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DEVELOPMENT OF A ROBOTIC ADDITIVE MANUFACTURING CELL BASED ON A LASER METAL DEPOSITION PROCESS AT THE UNIVERSITY OF COIMBRA AND THE UNIVERSITY OF BRASILIA

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Abstract. *This work showcases two Robotic Additive Manufacturing (AM) Cells that use Laser Metal Deposition (LMD) through Meltio hardware, one at the University of Coimbra (Portugal) and the other at the University of Brasilia (Brazil). The aim is to reflect on how these systems are developed to make compelling solutions for metal manufacturing. In consideration first are the equipment selected for each cell, both universities use Kuka robots a KR 70 R2100 at the University of Brasilia and a KR 60-3 at the University of Coimbra. Using a multi-laser deposition head with 6 converging lasers (200 watts each) the AM cells are capable of building with several materials, for example, stainless steels, mild steels, carbon steels, titanium, nickel, and copper. The University of Brasilia´s Meltio system was acquired in July 2022, giving an approximate investment for the cell of $180,000. This work focuses on the physical and logical integration/implementation in hardware (robot controllers, deposition heads, safety mechanisms, etc.), and in software (Computer-Aided Design/Computer-Aided Process Planning/Computer-Aided Manufacturing (CAD/CAPP/CAM)), elaborating on different material deposition strategies for planar and non-planar path planning (slicing), and multi-axis manufacturing. Next, the development of Digital Twins is presented and analyzed in virtue of the practicality to simulate and test different strategies in a virtual environment. Through this paper, a direct look at two universities´ outlooks on LMD manufacturing is presented, discussing different levels of developing AM cells and contributing to the current state of the art of LMD process and robotic systems.*

Keywords: Laser Metal Deposition (LMD), Additive Manufacturing, Robotic, Grasshopper, Digital Twin

1. INTRODUCTION

Laser metal deposition (LMD) is an additive manufacturing method, also known as Direct Energy Deposition (DED), Direct Metal Deposition (DMD), or Laser Cladding. It can be based on Wire or powder materials (Mahamood, 2017; Bian *et al.*, 2018). The additive manufacturing robotic cells developed by the University of Coimbra (UC) and the University of Brasília (UnB) use an LMD-Wire deposition head, which is a product of the Spanish company Meltio, called Meltio Engine Robot Integration. Both universities have chosen to use Kuka robots (`https://meltio3d.com/products/meltio-engine-robot/`). The Wire materials include stainless steel, mild steel, carbon steel, titanium, nickel, and copper.

The deposition head consists of six 200-watt diode lasers, totaling 1200 watts. These lasers are aligned using adjustable collimators in two directions to symmetrically divide the six laser beams along the perimeter of the Wire. By adjusting the lasers, the laser beam is concentrated 50% on the Wire and 50% on the substrate, ensuring better quality in material deposition. It is known that the key parameters of the LMD-Wire process are laser power, robot speed, and Wire feed rate (Zhong *et al.*, 2020; Schulz *et al.*, 2019). It is important to note that the Wire material, the dimensions of the part to be printed, the complexity of the part's geometry (hollow or solid), and the temperature gradient between the substrate and the position of the deposited weld bead, along with the material deposition strategy, all influence the final quality of the printed part.

According to Li *et al.* (2021) and Feenstra *et al.* (2021), the optimization of the LMD-Wire process typically uses laser power, robot speed, and Wire feed rate as input parameters. The output parameters considered are the dilution rate, aspect

ratio, and microhardness.

Both the University of Brasilia and the University of Coimbra employ Kuka robots for additive manufacturing (AM) purposes. The University of Brasilia's AM cell, powered by a KR 70 R2100 robot and equipped with a multi-laser deposition head featuring six converging 200-watt lasers, is capable of utilizing various materials including stainless steels, mild steels, carbon steels, titanium, nickel, and copper. In July 2022, the University of Brasilia acquired the Meltio system for approximately $180,000, focusing on the integration and implementation of hardware components (robot controllers, deposition heads, safety mechanisms) and software systems (CAD/CAPP/CAM) to enable different material deposition strategies. Additionally, the development of Digital Twins is explored as a means to simulate and test diverse strategies in a virtual environment. This study offers valuable insights into the advancements in AM cells and contributes to the state of the art in both LMD process and robotic systems, reflecting the perspectives of two universities.

The paper presents two Robotic Additive Manufacturing Cells developed by the University of Brasília (UnB) and the University of Coimbra (UC). The solutions associated with the Digital Twin platforms developed by UnB and Coimbra are then presented, including the functionalities provided, such as monitoring, simulation, and programming of Kuka robots, as well as the communication protocols and software used and developed. The paper also includes case studies. In the case of Coimbra, a real piece printed by the platform is presented. UnB presents a case study associated with the developed Digital Twin, without the actual printing of a piece, as the cell is still in the assembly process and is expected to be completed by September 2023. Furthermore, future works are presented, and the paper concludes with the final considerations.

