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Generation of 2.5D Deposition Strategies for LMD-based Additive Manufacturing

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Abstract

Additive manufacturing is a key technology of Industry 4.0. In the context of Laser Metal Deposition (LMD), the problem of automating the generation of the layer-by-layer deposition strategies is relevant because the laser path pattern and the process parameters determine the mechanical quality of the resulting part and the efficiency of the process. Many of the existing approaches rely on path planning strategies created for subtractive manufacturing. However, these techniques generate path patterns not suitable for LMD. This manuscript presents deposition strategies which are specific for LMD processes, including the laser path and the process parameters at selected control points. This manuscript considers diverse infill patterns for general polygonal regions. This manuscript also reports the implementation of a 2D region avoidance algorithm, used to reposition the laser head between regions and between layers. These transitions are important because current hardware maintains the material feeding while the laser is OFF. Our implementation is validated by the fabrication and verification of actual metallic parts using our algorithms in an LMD process. Future work is required on optimization of material savings and overall process performance.

Keywords: additive manufacturing; path-planning; laser cladding; Industry 4.0

Nomenclature

AM	Additive Manufacturing
LMD	Laser Metal Deposition
Laser	Source of the LMD system that provides the energy for the melting process

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Nozzle	Spout component of the LMD system that deposits the metal powder onto the build area
2.5D LMD	Laser Metal Deposition process in which the machine effector is able to translate in three linear axes but can perform the melting process only in two axes
$\Omega \subset \mathbb{R}^2$	Polygonal region in $\mathbb{R}^2$ which constitutes a 2D slice of the workpiece
$\partial\Omega \subset \mathbb{R}^2$	Subset of $\mathbb{R}^2$ that represents the boundary of Ω
$\{L_i\}$	Family of equidistant parallel lines in $\mathbb{R}^2$, $L_i \subset \mathbb{R}^2$, $i \in \mathbb{Z}$
$p_i \in \mathbb{R}^2$	Point that belongs to the line L_i
$\hat{u} \in \mathbb{R}^2$	Unitary vector that gives the direction of the family of lines $\{L_i\}$ (director vector)
$\hat{n} \in \mathbb{R}^2$	Unitary vector orthogonal to the family of lines $\{L_i\}$
$S_i \subset \mathbb{R}^2$	Set of segments that results from the intersection between the polygonal region Ω and the line L_i
$S \subset \mathbb{R}^2$	Set of segments that results from the intersection between the polygonal region Ω and the family of lines $\{L_i\}$
$\overline{P_1 P_2}$	Segment with endpoints P_1 and P_2

1. Introduction

The Industry 4.0 paradigm has revolutionized the industrial ecosystem by integrating smart systems in the production lines. Among all these new technologies, additive manufacturing (AM) has emerged as a crucial one, as it enables the fabrication of complex parts and the use of new materials [1, 2]. It also allows new production scenarios for personalized, lot-1 series, and a very high flexibility to produce quite different components with the same system. In particular, Laser Metal Deposition (LMD) plays a major role in the industry because of its applications in the reinforcement, reconditioning and repairing of high value components or the fabrication of industrial parts with complex and novel structures [3]. However, CAD-CAM design and other digital tools are still oriented to traditional manufacturing and do not match the fast-paced technical evolution of AM and LMD.

In this manuscript, we present a methodology for the generation of path planning for LMD in 2.5D, i.e. we consider that the machine effector translates in three linear axes but can execute the cladding process only in two axes. Particularly, due to typical hardware limitations in LMD real-world systems, we consider the case in which the metal dispensing through the nozzle is not interrupted at any time, while the other process parameters (e.g. process speed and laser power) can vary between metal melting stages. For this reason, we develop a 2D region avoidance algorithm to execute the transition movements, so that unmelted metal powder does not adhere on the surface of the part that is being built when the laser is OFF. The methodology is evaluated via physical experimentation using a fiber laser *IPG YLS-6000* and stainless steel *316L* as powder material.

