COBEM 2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING

ABCM Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0208
DEVELOPMENT OF A DIGITAL TWIN FOR A ROBOTIC ADDITIVE MANUFACTURING SYSTEM BASED ON A LASER METAL DEPOSITION (LMD) PROCESS

Alberto José Alvares
Igor Lacroix
Marco Maron
Brayan Stiven Figueroa
Lucas Araújo
University of Brasilia, Department of Mechanical and Mechatronics Engineering, Brasília, CEP 70910-900, Brazil.
alvares@alvarestech.com igorlacroixarquitetura@gmail.com marcoadlmaron@gmail.com brayan.s.figueroa47@gmail.com lucas.sda.araujo@gmail.com

Abstract. *This work presents a computational architecture and implementation of a Digital Twin (DT) for a robotized additive manufacturing cell that uses the Laser Metal Deposition with Wire (LMD-Wire) process. The system is composed of an LMD-Wire head from Meltio3D and a Kuka KR 70 R2100 robot. This becomes even more relevant in emerging technologies such as LMD manufacturing, where a direct energy source based on a Diode Laser, for example, is used to selectively melt a layer of metallic material fed by Wire, as in the case at hand, or powder. To develop the Digital Twin, this work uses ISO 23247 as a reference and the CAD environment Rhinoceros-Grasshopper associated with the Kuka.Sim simulation platform, aiming to develop a CAD/CAPP/CAM (Design, Process Planning, and Additive Manufacturing) platform for the robotized cell using the laser metal deposition head. The Digital Twin should be able to perform 3D modeling of complex parts with different geometries, planning different slicing strategies, planar and non-planar parts, depending on the complexity of the part, simulating the robotized additive manufacturing cell, and generating Kuka KRL (Kuka Robot Language) code in the Rhinoceros-Grasshopper environment. Next, the generated program in the KRL code is sent to the Kuka simulator, Kuka.Sim, which will perform a realistic simulation of the cell, being a Digital Twin of the physical cell. Using Kuka.Sim, which will be one of the elements of the Digital Twin Platform, the program connects the digital environment with the physical setup (Kuka robot and Meltio LMD tool), being in perfect harmony and mirroring, in real-time, the digital world to the physical world.*

Keywords: *Laser Metal Deposition (LMD), Digital Twin, Additive Manufacturing, Robotics, ISO 23247, Industry 4.0.*

1. INTRODUCTION

Industry 4.0 main objective is to obtain products with greater efficiency and precision through digitization and the use of machines, being driven by technological advances such as additive manufacturing (Jan *et al.*, 2023). Laser metal deposition (LMD) is one of the additive manufacturing (AM) processes that consists of generating metal deposition trajectories using Wire or powder from a CAD model with a focus mainly on the aerospace application (Garmendia *et al.*, 2019; Gu and Li, 2019).

The integration of additive manufacturing processes and robotics led to the creation of robotic LMD metal additive manufacturing cells that promise benefits in flexibility as well as in the production economy (Bremer *et al.*, 2019). The Digital Twin of a robotic LMD Wire additive manufacturing cell is a virtual replica that simulates and models the metal laser deposition process using a robot that manipulates and feeds the Wire material for design simulation, optimization, and monitoring in real-time significantly improving the quality, efficiency, and maintenance of additive manufacturing making it an effective means for the integrated development of design and manufacturing (Feng *et al.*, 2022).

The industry and the modern world demand the production of quality metal parts, customized, with reduced costs and production times, longer useful life, and rapid prototyping, where real-time monitoring processes in manufacturing processes have been made possible. manufacture of these parts is of vital importance. To meet the demands required by the aerospace, defense, automotive, and biomedical industries, additive manufacturing focuses on the production of metallic components of complex geometries, including metals, alloys, and metallic compounds, having metal deposition by laser (LMD) as one of the most versatile processes in this manufacturing process (Yan *et al.*, 2020). The use of the LMD in the manufacturing processes of metal parts sometimes presents errors in the newly built component due to rapid heating and solidification and can cause shape deviations and cracks (Biegler *et al.*, 2018). The manufacture of planar and non-planar metal parts requires a high cost, which is why the errors present in the manufacture of these lead to high costs and an increase in production time since they require corrective analysis in possible cases without being able to use predictive analysis. because traditional methods do not have access to monitoring data in real-time.