2. ROBOTIC ADDITIVE MANUFACTURING CELL OF UNB

The Robotic Additive Manufacturing Cell of UnB using the LMD-Wire process consists of a Kuka KR70 R2100 robot and the Meltio Engine Robots LMD-Wire system. The cell is currently being assembled (Fig. 1) inside a metal enclosure with dimensions of 4.75x5x3.5 m and is expected to be operational in September 2023, as all the equipment, systems, and components are already available. The enclosure is fully enclosed and equipped with four Safety Laser Windows (976 nm wavelength Laser Filter) to ensure operator safety.

A door interlocking system is in place using a Safety Relay connected to the emergency stop buttons of both the Kuka KCR v5 controller and the Meltio system. This system ensures that the cell can only operate when the door is closed.

A table with a height of 300 mm is used, and on top of the table, there is a metallic workpiece, and a substrate measuring 300x300x35 mm. The metallic deposition cords will be added to this substrate through additive manufacturing, forming the final piece.

The equipment cost was 800,000 Brazilian Reais, and the cost of other components was 50,000 Brazilian Reais. The project received support from a FAPDF (Foundation for Research Support of the Federal District), amounting to 1 million Brazilian Reais. Up to this point, 850,000 Brazilian Reais have been spent. To complete the Meltio/Kuka integration, the startup of the Kuka robot and operator training are pending, scheduled for August 2023. This also includes securing the robot to the floor using Fischer chemical anchors, as well as the physical and logical integration of the Meltio LMD-Wire deposition head. The training for the Meltio LMD-Wire system took place in Spain in September 2022, and the Meltio Engine Robots are currently stored in a box at the back of the image shown in Figure 1.

On the office desk (Fig. 1), outside the Cell, a computer will be installed with software such as Kuka.sim, Rhinoceros, and Grasshopper, along with other applications used in the development of the Digital Twin computational platform. A USB camera will be installed for both on-site and remote monitoring of the deposition process. The Meltio and Kuka controllers, as well as a chiller for cooling the Meltio LMD-Wire deposition head, will be installed outside the Cabin, next to the desk.

The cell is being developed by the Industrial Automation Innovation Group (GIAI) at the University of Brasília (UnB) and is the first robotic additive manufacturing system in Brazil, as well as in Latin America.

3. UNIVERSITY OF COIMBRA LMD ROBOTIC CELL

The University of Coimbra´s vision for developing an additive manufacturing system is to further push limits in terms of geometry, performance, efficiency, and sustainability. To start, a reflection was made on how to focus developments given the multifaceted research problems that currently exist. In this context a general hardware layout was drawn with 3 main components: (1) A robot, (2) A deposition tool, and (3) the build surface (in this case a table). The robot selected was a KUKA KR60-3 which has 6 axes, a 2033 mm reach, and a 60 Kg payload, for the deposition tool an LMD-Wire tool (MELTIO Engine) was chosen and finally a standard welding table with 1x1.5 m2 area was acquired.

Different combinations of hardware are relevant to consider and are implemented by different institutions (Svetlizky *et al.*, 2021). Although serving the same purpose these solutions try to improve the stability and flexibility of the manufacturing process, for instance, the use of a rotational table for a more accessible non-planer 3D printing of complex designs (Maffia *et al.*, 2023).

With this layout, the primary problem discussed was the control logic/methodology. In this regard different strategies
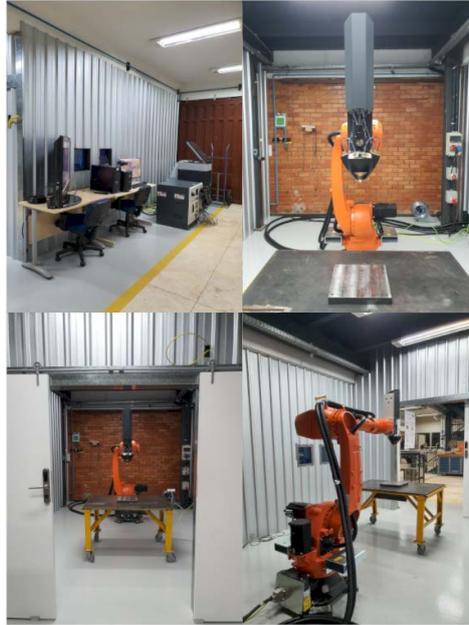
Figure 1. LMD-Wire Robotic Additive Manufacturing Cell in assembly: Kuka KR70 R2100 and Meltio Engine Robots.

were explored (Pires *et al.*, 2022; Ribeiro *et al.*, 2019; Pires and Azar, 2018), ultimately deciding on a more open solution that can be adapted to the needs of the research, as described in Pires *et al.* (2022). To achieve this, the methodology is structured loosely as: Start by defining process planning (slicing, parameter definition, and robot configurations), using this information outline a generic file with AM instructions (similar to g-code), then launch the generic file in the preferred system, finally as it is manufacturing, control some parameters like cooling rate and also get feedback data (i.e., robot deviations in path). In the robot controller, this is defined with 3 asynchronous tasks (Fig. 2): the first uses a TCP/IP socket to control the state of the robot, the second task focus exclusively on handling data communication by sending UDP datagrams at set time intervals and the third task handles any motion of the robot. This last task is where printing protocols are established, namely by defining subroutines for different welded features (linear welds, corner welds, overlaps, etc.).