We present in Section 2 a systematic review of the related work. We describe the approach for the generation of path planning for 2.5D LMD and display the results of its implementation in Sections 3 and 4, respectively. Finally, we conclude the manuscript and make suggestions for further work in Section 5.

2. Literature Review

2.1. Path Planning in Laser Metal Deposition

Path planning in LMD tackles two problems in the manufacturing process: 1) the generation of the trajectory that the laser must follow and 2) the determination of the process parameters (e.g. laser power, process speed, powder flow) at every point of the trajectory.

The temperature history has a significant impact in the mechanical and structural properties of the built parts manufactured by LMD. In this context, path planning plays a major role in LMD, since the temperature history is intrinsically linked to the tool trajectory and process parameters [4, 5].

Path planning strategies in AM are mainly based on the more mature path planning techniques used for subtractive manufacturing. It is often necessary to adapt these techniques, so that they are suitable for AM [6, 7]. However, in the context of metal AM, previous research is mainly focused on Wire Arc Additive Manufacturing (WAAM) [7–10] and few works address LMD [6, 11, 12].

2.1.1. 2D Infill Geometries

Ding et al. [7] summarize the principal infill strategies used in the context of AM, namely raster, zig-zag, contour-offset and spiral. Related works propose variations of these four strategies that overcome some difficulties associated with each one. Flemmer et al. [13] propose a zig-zag infill that uses the medial axis of the 2D region instead of straight lines, which reduces the number of turning points. Xiong et al. [14] present a novel infill based on the level-set method that eliminates the voids that appear in traditional contour-offset infill. Ding et al. [7] and Jin et al. [15] consider a hybrid approach in which the contour-offset and zig-zag strategies are used together to reduce the geometrical inaccuracies that may appear when only zig-zag patterns are used.

Other works focus on the solution of particular problems related to the path-planning process. Liu et al. [9], Routhu et al. [16] and Xiong et al. [14] address the problem of material accumulation due to the sharp corners that appear on zig-zag or contour-offset patterns. Ding et al. [7] present a path-planning based on a divide-and-conquer approach by decomposing the polygonal zones in every slice into convex polygons which are simpler to fill. Michel et al. [10] show a solution in which the process parameters can vary in different zones of a continuous path. Thus, an experienced user can configure special process parameters in zones with a challenging geometry. However, far too little attention has been paid to process parameters configuration during path planning. Likewise, apart from Ding et al. [7], there is a general lack of research in the problem of connecting paths in the layer (intra-layer) and between layers (inter-layer).

2.2. Conclusions of the Literature Review

In our literature survey we have found that the path planning for AM is mainly based on subtractive manufacturing strategies. In general terms, subtractive manufacturing strategies are the core of path planning in LMD. However, it is also clear that these techniques should be adapted to meet the constraints of LMD.

We have found active research lines that tackle the particular issues (such as voids appearance and material accumulation in sharp corners) that arise from the direct use of subtractive manufacturing techniques in LMD. However, few studies consider the following two important needs properly: 1) continuous process parameters configuration during deposition and 2) the generation of intra- and inter-layer connections paths that fulfill the requirements of LMD. We present in this article a methodology that explicitly addresses both issues.

3. Methodology

3.1. Workflow of the Generation of Trajectories in 2.5D

In this work, we focus on the generation of the path planning for an LMD system restricted to 2.5D, i.e. the machine effector is able to translate in three linear axes but can perform the deposition process only in two axes. The procedure we follow is divided into four steps (see Fig. 1):