ISO 23247 provides the architecture in the manufacturing framework for digital twins using automation and integration systems. Digital twins have the potential to be important in achieving smart manufacturing therefore ISO 23247 proposes a framework that can enable context-dependent implementations as well as promote component composition and reuse of digital twins (Shao and Helu, 2020; Liu *et al.*, 2022).

This paper presents the computational architecture and implementation of a Digital Twin (DT) for a robotic additive manufacturing cell that uses the Laser Metal Deposition with Wire (LMD-Wire) process. The article begins with the presentation of the literal review related to the most recent investigative work on metal additive manufacturing by LMD-Wire focused on digital twins (DT) and integrated into robotic metal additive manufacturing cells in the context of Industry 4.0. The following describes the development of digital using the ISO 23247 standard as a reference, which provides the architecture in the manufacturing framework of Digital Twins (DT) using automation and integration systems where the Rhinoceros-Grasshopper CAD associated with the Kuka simulation platform is integrated. It presents the development of a CAD/CAPP/CAM (Computer Aided Design, Computer Aided Process Planning, Computer Aided Manufacture) platform that generates Kuka KRL (Kuka Robot Language) in the Rhinoceros-Grasshopper environment and the simulation of the program in the Kuka.sim environment. The article ends with the presentation of the proposed Digital Twin showing the connection of the digital environment with the physical configuration (Kuka robot and Meltio LMD tool) in perfect harmony and reflecting the digitized physical world in real-time.

2. ROBOT-BASED ADDITIVE MANUFACTURING LITERATURE REVIEW

According to Lettori *et al.* (2022), robot-based additive manufacturing (RBAM) is emerging as a promising solution to increase manufacturing flexibility, utilizing robots in additive manufacturing processes. In particular, part orientation, multiaxial deposition, slicing, and infill strategies must be properly evaluated to obtain satisfactory outputs and avoid printing failures. Some advanced features can be found in commercial slicing software (e.g., adaptive slicing, advanced path strategies, and non-planar slicing), although the procedure may result excessively constrained due to the limited number of available options. Several approaches and algorithms have been proposed for each phase and their combination must be determined accurately to achieve the best results. This paper reviews the state-of-the-art works addressing the primary methods for the representation of geometries and the subsequent geometry processing for RBAM.

Pires *et al.* (2022) present a review of the role of robotics in various AM technologies to underline its importance, followed by an introduction of a novel and intelligent system for directed energy deposition (DED) technology. Design/methodology/approach AM presents intrinsic advantages when compared to conventional processes. The objective of this paper is to identify the fundamental features of an intelligent DED platform, capable of handling the science and operational aspects of advanced AM applications. Consequently, introduce and discuss a novel robotic AM system, designed for processing metals and alloys such as aluminum alloys, high-strength steels, stainless steels, titanium alloys, magnesium alloys, nickel-based superalloys, and other metallic alloys for various applications.

Cuevas and Pugliese (2020) explain how to transform a design into a series of curves and paths for a 3D printer to use; to write and create G-code directly within Grasshopper, without the use of scripts or plug-ins. The book focused mainly on clay 3D printing, but the same logic can be applied to thermo-filament 3D printing (FDM) as well. The methods taught, open up a wide range of new possibilities when 3D printing, like non-planar 3D printing or non-conventional paths for the 3D printer.

