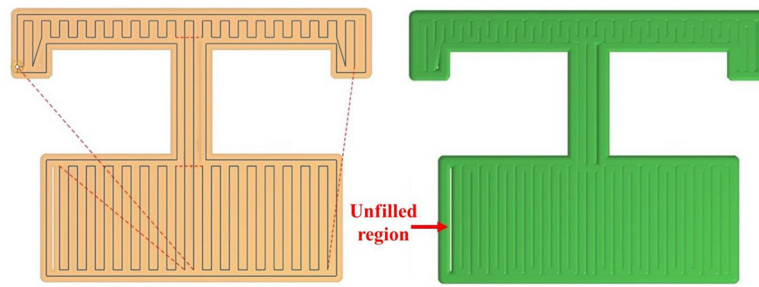
Figure 9 Offline simulations of trajectories for “Part 3”, using the strategies

Notes: (a) zigzag 0°; (b) zigzag 90°; (c) contour-parallel inside-out; (d) contour-parallel outside-in; (e) enhanced-pixel for odd layers; and (f) enhanced-pixel for even layers

Source: Figure by authors

The contour-parallel strategy is potentially not applicable for more complex parts, not due to efficiency-related issues, but because of the proneness of imperfections. For instance, in the case of “Part 1” [Figure 7(c) or (d)], the starting/beginning of the deposition became narrower than the offset distances calculated by this strategy between the tracks. Therefore, a material

accumulation will occur in this position, which will put the entire building process at risk. In “Part 2”, the voids left by this strategy [Figure 8(c)] are critical. However, a possible solution for printing using the concept of contour-parallel would be to use the adaptive medial axis transformation (A-MAT) strategy presented by Ding *et al.* (2016). As proposed by the authors, A-MAT is an

Figure 10 Unfilled region in “Part 1” due to the non-multiplicity of scan vectors in the zigzag strategy, in a hybrid contour-parallel strategy

Source: Figure by authors

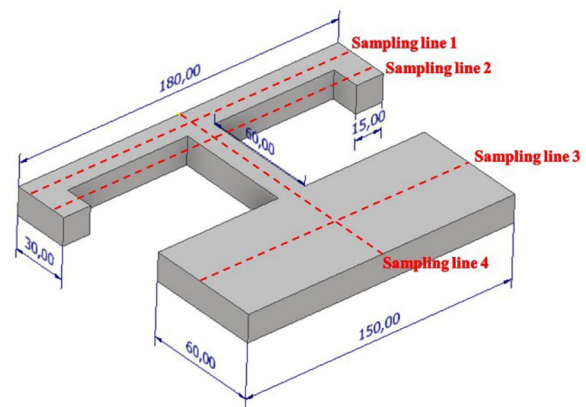
improvement of the author's strategy named medial axis transformation (MAT), based on an inscribed contour approach. Contour spacing and re-parametrisation were applied in A-MAT to guarantee continuous paths for two-dimensional geometry, addressing non-continuous trajectory problems in MAT. More clarifications on MAT and A-MAT strategies can be found in the reference. In relation to “Part 3”, the voids left at the truss intersection bars can be solved with an adaptation of the contour-parallel algorithm to make corrections at the intersections, as proposed by [Nguyen et al. \(2020\)](#), in addition to promoting continuous deposition.

However, it is worth mentioning that all suggestions for improvements (regardless of the trajectory strategies) would come true from experimental tests, that is, there is a need to know the input parameters (e.g. material, process, wire diameter, deposition speed and wire feed speed) and the respective output (e.g. bead height and width) of the process. In the case of A-MAT, trajectories are generated with scan lines that are not equidistant from each other, so there is a need to change parameters during the deposition to have these spaces filled. Concerning [Nguyen et al.'s \(2020\)](#) solution, the displacement of trajectories in angle corners is not calculated but rather experimentally raised and predicted with the aid of machine learning algorithms.