1. **Polygon decomposition:** The polygonal domain $\Omega \subset \mathbb{R}^2$ defines the area to be filled. The polygonal domain Ω may contain holes, i.e. areas that should *not* be filled. We decompose Ω into simple polygons and organize them in a tree hierarchy. Fig. 1b shows the resulting tree for the polygonal region in Fig. 1a. Notice that each simple polygon in this tree can represent either a portion of material to be filled or a hole in its *parent* polygon. The strategy followed implies that in each particular slice (i.e. Z level) we hierarchically decompose the existing polygonal regions. This decomposition allows for the accommodation of polygons with holes that may exist inside other polygons (and so on). This tree-like representation also allows for the inclusion of orientation (clockwise or counter-clockwise) for external or internal polygon borders.
2. **2D infill generation:** The goal at this stage is to obtain a geometrical representation of the path lines in which material has to be deposited. Here, we process those polygons that represent areas to be filled. Fig. 1c shows that, when generating the infill for these polygons, we also consider that their holes should be avoided. Further details for the infill pattern implemented in this work are given in Section 3.2.

3. **Local 2D trajectory generation:** At this stage, the trajectory of every layer is generated (see Fig. 1d). It is important to remark that a trajectory includes both geometrical and processing aspects: process speed, laser power, powder flow and all the other processing variables are defined at this stage. More details on the trajectory generation can be found in Section 3.3.
4. **Global trajectory generation:** After the generation of the trajectory for each layer, it is still necessary to connect consecutive layers. Current available hardware maintains the material feeding when the laser is OFF. Unmelted powder particles on the surface of the previously deposited layers can affect the quality of the next layers. Thus, the inter-layer connection paths must avoid the previously deposited layers to prevent the deposition of metal powder on the surface of the building part. More details on how we generated valid connection paths are given in Section 3.4. An example of a global trajectory is shown in Fig. 1e.

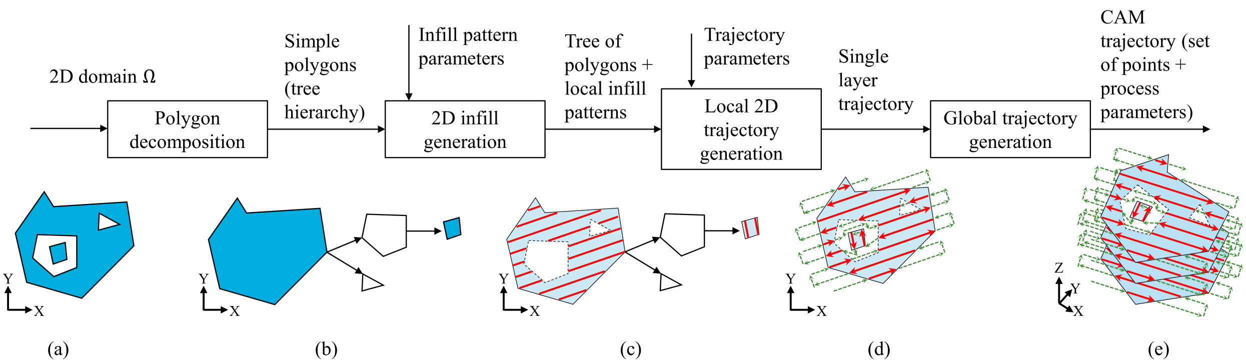


Fig. 1: Workflow for the path planning for prismatic parts in 2.5D.

3.2. 2D Infill Generation

The infill generation marks the places in which the metal powder will be deposited and fused. It means that only *geometrical* considerations are considered at this stage. In this work, we implemented a pattern formed by uniformly separated parallel lines, that is suitable for raster and zig-zag trajectories.

In order to implement the parallel-lines infill pattern, we first solved the following problem: to find the intersection of a line with a 2D polygonal region. The problem was formalized using the traditional *Given-Goal* approach following the main idea in [17].

Given

1. 2D closed and bounded polygonal region $\Omega \subset \mathbb{R}^2$, that may contain holes.
2. A line L_i, with unitary director vector $\hat{u} \in \mathbb{R}^2$.
3. A point $p_i \in \mathbb{R}^2$ that belongs to L_i ($p_i \in L_i$).