Another important consideration was placed on the safety and communication connections in the system, specifically how the robot and deposition tool are interconnected. For the solution at the University of Coimbra, the I/O connection was made using EtherCAT modules (Kuka) and Meltio´s connectors. A safety system using the X11 interface (Kuka) was done to ensure that if the robot detects an error state (for example caused by a collision) the Meltio tool will deactivate the feed system and lasers, conversely if the tool enters an error state the robot will also stop.

With the system enclosed, and prepared. There are some important questions to address, specifically: how to define the printing procedure and how to interface with the system. The latter is simple to address, the user can export the printing procedure as a KRL (Kuka Robot Language) program and run directly in the robot, but given the methodology implemented this KRL program is instead a generic text or XML file that is executed when a user selects it through a TCP/IP command using a developed Graphical User Interface (GUI) (Fig. 2).

The printing procedure is more complex to establish because it is dependent on the deposition process, and hardware layout. The challenge is defining each layer considering the deposition process (fusion, melt pool, heat affected zone, etc.) and maintaining attributes like focal point and focal distance constant. To simplify this problem, the initial approach was to take advantage of ready-made software packages at the different stages of defining the printing procedure, as detailed in the following bullet points:

- Stage 1 Material Modelling – Define a material deposition model according to available process parameters, obtained from previous experiments.

- Stage 2 Slicing – Using open-source slicing software (Cura, Slic3r, etc.) explore different CAD segmentation strategies. Obtaining a g-code file with welding trajectories.

- Stage 3 Path Planning – Adapt the deposition trajectories to account for tool orientations, workspace restrictions and evaluate singularities.

- Stage 4 Comparative analysis – Compare different solutions (stages 1-3) to find the optimal set of instructions that minimize defects, distortions, and instabilities.

- Stage 5 Code Conversion – Format printing instruction to a readable format by the robot controller (KRL or generic code).

With this logic defined and integrated, the system has the base necessities to function.
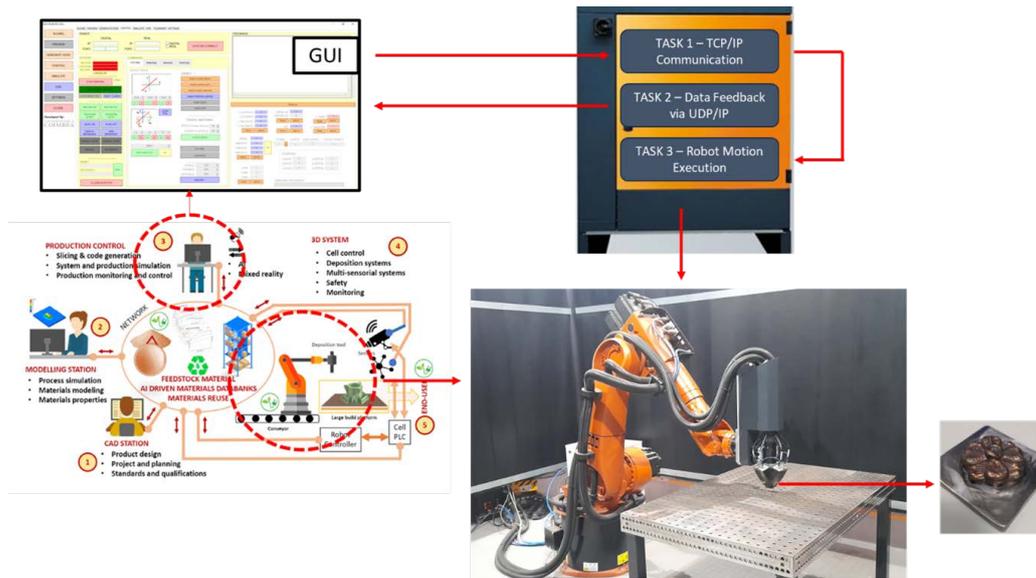
Figure 2. Hardware Layout of UC´s LMD system, as well as the main data connections between user and component for control of the Robot. Adapted from Pires *et al.* (2022).