Finally, a good balance between the trajectory distance and building time was reached with the enhanced-pixel strategy. In the most critical cases, Parts 2 and 3, the difference to the zigzag strategy did not exceed 5% of the total building time per layer, which represented in this case study less than 30 s (about one minute for two layers, as shown in [Table 2](#)). However, the zigzag strategy promoted layer regions that were not filled by the set of scan vectors, reducing time and distance. The enhanced-pixel strategy has ensured a complete filling of a layer, because the algorithm discretises the entire layer with interconnected nodes to generate a trajectory. In addition, the enhanced-pixel strategy generates continuous trajectories for all parts studied, avoiding non-conformities from arc interruptions.

As demonstrated with the above simulations using different shapes of printable parts and trajectory planning strategies, operational efficiency analysis is complex. The criteria are not harmonious and directly related. Satisfactory attendance of a criterion with one strategy does mean that the others will be attended with the best performance. A good performance of one criterion can disguise imperfections in the built part (for example, an unfilled region due to the lack of a scan line) that might be noted only in the actual processing. Therefore, the qualification

of operational effectiveness of the proposed enhanced-pixel strategy was conducted in a holistic manner. At least for the current studied cases, the enhanced-pixel strategy, compared to the zigzag strategy, can be considered very efficient, with

Figure 11 “Part 1” with its respective dimensions and sampling lines for dimensional analysis

Source: Figure by authors

Table 3 Experiment settings for building ‘part 1’

Process	Pulsed-GMAW
Arc deposition equipment	Fronius CMT – TransPuls Synergic 500
Rig	3-axes CNC gantry (500 × 500 × 300 mm)
Substrate	SAE 1020 carbon steel (200 × 200 × 12 mm)
Substrate cooling	Active cooling (NIAC)
Feedstock (wire)	AWS ER90S-B3 – ϕ 1.2 mm
Shielding gas	Ar + CO ₂ (4%) – 15 L/min
CTWD	17 mm
Deposition speed	40 cm/min
Wire feed speed	5.2 m/min
Current	175 A
Voltage	23 V
Interlayer temperature	80 °C (monitored with a pyrometer along the sampling lines [Fig. 11])

Notes: NIAC = near-immersion active cooling, described in [Da Silva et al. \(2020\)](#); CTWD = contact tip to work distance

Source: Table by authors

competitive building times and moving distances, not presenting non-deposition paths (continuous deposition). In addition, the zigzag strategy is more prone to imperfections.

4. Operational effectiveness

Operational effectiveness can be defined as doing things correctly, that is, your outputs are in accordance with the plan and within the quality recommendations for which it is intended. This paper used this concept to assess how effective the enhanced-pixel strategy could be in targeting the nominal geometry of a part, comparatively to another trajectory planning strategy (i.e. zigzag, which was shown to be very operationally efficient in the previous section).

4.1 Methodology

“Part 1” presented in Figure 4(a) was arbitrarily selected to be physically built (and not simulated) according to the strategies presented in the operational efficiency section, Figure 7(a) and (b) related to the strategy zigzag, and Figure 7(d) and (e) to enhanced-pixel strategy. The part was not also built with the contour-parallel strategy due to the non-conformities already raised in the offline simulations.

The dimensional details of the built parts are presented in Figure 11. In addition, this figure shows four sampling lines that have been defined for dimensional analysis.

Sampling lines 1 and 2 pass through specific regions of the T-intersection that, according to Nguyen *et al.* (2020), may present

areas conducive to geometric non-conformities. Sampling line 3 passes exclusively through the bulky region, and Sampling line 4 passes longitudinally through a part that makes it possible to analyse the narrow and bulky regions. For comparison, holistic and roughness analyses (using the arithmetic average roughness parameter, R_a), according to equation (1), were carried out.