Goal

To find the set of segments of L_i that lie inside or on the boundary of Ω, that is, to find the set S_i:

$$S_i = \{(s_0, s_f) : s_0 = p_i + \alpha_0 \hat{u} \in \partial\Omega, s_f = p_i + \alpha_f \hat{u} \in \partial\Omega, p_i + \alpha\hat{u} \in \Omega, \alpha_0 < \alpha < \alpha_f\}.$$

Our implemented pattern is formed by intersecting a family of parallel lines $\{L_j\}$ ($j \in \mathbb{Z}$) with the polygonal region Ω. The set $\{L_j\}$ can be uniquely defined with:

1. a unitary director vector $\hat{u}$ which denotes the direction of the lines,
2. a point p_0 that belongs to L_0 ($p_0 \in L_0$),
3. a parameter $d > 0$ which denotes the separation between the lines.

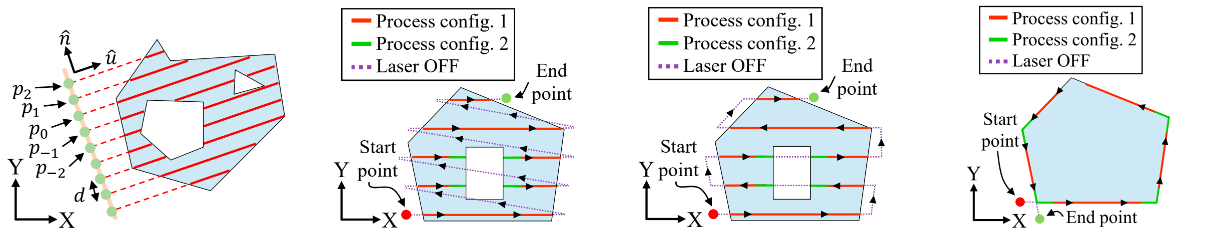
The resulting set S of the intersection segments between the family of lines $\{L_j\}$ and the polygonal region Ω can be obtained by solving several times the formerly posed problem:

$$S = \bigcup_{j \in \mathbb{Z}} S_j,$$

where $p_j \in L_j$ are obtained using the following expression:

$$p_k = p_0 + (kd)\hat{n},$$

where $\hat{n}$ is orthogonal to $\hat{u}$ and $k \in \mathbb{Z}$. A graphical representation of the involved entities and the expected output is given in Fig. 2a.



(a) Infill of polygon with holes using a family of parallel lines.

(b) Idle return (raster) trajectory.

(c) Active return (zig-zag) trajectory.

(d) Continuous trajectory (currently only for boundaries).

Fig. 2: Implemented methods for path planning in 2D. (a) Infill generation and (b)–(d) trajectory strategies.

3.3. CAM Trajectory Generation

The path planning encompasses two main aspects: the determination of the path that the tool follows and the process parameters at each point of the defined path. The geometrical aspects of the deposition path are determined in the previous stage of the workflow (infill generation). There are two questions that remain to be solved: 1) how to traverse the generated infill pattern and 2) how to connect the independent regions without affecting the quality of the workpiece.

In comparison with previous works, we dedicated special attention to the second issue, which refers to the movements of the laser head while it is OFF. Since current hardware maintains the material feeding along all the building process, it was important to prevent the deposition of powder particles on top of the surface of the workpiece with the laser OFF. Section 3.4 describes our approach to generate them. We refer henceforth to these subsets of the trajectory as *idle* paths.

We implemented three types of trajectories to traverse the infill patterns: 1) raster or idle return, 2) zig-zag or active return, and 3) continuous (only implemented for polygon contours), which are shown in Fig. 2. Figs. 2b– 2d exhibit red and green regions, which denote different process parameters configurations. The reader may observe that the green regions (*Process config. 2*) mark challenging zones where the deposition process must be adjusted (e.g. the presence of holes or corners). Although Figs. 2b– 2d show only two process configurations, the implemented software allows several configuration adjustments on a deposition segment.