4. DIGITAL TWIN PLATFORM OF THE UNIVERSITY OF BRASILIA

The Digital Twin (DT) implemented in the UnB Cell is based on the ISO 23247 standard (ISO 23247-1 (2021)), which describes a Digital Twin Framework for Manufacturing. Figure 3 illustrates the four layers of UnB's DT proposal.
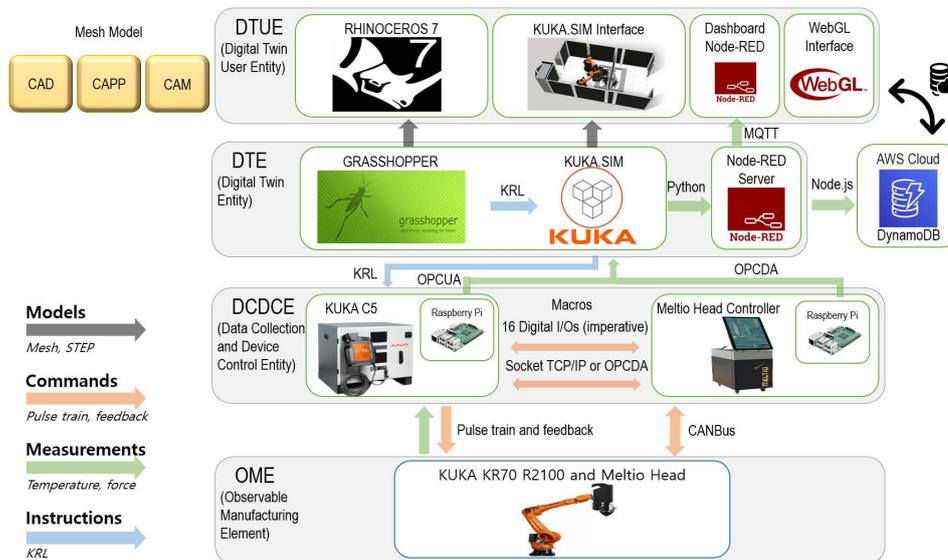

Figure 3. Digital Twin architecture for parameterization of planar and non-planar additive manufacturing and robot life cycle simulation with ISO 23247 framework.

The first layer, looking from bottom to top in Figure 3, corresponds to the observable manufacturing entity/element domain, where the Kuka KR70 R2100 robot and the Meltio Engine Robots LMD-Wire system are located, from which process data and machine status will be collected.

The Kuka KR70 R2100 robot is integrated with the Meltio Engine Robots LMD-Wire system, using OPC-UA, OPC-DA, TCP Sockets, and CANBus protocols to obtain machine data. A Raspberry Pi 2 was used to establish the communication channel with the LMD-Wire robot, acting as the OPC-UA/OPC-DA/CANBus/Sockets Ethernet-TCP/IP gateway. The Meltio/CANBus communication protocol consists of a set of macro-commands that can be sent to the machine to retrieve machine data or control any of the actuated devices.

The second layer of the architecture corresponds to the domain of data collection and control of actuated devices

present in the previous OME domain. In this part of the architecture, a development board with a Raspberry Pi 2 micro-processor has been used as a data acquisition system embedded in the machine structure and connected to it via Ethernet TCP/IP.

A server application has been developed using JavaScript technology in the Node.js execution environment, which is embedded in the Raspberry Pi 2 computer. This application communicates with the machine via TCP/IP, sending the macro-commands of the Meltio application protocol to retrieve the desired data and make them available to the DT domain through different TCP/IP sockets (communication channels) using OPC-UA, OPC-DA, and MQTT application protocols, which are recommended by ISO 23247.

The third layer constitutes the domain of the DT, which represents the core of the developed system. At this point, there are application services and DT functionalities that are provided to interested users, which can be end-users and/or other systems. The services provided by the DT in this work are monitoring with 2D visualization (dashboard) and CAD/CAPP/CAM with 3D visualization (3D simulation) of the LMD-Wire Robotic Additive Manufacturing Cell, which are the basic services outlined by ISO 23247. The Rhinoceros-Grasshopper (CAD/CAPP/CAM), Kuka.Sim (Simulation), and Node-RED (monitoring and storage of data in a database) platforms are used.

The fourth layer, the Digital Twin User Entity domain, consists of the individuals or systems interested in consuming the services provided within the DT domain. In this case, the users are the members of the LaDPRER laboratory at the University of Brasília who make use of the machine.

The Rhinoceros-Grasshopper is used as a CAD/CAPP/CAM system, where a mesh model of the part to be printed is imported, and parameters for the printing process are configured, such as layer height/width, laser power, robot speeds, Wire feed rate, substrate dimensions, among others. The CAPP/CAM module performs process planning and generates the KRL program for the Kuka robot. The program is then sent to Kuka.Sim, which conducts a simulation of the printing process to validate the generated KRL code.

The process variables are monitored and presented on an online 2D dashboard, using HTTP and MQTT protocols, with the aid of Node-RED. The monitored variables are stored in a cloud-based database (AWS) for future use, including predictive analysis algorithms such as predictive maintenance.