2.1 Benchmark of CAD/CAPP/CAM systems for robotic additive manufacturing LMD-Wire

The material deposition strategies using Robotic LMD-Wire are classified based on the geometry of the piece to be created, 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. These strategies can be categorized as slicing strategies: Planar (Part1); Multi-planar (Part2); Non-planar (Part3); Segmented (Part4); Angled Printing (Part5); Radial Printing (Part6); Cladding (Part7); Revolved Printing, Hollow Parts (Part8); Contour with 1 or more Material Deposition Cords (Part9); Solid (Part10).

Table 1 presents the main software platforms available for CAD/CAPP/CAM (Computer-Aided Design, Process Planning, and Computer-Aided Manufacturing) applied in Robotic Additive Manufacturing using ABB and Kuka robots, associated with the types of parts/slicing listed above, with the option of using a 2-degree-of-freedom positioning table. In the case of the mentioned architecture, there is no positioning table, only the Kuka KR70 R2100 robot.

The softwares companies CAD/CAM that have joined Meltio Engine's Software Partner ecosystem for hybrid and robotic platforms (`https://tinyurl.com/mdzbp86y`) include SKM DCAM by SKM Informatik; AdaOne by Adaxis; AiSync by AiBuild; Esprit by Hexagon; Fusion 360 by Autodesk; Aplus+Mastercam by Camufacturing and Mastercam; Hypermill by OpenMind; SiemensNX by Siemens; Hy5CAM by 1ATechnologies; RobotStudio 3D Printing PowerPack by ABB; and SprutCAM X by SprutCam.

Table 1. Benchmark CAD/CAPP/CAM Systems Robotic Additive Manufacturing.

Software Plataform	Part1	Part2	Part3	Part4	Part5	Part6	Part7	Part8	Part9	Part 10	Cost (Euro)
SKM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	45000
ADAXIS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	7500
Ai Build	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	27000
Meltio Gcode/Rapid/KRL	Yes	No	No	No	No	No	No	No	Yes	Yes	Free
ABB Studio	Yes	No	No	No	No	No	No	No	No	No	5000
Kuka.Sim	No	No	No	No	No	No	No	No	No	No	8000
MasterCam Aplus	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	7500
OpenMind	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	43000
Siemens NX	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	50000
Grasshopper/Rhino	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1000
Simplify3D	Yes	No	No	No	No	No	No	No	Yes	Yes	300
RoboDK	Yes	No	No	No	No	No	No	No	Yes	Yes	1500

3. ROBOTIZED ADDITIVE MANUFACTURING CELL

The Robotic Additive Manufacturing Cell using the LMD-Wire process consists of a Kuka KR70 R2100 robot and the Meltio Engine Robots LMD-Wire system. The cell is currently under assembly (Fig. 1) inside a metal enclosure with dimensions of 4.75x5x3.5 m, and it will be operational in September 2023. All the equipment, systems, and components are already available. The enclosure is fully enclosed and features four Safety Laser Windows (980nm Laser Filter) to ensure operator protection.

Figure 1. LMD-Wire Robotic Additive Manufacturing Cell in assembly: Kuka KR70 R2100 and Meltio Engine Robots.

There is a door interlocking system 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) project, 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, Rhino 3D, 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.

4. DT REFERENCE MODELS FOR MANUFACTURING

Lu *et al.* (2020) present a study to clarify definitions and connotations of Digital Twins in the context of Smart Manufacturing, highlighting application scenarios, research focuses, and potential perspectives toward the future of Digital Twins in the field of advanced manufacturing systems. The paper proposes a reference model for Digital Twins consisting of three layers: 1) an information model that represents abstractions of physical entities; 2) a data processing module that generates knowledge from collected data; and 3) a bidirectional communication mechanism that enables interaction between the physical space and the digital space.

One of the most widely accepted definitions of Digital Twin (DT) introduced by NASA in 2012 defines it as "an integrated, multi-physics, multi-scale, and probabilistic simulation of a built vehicle or system that uses the best available physical models, sensor updates, historical data, etc., to mirror the life of its corresponding counterpart" Glaessgen and Stargel (2012).