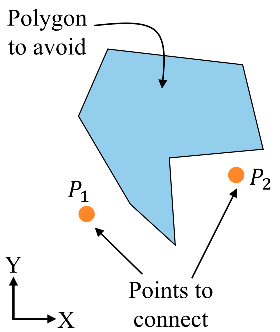
3.4. Generation of Idle Paths

One of the main differences between LMD and subtractive manufacturing is in the generation of the idle trajectories. In contrast to subtractive manufacturing, the idle paths affect the quality of the final part. The main reason is that for many LMD systems, the powder is supplied during all the process, even when the laser is OFF. It is known that unmelted material can cause structural defects [18]. Therefore, we included the restriction to avoid the building piece when generating the idle paths.

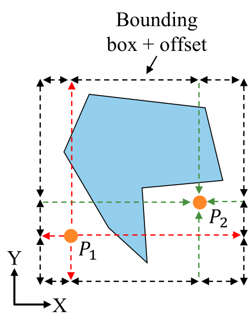
We used a graph-based approach to deal with this problem. Fig. 3a shows a geometric configuration in which the segment $\overline{P_1P_2}$ invades the building piece. In order to find a feasible solution, we construct an undirected weighted graph G using the bounding box of the building piece:

1. P_1, P_2 are added as nodes of the graph G (nodes 1 and 2 in Fig. 3c).
2. The corners of the bounding box are added as nodes of the graph G (nodes 3–6 in Fig. 3c).
3. Axis-aligned escape routes are found from P_1 and P_2 to reach the bounding box without invading the building piece. The points in the bounding box belonging to these escape routes are added as nodes of the graph G (nodes 7–14 in Fig. 3c).
4. The edges that connect the nodes in the graph G are generated. Only axis-aligned edges are considered (see Fig. 3b).
5. The distance between the nodes of the graph is assigned as the weight of each edge, except for those edges that invade the building piece. In that case, the weight is set to infinity. The resulting graph is shown in Fig. 3c, where $d_{i,j}$ denotes the Euclidean distance between nodes i and j.

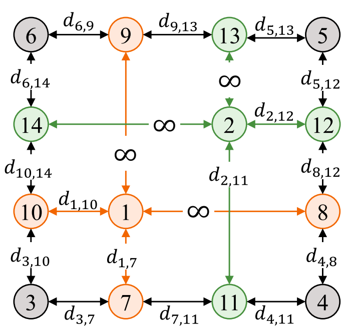
We implemented Dijkstra's algorithm to find the shortest path that connected P_1 and P_2. It is important to remark that the resulting path given by the Dijkstra's algorithm is the shortest path in the generated graph, which does not imply it is the shortest path in the geometric configuration. On the other hand, when only infinite-length paths exist, P_1 and P_2 are connected directly.



(a) Entities involved in the polygon avoidance problem.



(b) Trajectories which use a 2D bounding box to join P_1 and P_2.



(c) Graph expenses of the orthogonal trajectories in (b).

Fig. 3: Traversal strategy to reposition metal dispenser nozzle (while laser is OFF) between working stages.

4. Results

4.1. CAM Trajectory Generation

One of the keys of our proposed methodology is the decomposition of the polygonal region into simple polygons. Fig. 4a shows a complex polygon region in which one can identify three disjoint zones where the material is to be deposited. The decomposition of this complex region into simpler polygons allows the generation of a custom infill for each polygon in a natural manner.

Figs. 4b–4d present the path planning to build two solid (filled) parts and Fig. 4e shows the path planning for a thin-wall structure. Fig. 4b shows the resulting path to build a solid piece without holes. The path is generated using a zig-zag strategy and the laser head only moves upwards in layer-to-layer transitions (i.e. the X and Y coordinates of the end point of layer i coincide with the start point of layer $i+1$).

Figs. 4c and 4d show two trajectories to build a solid part with a hole. The deposition lines are traversed using the zig-zag trajectory. In contrast to the Fig. 4b, in this case the laser head must be repositioned in inter-layer transitions, since the start point of each layer is the same (X and Y coordinates). In Fig. 4c is observed that the repositioning path line (green line) crosses the polygon. On the other hand, the repositioning path in Fig. 4d goes around the polygon, preventing that unmelted powder material adheres to the surface of the building part. This path was obtained using the graph-based approach for polygon avoidance.