5. DIGITAL TWIN PLATFORM OF UC´S LMD SYSTEM

At the University of Coimbra the same hardware layout was modeled in RoboDK software (Fig. 4), and to adhere to the same printing logic (using generic files) a Python code was integrated into RoboDK simulation. Because of the use of third-party software to simulate the robot, the accuracy of the simulation is not perfect, as the code interpretation, signal simulation, and motion processing is different. That said for simple kinematics it can be used to validate the deposition trajectories.

To complement the Digital Twin, the focus has been made to fully monitor the manufacturing process in situ. Although this feature is not fully developed for the LMD system, the methodology for storing, and analyzing this data is being researched with UC´s LMD-Wire system. The intent is to have the data gathered in real-time to dynamically adjust the printing process, in essence as a closed feedback loop that works as a cyber-physical system.
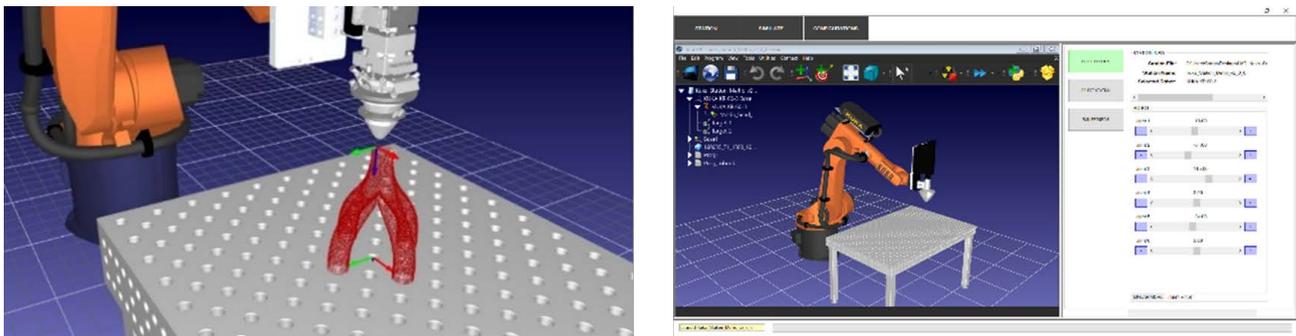

Figure 4. RoboDK station of UC´s LMD layout.

6. CASE STUDIES: MATERIAL DEPOSITION AND SIMULATION

6.1 University of Coimbra

Regarding the material deposition, the starting approach was to manufacture simple geometries (walls and cubes) to understand the significance of each parameter (Laser Power, path sequence). For these experiments, stainless steel 316LSi Wire was welded together with a pure argon shielding gas. This paper presents initial observations of a case study.

Table 1. Slicing Parameters and Meltio Parameters were used for the Cube case study.

Parameter	Value
Layer Width	1.2 mm
Layer Height	1 mm
Laser Power Meltio	700-900 W
Feed Speed Meltio	15-16 mm/s
Infill Type	Rectilinear at 45 degree
Perimeter	1 Perimeter
Overlap	12%

Figure 5. LMD Cube was produced at the University of Coimbra.

6.1.1 Case study: LMD cube

The first case study is a simple cube with 40x40x40 mm3 volume (Fig. 5) done together with Meltio staff during the installation of the laser system. The slicing was done using UltiMaker Cura with the parameters in Table 1.

To determine the feed speed the conservation of volume (equation 1) was used, where considering a travel speed (S) of 10 mm/s and Wire diameter (D) of 1 mm, and assuming that the deposited material takes a rectangular shape with a section area of 1.2x1 (WxH) mm2, the calculated feed speed (Fs) is 15.3 mm/s, Equation (1).

$$F_S * \Pi * (D/2)^2 = W * H * S \tag{1}$$

Since the effect of a cold substrate is not considered, during manufacturing there was a need to adjust both the laser power and feed speed whenever perceived distortion is noticed or when the load cell indicates a significant deviation. This means that the process parameters used fall in the range present in Table 1.

The intent is to highlight the different stages in manufacturing. In this light, the start consideration was to define a model for the deposition. Using these parameters do the slicing (division of the CAD model into layers) and then during manufacturing adjust the printing process. It is worth noting that the accessible parameters during fabrication were the robot´s travel speed, the cooling rate, the laser power, and the feed rate. Although it is possible the adjustment of the Cartesian coordinates, not enough data is available to accurately make these corrections.

Another observation is that the start and end of the deposition process have different geometrical properties, presenting a visible irregularity at the start and end of a trajectory. Lastly, the importance of a well-centered focal point (with 50% of energy in the Wire and the other 50% in the substrate) is observed to affect the fusion of material, contributing to surface defects when not balanced correctly. This last observation lacks validation, demonstrating a need to better document defects and the effects of different proportions of energy distribution, which is challenged by the mostly manual process of aligning lasers.