$$R_a = \frac{1}{n} \sum_{i=1}^n |h_i - H| \quad (1)$$

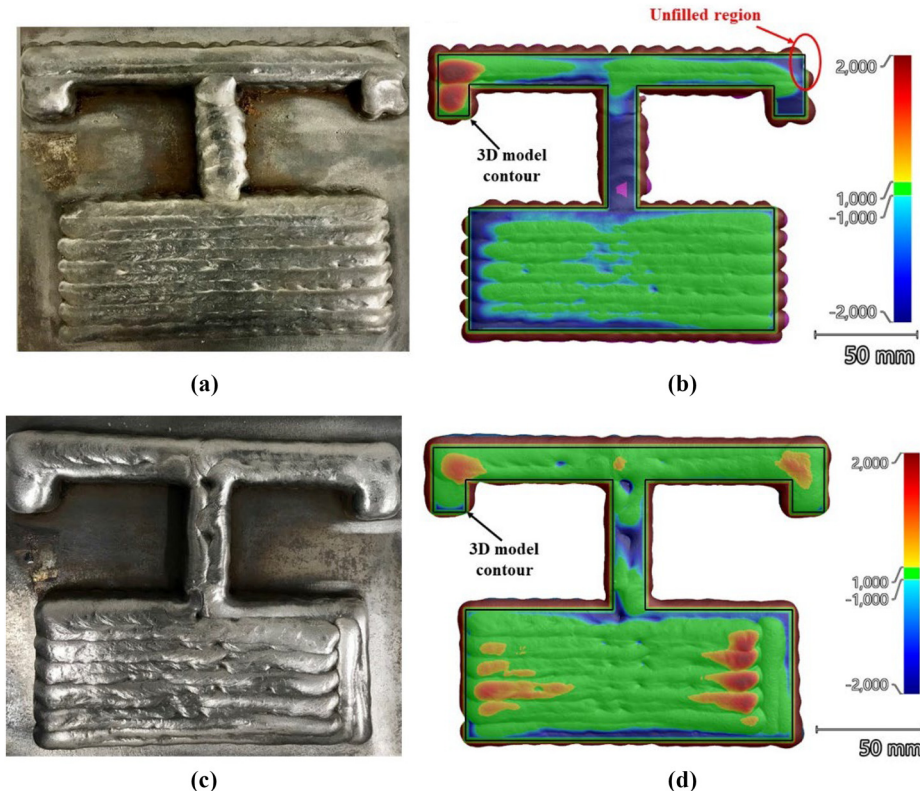
where n is the number of sample points, H is the average height of the weld bead and h is the height of each sample point on the weld bead.

Beads with 2.49 mm height and 6.60 mm width were generated according to the experimental configurations of the builds presented in Table 3. According to these dimensions and the overlap model proposed by Ding *et al.* (2015), the stepover distance was configured at 4.87 mm. The built parts were afterwards dimensionally scanned using a 3D HandyScan 3DTM scanner from Creaform. The meshes obtained by the scanning were compared with the 3D model surface using the VXEelements software, from the same scanner company. A programme, developed in Python, was used to perform the analyses on the sampling lines.

4.2 Results and discussions

Figure 12 shows the built parts and their respective digitised meshes, indicating the geometric deviation characterised by the

Figure 12 “Part 1” and its respective scanned meshes, according to the deposition strategies