As mentioned in the methodology, another important aspect in our approach is to include transition points in the design of the trajectory so that the process parameters are adapted to enhance the quality of the final piece. In Figs. 4c and 4d it can be observed that when building solid pieces, transition points are added in the neighborhood of the hole. On the other hand, Fig. 4e shows that transition points are added at the sharp corners (angles less than 90°) of the thin-wall pieces, since the material tends to accumulate at these zones. However, the location of the transition points as well as the value of the process parameters at these points are still subjects of research.

4.2. Experimental Validation

In order to validate the presented approach, we performed three tests using a powder-fed LMD machine. The powder material used for the experiments was *AM 316L* (*EN 1.4404*), from Höganäs. The experiments were performed using a high power fiber laser (*IPG YLS-6000*), with wavelength of 1070 nm, and guided to the optical head by means of a 1000 μm core diameter optical fiber. The optical head was mounted in a 3 linear axis system.

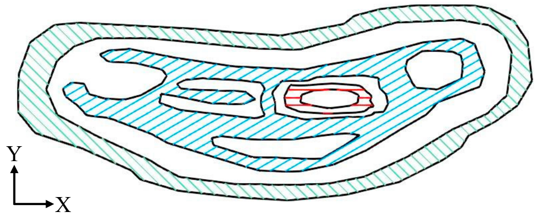
Metallic powder particles were delivered to the process zone through a coaxial nozzle, using Nitrogen as carrier gas. Also, that gas was used to generate a protective atmosphere during the deposition process. A schematic layout of the used LMD system is shown in Fig. 5a. Table 1 reports the LMD process parameters (consulted from Ref [11]) used in producing the actual workpieces in our experiments.

Table 1: Process parameters used for the physical experiments [11].

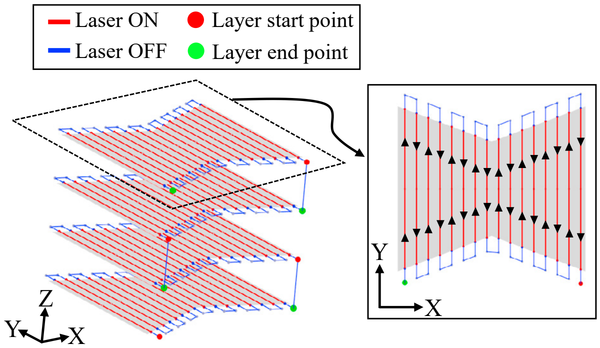
Parameter	Value	Units
Process speed	13	mm/s
Laser power	2500	W
Powder flow	25	g/min
Overlap percentage	30%	N/A

The results of the experimental tests can be observed in Fig. 5. The path planning for each test was calculated using the presented approach. We also automatically generated the instructions that served as input for the machine (in G-Code format). Figs. 5b and 5c show the resulting parts after using a zig-zag strategy to fill 2D areas with and without holes. The two tests were satisfactory, since the final pieces represent adequately the expected geometry. However, some height variations can be observed in the boundaries (internal and external), where the deposition starts or ends.

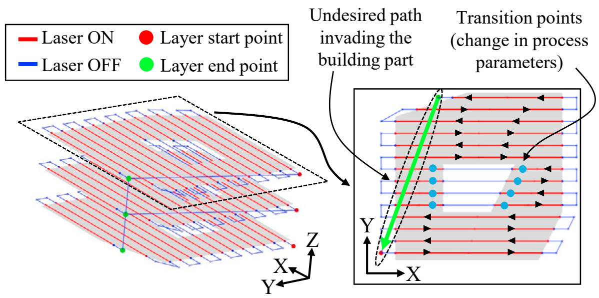
Fig. 5d depicts a thin-wall structure produced using a continuous strategy. An excess of deposited material is present at the junctions of straight nozzle trajectories. The quantification, explanation and correction of such an effect is the matter of another manuscript by the research team.