6.2 University of Brasilia

In the case of UnB, the Robotic Additive Manufacturing Cell is currently under assembly. The equipment has already been acquired by UnB, and the final assembly is scheduled to be completed by September 2023. Therefore, the Digital Twin (DT) of the Cell, associated with CAD/CAPP/CAM functionality, simulation, and web-based monitoring, will be presented.

6.2.1 CAD/CAPP/CAM using Rhinoceros and Grasshopper

An algorithm was developed in Grasshopper for CAD/CAPP/CAM, associated with programming, simulation, and generation of programs in KRL (Kuka Robot Language) format for material deposition strategies. The algorithm enables the creation of contour deposition paths for parts with either one or two material deposition cords. It also allows for the slicing of hollow parts, where deposition cords are associated with the part's contour using a planar slicing approach. The URL `https://www.youtube.com/watch?v=UsXkto9vljg` (Alvares and Lacroix, 2023a) provides a video demonstrating the algorithm in action and the simulation in Rhinoceros. The Grasshopper Robots add-on is used, which allows

programming for ABB, Kuka, and Universal (UR) robots. While there are other add-ons for robots (FuroBot, KukaPRC, RoboDK), the Robots add-on is the most interesting as it works with Kuka and ABB robots.

To generate the deposition strategy for contouring hollow parts, it is necessary to obtain the coordinate points of the contour (X, Y, Z) and the tool orientations (A, B, C). Depending on the input object, the file format of the part (BRep, Curve, or Mesh), the following procedure needs to be followed: BRep => Curves => Polylines => Points/Vectors => X, Y, Z, A, B, C (Cuevas and Pugliese, 2020).

Figure 6 shows the CAD/CAPP/CAM algorithm developed in Rhinoceros-Grasshopper. The left side of the figure represents the DT of the Cell displayed in Rhinoceros, while the right side shows the CAPP/CAM algorithm developed in the Grasshopper environment using the Robots addon, among others, which enables the generation of KRL code compatible with Kuka robots. In the URL `https://youtu.be/UsXkto9vljg`, a video is presented demonstrating the use of the CAD/CAPP/CAM algorithm (Alvares and Lacroix, 2023a), showcasing the development details.
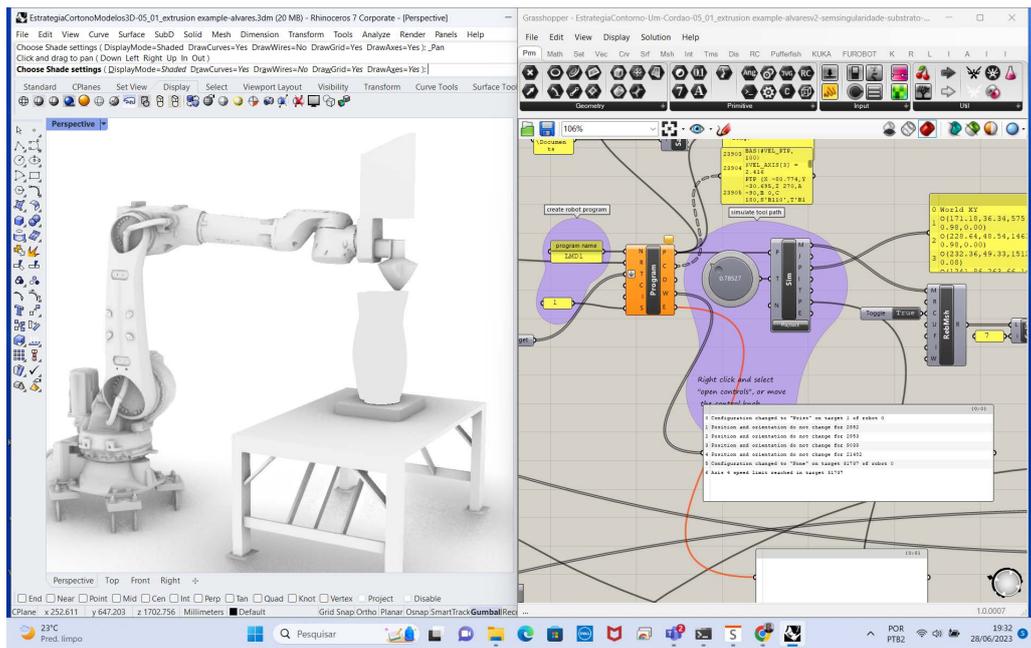

Figure 6. Algorithmic CAD/CAPP/CAM Rhinoceros-Grasshopper to contour hollow parts.