Several proposals of reference models and architectural frameworks for implementing Digital Twins in manufacturing, as well as related works, are presented below.

4.1 DT framework for manufacturing by STEP Tools, Inc.

STEP Tools (2016) proposed an interoperable architectural framework for implementing Digital Twins in machining processes during the demonstration meetings that took place in 2016 with participants from Boeing, OMAC, and ISO's TC184/SC4 committee. The framework enables closed-loop manufacturing execution using real-time results from dimensional and geometric inspection, employing standards such as STEP-NC, MTConnect, and QIF (Quality Information Framework).

The high-level STEP-NC model developed by ISO and led by STEP Tools enables the integration of data describing geometry, tolerances, machining operations, and inspection results that can be transferred through a single file format. MTConnect provides process monitoring data to be used by web clients via TCP/IP. And QIF is used to gather inspection results and assess the quality of the parts.

4.2 RAMI 4.0 reference model

The Reference Architecture Model for Industry 4.0 (RAMI 4.0) Hankel (2015) establishes standards to be used and is described in three dimensions:

- "Hierarchy Level" (IEC 62264, IEC 61512): Dimension associated with hierarchical levels, including the intelligent product up to the connected world;
- "Life Cycle & Value Stream" (IEC 62890): The second dimension refers to the product's lifecycle and value flow, from its conception, through production and maintenance, to end-of-life;
- "Layers": The third dimension corresponds to the mapping of systems and machines, referred to as assets, into their virtual representations, known as digital twins, from devices to business entities.

The Asset Administration Shell (AAS) is a fundamental element of the architecture. According to Kerin *et al.* (2023), the AAS of RAMI 4.0 has been described by some as a digital twin, but it remains immature. The term "Digital Twin" is referenced only once in the standard (RAMI 4.0 - Plattform Industrie 4.0 Part 1, 2019).

4.3 ISO 23247 - DT framework for manufacturing

The standard ISO 23247-1 (2021) was developed by the ISO Technical Committee TC 184/SC 4 to standardize an implementation architecture framework for Digital Twins in industrial manufacturing applications within the context of Industry 4.0. The framework guides how to build a Digital Twin for manufacturing, specifying how systems can interoperate and how data from different sources can be integrated. The framework consists of four domains represented by four different application layers (Cabral *et al.*, 2023).

The first layer deals with the domain of Observable Manufacturing Elements (OMEs), which are all the devices, sensors, machines, materials, products, and other physical elements on the factory floor that are of interest for monitoring and control purposes.

The second layer represents the domain of Data Collection and Device Control Entities (DCDCE), which enable the monitoring and data collection from sensor devices in the OME domain, as well as the control of actuated devices within the same domain.

The DCDCE's main task is to maintain synchronization between the OME domain and the digital entities. The digital entities are located in the third layer, which corresponds to the DT domain. This domain is responsible for enabling the provisioning, management, monitoring, and optimization of the system as a whole. The OMEs are modeled and synchronized within this domain to provide services such as monitoring, simulation, status analysis, and others. It is important to mention that this domain constitutes the core of the framework, and DT entities should be capable of interacting and being integrated with other internal and external DT entities to ensure system interoperability.

Finally, we have the user domain, where entities such as people, devices, or other systems exist, utilizing the services and applications provided by the DT domain.

The ISO 23247 standard outlines an implementation framework for the "Layers" of the RAMI 4.0 model, incorporating the Digital Twin concept and the interaction between the physical and digital realms while proposing a Business Model based on exploratory functionalities organized into six layers: Asset, Integration, Communication, Information, Functional, and Business. Unlike the other dimensions of the RAMI 4.0 model, the DT (Digital Twin) dimension within the "Layers" of RAMI 4.0 does not have an associated standard as of the present date.