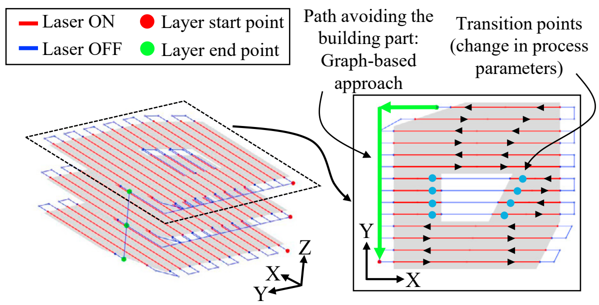
(a) Tree-based hierarchical decomposition of 2D region, with diverse infill patterns.



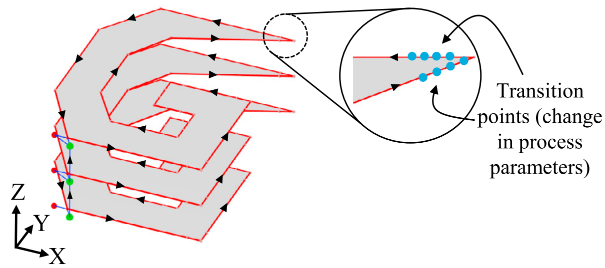
(b) Inter-layer positioning of nozzle using diverse transition (X, Y) resting points.



(c) Inter-layer positioning of nozzle using a constant transition (X, Y) resting point. Idle-laser trajectory crosses the workpiece slice.

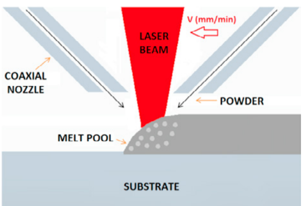


(d) Inter-layer positioning of nozzle using a constant transition (X, Y) resting point. Idle-laser trajectory does not cross the recently executed workpiece slice by using the graph-based method for polygon avoidance.

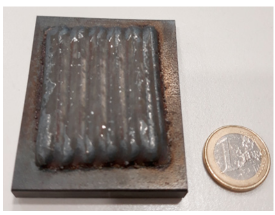


(e) Process parameters control in boundary sharp corners due to redundant material delivery.

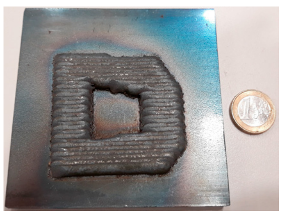
Fig. 4: Some resulting implementation features for LMD.



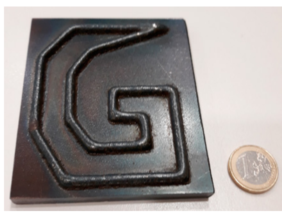
(a) Schematic layout of the coaxial laser cladding system [11].



(b) Polygonal region without holes filled with continuous-line hatching pattern.



(c) Polygonal region with holes filled with continuous-line hatching pattern.



(d) Thin-wall structures.

Fig. 5: Actual workpieces from powder-fed LMD hardware, using the software implemented and reported in this manuscript.

5. Conclusions

In this manuscript we presented a methodology for the generation of 2.5D path planning for LMD. The presented approach considered not only the geometrical aspects of the toolpath generation but also (1) incorporated a graph-based region avoidance algorithm to alleviate hardware limitations and (2) provided the user the control to use several process parameters in a single deposition segment.

We implemented (1) the raster and zig-zag trajectories to fill a 2D polygonal zone that may contain holes and (2) a continuous trajectory to be used for thin-wall structures. These approaches were validated via physical experimentation using a powder-fed LMD system. The results of this study showed that subtractive manufacturing path planning methods can be used to LMD, even though it is necessary to adapt them to fulfill the particular constraints of LMD. Further work is needed to implement and validate additional infill strategies, such as spirals. It would also be interesting to seek approaches that minimize idle time and material waste.

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