6.2.2 Simulation with Kuka.Sim

Figure 7 presents the simulation of the KRL code in the Kuka.Sim environment generated by the CAD/CAPP/CAM algorithm in the Rhinoceros-Grasshopper platform, associated with the algorithm developed for the material deposition strategy with planar slicing for contour (hollow) parts, such as vase-like geometries.

The URL `https://youtu.be/ukc_CrEFBRE` presents a video showing the simulation with Kuka.Sim (Alvares and Lacroix, 2023b) associated with the KRL program generated by the CAD/CAPP/CAM algorithm based on Grasshopper (Figure 7).

6.3 Online monitoring with Node-RED and MQTT

To enable real-time monitoring via the web and store data for predictive analysis, we chose to use the cloud database provided by AWS (Amazon Web Services).

In this phase of implementing the Robotic Additive Manufacturing Cell LMD-Wire, the Kuka.Sim platform will be used as a data generator to feed the functionality planned in the Digital Twin (Fig. 3), using Python programming integrated with the Kuka.Sim platform.

The web-based monitoring of the program running in Kuka.Sim, either in simulation mode or in real-time monitoring of the active Kuka robot (online mode), can be viewed in Kuka.Sim. Therefore, the monitoring usage and the data history stored in the database via the web can occur in both simulation mode (robot offline) and online mode (robot online).

Using the developed Python program, the following data is obtained via the MQTT protocol, which accesses the data published by Kuka.Sim. The Node-RED server accesses the MQTT server and provides a 2D dashboard (Fig. 8) displaying the graphs of each monitored variable (`https://youtu.be/lTZk7mai2Js`). Additionally, the data is stored in the AWS database. The following real-time measurements are monitored: Axis position: Indicates the positions of
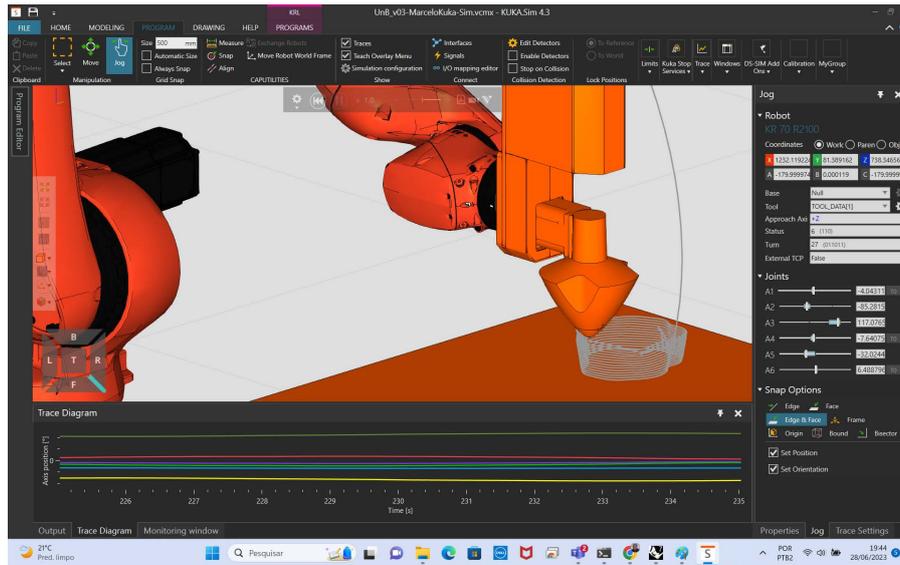
Figure 7. Simulation with Kuka.Sim to contour hollow parts.

the selected axes; Axis velocity: Indicates the velocity of the selected axes; Axis acceleration: Indicates the acceleration
of the selected axes; TCP position: Indicates the position of the TCP in the WORLD coordinate system; TCP velocity:
Indicates the velocity of the TCP; TCP acceleration: Indicates the acceleration of the TCP; BBRA Indicates the current
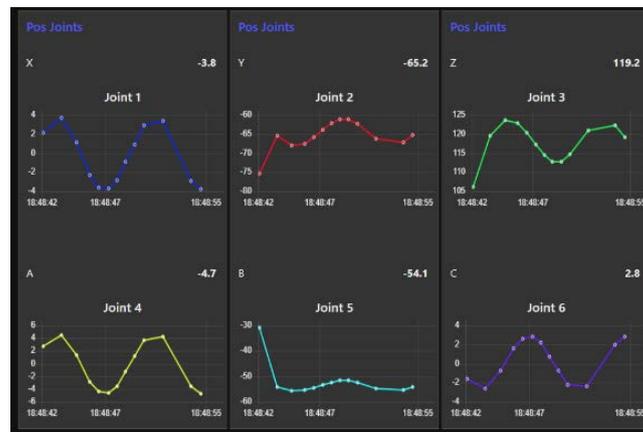override.

Figure 8. 2D dashboard generated by the Node-RED platform using the MQTT protocol.