Notes: (a); (b) with zigzag; (c); (d) with enhanced-pixel

Source: Figure by authors

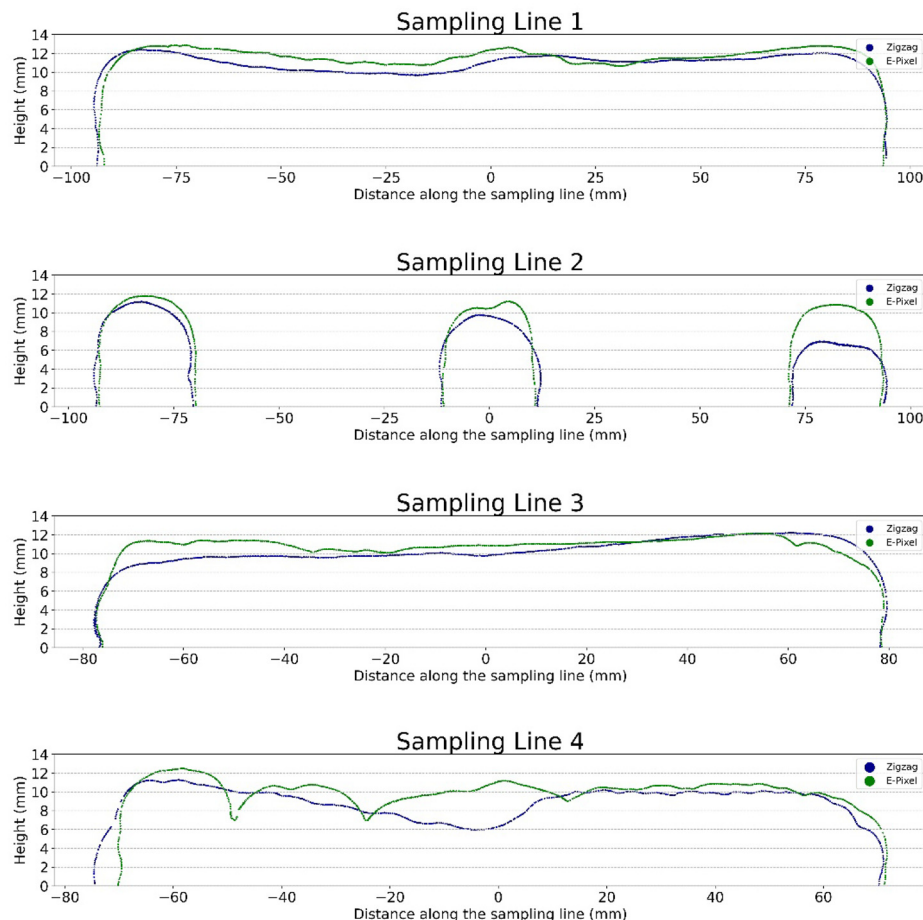
relative distance between the built part and the 3D model. The part created with the enhanced-pixel strategy, [Figure 12\(c\)](#) and [\(d\)](#), presents a larger region with green colouration, which indicates that much of the build is within the tolerance of 1.00 mm (chosen arbitrarily in this work). The part built by the zigzag strategy, [Figure 12\(a\)](#), presented an unfilled region, as highlighted in red in [Figure 12\(b\)](#). This was probably due to the absence of a scan vector in that region to fill the part in the trajectory shown in [Figure 7\(a\)](#) (x -axis 0° scan vectors) and did not support the beads deposited in the next layer, using 90° scan vectors [[Figure 7\(b\)](#)]. Then, a molten pool collapse probably occurred in this area. It can also be noted regions in dark blue (which characterise dimensional deviations below -2.0 mm) in [Figure 12\(b\)](#), enclosed in the narrow regions close to the arc striking and stopping [see [Figure 7\(a\)](#) and [\(b\)](#)]. [Hu et al. \(2018\)](#) said this may cause geometric irregularities. It is noteworthy that, using the conventional zigzag strategy, building continuously a layer is impossible. Recently [Wang et al. \(2019\)](#) presented an algorithm that can generate a zigzag with continuous scan for WAAM. [Gomez et al. \(2022\)](#) suggested something similar, an algorithm that can generate a hybrid scan (contour + zigzag) continuously. However, this author assessed this approach only on polymers, yet promising for WAAM application.

The enhanced-pixel strategy led to a satisfactory dimensional aspect, probably due to both the variation of trajectory between layers and a continuous trajectory. In agreement with the hypothesis presented, [Wang et al. \(2019\)](#) stated that the variations in the trajectory between layers contribute to reducing the accumulation of height errors on the surface as the layers are deposited. It is important to note that in the column connecting the upper arms of “Part 1” shape to its base, the shortage of material (dark blue colour) in [Figure 12\(c\)](#) and [\(d\)](#) presents an aspect of imperfections. However, as far as the trajectory (not deposition parameters) is concerned, when comparing [Figure 12\(a\)](#) and [\(d\)](#) to the larger area with dark blue colour in [Figure 12\(a\)](#) and [\(b\)](#), one can conclude that this flaw is much more prominent when using the zigzag strategy.