7. FUTURE WORKS

7.1 University of Coimbra

The ongoing developments described in this paper give a window into how UC has structured the LMD solution, there
are however many research questions to address. The current focus now is on building compound knowledge through
a streamlined data storage, analysis, and fusion platform. In this phase, it is intended to integrate temperature sensors
(pyrometry), and 3D scanning and connect data acquired from the LMD-Wire tool to a database for monitoring. To
extract meaningful data, it is being explored some prediction methods (like neural networks, and multi-factorial analysis),
the aim is to use this information to create more accurate models for the path planning (slicing) of a CAD model. And
to standardize welding procedures, more concretely lay out important factors and parameters to specific welded features
(ex. corner transitions). The vision is that with the data acquired in situ, the behavior of a component during its life can be
predicted, minimizing or removing the need for destructive tests and promoting adoption by industry. Another important
focus is on further developing the control logic with other welding strategies (ex. weaving). And to provide more tools
for controlling the system in real-time, in this case through the GUI.

With these main focuses, different case studies are to be explored to validate and challenge the LMD system, to better understand the manufacturing process, and to demonstrate de usability of LMD parts in the industry. Furthermore, a more in-depth study to evaluate LMD parameters is going to be conducted following response surface methodology to understand the effect of the parameters on the material behavior (hardness, residual tensions, etc.), compared to the current State of Art.

Among other initiatives, the last highlighted in this paper is the current effort to connect slicing, the material deposition process, and welding trajectories into one solution. Some reflections are present in literature, for example in the discussions of the DFAM (Design for Additive Manufacturing) methodology, however, there is a lack of flexible and available solutions, mostly because of the variability of the material, and AM systems.

7.2 University of Brasilia

The next phases of the development of the UnB solution are associated with the logical and physical integration of the Kuka robot with the Meltio head, which is expected to be completed by the end of September 2023. Following that, the entire development of the DT platform described will be integrated with the online assets, the observable element, including the Kuka robot and the Meltio head, and will also have the capability to use the offline solution with Kuka-Sim.

With the completion of the integration process into the DT platform, new material deposition algorithms will be developed. The material deposition strategies using Robotic LMD-Wire are classified based on the type of geometry of the desired part, associated with Planar, Non-Planar, Revolved Surfaces, Curve Frames, and Between Surfaces slicing techniques. Additionally, Variable Deposition Rate or Constant Deposition Rate can be used. The following slicing strategies will be implemented: Planar, Multi-planar, Non-planar, Segmented, Angled Printing, Radial Printing, Cladding, Revolved Printing, Hollow Parts, Contour with 1 or more Material Deposition Cords (already implemented), and Solid.

There are plans to develop predictive analysis using Artificial Intelligence algorithms such as Neural Networks applied to predictive and prescriptive maintenance of the integrated platform consisting of the Kuka Robot and the Meltio LMD-Wire head. This will involve leveraging Big Data Analytics to analyze large volumes of data and extract valuable insights for optimizing maintenance processes. By utilizing advanced AI techniques, it will be possible to detect potential failures or anomalies in the system, predict maintenance needs, and provide recommendations for proactive maintenance actions. This approach aims to improve overall system performance, reduce downtime, and enhance the efficiency of the additive manufacturing process.

8. CONCLUSIONS

This article describes two Robotic Additive Manufacturing Cells using the LMD-Wire process, one at the University of Brasilia and another at the University of Coimbra.

The article presents the characteristics of the solutions associated with the implementation of Laser Safety Cabinets, as well as the hardware and software solutions adopted and the conceived Digital Twin. The Cell at the University of Coimbra has been in operation since mid-2022, while the Cell at the University of Brasilia is nearing completion and is expected to be operational in September 2023. The case studies presented refer to the printing of parts at the University of Coimbra and the programming, simulation, and monitoring without the actual printing of parts at the University of Brasilia.

The main contribution of this research is to present the solutions and challenges of Robotic Additive Manufacturing using LMD-Wire, from the perspective of two research groups in Brazil and Portugal. These groups are developing complementary solutions and approaches that can serve as guidelines for other implementations, serving as a guide for options to deploy and popularize this rapidly growing technology worldwide. According to Meltio, more than 200 LMD-Wire systems have already been installed in over 40 countries, with the one at the University of Brasilia being the first in Brazil.

One of the biggest challenges is the generation of code for the robot associated with multiple axes, such as six or eight axes (a robot with positioning tables), due to the high cost of CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) systems. Annual licenses for these systems can range from $8,000 to 50,000 Dollars depending on the supplier. However, there are two companies/startups, Ai Build, and Adaxis, that provide simulation and programming platforms capable of implementing various deposition strategies. These platforms offer features such as Planar Slicing, Non-Planar Slicing, Revolved Surfaces, Curve Frames, and Between Surfaces, as well as the option to use Variable Deposition Rate or Constant Deposition Rate (Section 7.2).

9. ACKNOWLEDGMENTS

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