The two-dimensional surface contours at the sampling lines are presented in [Figure 13](#). [Figure 13\(a\)](#) shows that the enhanced-pixel strategy generated a slightly smoother contour, above the 11-mm quote (axis of the ordering direction of the nodes). The zigzag strategy provided a silhouette with depression below the 10-mm. Similar outcomes were observed with the outlines of [Figure 13\(c\)](#).

Based on Sampling line 2, [Figure 13\(b\)](#), there is an apparent lack of material (approximately 4 mm lower) in the rightmost

Figure 13 Two-dimensional contours at the sampling lines defined in [Figure 11](#) from the parts built with the zigzag (Zigzag) and enhanced-pixel (E-Pixel) strategies



Source: Figure by authors

region with the zigzag strategy, precisely where the arc stopping occurred and where there would be an unfilled region due to the absence of a scan vector, as already commented. The enhanced-pixel strategy, in turn, does not generate these non-conformities, because it is a space-filling strategy, that is, they fully fill an area and generate continuous trajectories with only one arc striking and stopping per layer. In addition, the enhanced-pixel strategy has the advantage of a continuous, closed-loop deposition, where the layer starts and ends overlap. With the use of the enhanced-pixel strategy, non-conformities occurred near the T-section of the part, which is a region prone to this failure. As can be seen in Figure 13(d), the enhanced-pixel strategy showed a more satisfactory contour, being its dimensional variations not below the quote of 7 mm (even with the lack of material found).

Summarising the results presented and discussed holistically, Table 4 shows the average roughness for the four sample lines. These results indicate that the enhanced-pixel presents shorter geometric deviations than the zigzag strategy for three of the sampling lines, which asserts its advantage in this case study.

One must remember that not excessive surface non-conformities can be resolved with surface machining. Figure 14 presents the part made with the enhanced-pixel strategy after machining. The part built with the zigzag strategy would be more challenging to machine (more buy-to-apply index).

5. Conclusions and future work

This work aimed to investigate improvements in the basic-pixel strategy and its operational efficiency and effectiveness compared with conventional strategies. From the results, it was concluded that:

- The improvements presented for the pixel strategy (here called enhanced-pixel), such as a new way of sorting nodes and the insertion of a new heuristic for trajectory planning, were positive towards the strategy performance in terms of trajectory distance.
- The random choice of the node at the beginning of the trajectory has shown to be more efficient than the choice of a node belonging to the periphery of the discretised nodes when using the enhanced pixel strategy.
- The enhanced-pixel strategy presents satisfactory operational efficiency (acceptable distances and building time) and effectiveness (lower dimensional deviation compared to the 3D model) than the zigzag and contour-parallel strategies, at least when applied in the case studies builds (shape and dimensions).

Therefore, the enhanced-pixel strategy, as proposed in this article, can be a candidate for building efficient and effective complex parts. In addition, considering the results obtained in the built part presented in Figure 14 (a shape with bulky and narrow regions), there is evidence that the enhanced-pixel strategy can be applied to builds with narrow regions. Therefore, an investigation will also be carried out in this sense, with more demonstrator parts and with greater complexity. However, it is worth mentioning that due to the flexibility of the enhanced-pixel strategy, many other adaptations to the algorithm can be made to improve operational efficiency and operational effectiveness.

As a limiting factor, even with the operator's ability to limit the search for the best trajectory (done primitively by a greedy

Table 4 R_a and lower surface value for all the sampling lines

Sampling line	R_a (mm)		Lower surface value (mm)	
	Zigzag	Enhanced-pixel	Zigzag	Enhanced-pixel
1	0.69	0.64	10	11
2	1.78	1.82	7	11
3	0.93	0.58	8	8
4	1.43	0.98	6	7

Source: Table by authors

Figure 14 "Part 1" built with enhanced-pixel strategy after top surface machining



Source: Figure by authors

algorithm), the improvement ended up with an increased computational time to find a good trajectory. So, further progress on the current enhanced-pixel strategy will focus on a smart approach for selecting the best trajectories. Another planned advance for enhanced-pixel will be its hybrid application with the contour strategy and an application using the polygonal division concept.

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Corresponding author

Americo Scotti can be contacted at: americo.scotti@hv.se