The initial work led by STEP Tools and the ISO/TC 184/SC 4 Industrial Data Committee resulted in the development of AP 238 (STEP-NC standard), which led to the emergence of ISO 23247. The framework proposed by STEP Tools in 2016 STEP Tools (2016) was instrumental in the development of the ISO 23247 standard, providing a solid foundation by considering industry requirements and the needs of CAD/CAM systems and CNC machines. This standard, in turn, established standards and protocols for information exchange and interoperability among manufacturing systems, driving automation and process optimization in a significant manner.

In this work, the DT framework for manufacturing standardized by ISO 23247 is taken as a basis for the design of a DT implementation architecture aimed at monitoring using a 2D dashboard and a CAD/CAPP/CAM environment for process planning, CAD/CAM programming, and 3D simulation of a Robotic Additive Manufacturing Cell using the LMD-Wire process, which will be described in section 5. According to ISO 23247, the functionalities present in the DT have different levels of maturity and complexity: monitoring, remote access, 3D simulation, command, control, optimization, and predictive analysis (e.g., Predictive Maintenance), allowing feedback in the view of the end-user or the physical machine. These functionalities can be explored as cloud services, thus creating a new business model, product-service, for the manufacturer of the intelligent machine.

4.4 Related works digital twin

In this subsection, the literature references are made to works specifically dealing with the design and development of DTs for machining processes in machine tools. However, a more comprehensive literature review study is conducted by Huang *et al.* (2021), where they analyze over 300 manuscripts on AI-based DT technologies for Industry 4.0 used from 2016 to mid-2020, considering a wide range of applications in the manufacturing field.

The concept of a cyber-physical machine tool, referred to as machine tool 4.0, was initially proposed by Professor Xu (2017). This concept was brought to the implementation level in the work by Liu *et al.* (2019), which describes the development of a cyber-physical machine tool platform based on OPC-UA and MTConnect communication protocols to enable efficient interoperability with other machines and software applications. In another work by Kubota *et al.* (2020), they expand the capabilities of the cyber-physical machine tool platform by incorporating a high-level data model based on STEP-NC using an object-oriented framework with machine and component-related information.

Luo *et al.* (2020) propose a unified multi-domain modeling method for constructing digital twins of machine tools, specifically targeting predictive maintenance and fault diagnosis applications. They demonstrate the capability of the model by predicting and diagnosing faults in a CNC machining center.

Qiao *et al.* (2019) present a five-dimensional digital twin model based on a hybrid prediction model that utilizes deep learning techniques to enhance the prediction of machine tool conditions. They validate the proposed model using machine vibration data in a machining process.

Tong *et al.* (2020) present a real-time machine monitoring service application using multi-sensor fusion technology to perform data acquisition and processing from certain critical parts of the machine. Validations are conducted through examples of applications using the developed digital twin to visualize and analyze process data, machine status, and energy consumption.

Cabral *et al.* (2023) present the development and implementation of a Digital Twins architecture for machining using a CNC Haas Mini Mill machine. The proposed architecture is based on the current Digital Twins framework for manufacturing normalized by ISO 23247. MQTT and MTConnect protocols transfer machine status and process data to cloud platforms for storing, monitoring, visualization, and simulation activities. This approach was validated in a real CNC machine and it is feasible to be applied to other machines and manufacturing processes.

The reviewed literature up to the present date does not report specific architecture framework specifications for Digital Twin using the ISO 23247 standard for Additive Manufacturing, despite its publication being in November 2021. This work aims to develop and validate a Digital Twin architecture for monitoring using a 2D dashboard and a CAD/CAPP/CAM environment for process planning, CAD/CAM programming, and 3D simulation of a Robotic Additive Manufacturing Cell using the LMD-Wire process.

5. DT ARCHITECTURE PROPOSAL BASED ON ISO 23247

Figure 2 illustrates the proposed architecture for the implementation of a DT in compliance with the ISO 23247 standard, developed in this work. As stated by the standard, the four application domains, synchronized among themselves, are consolidated in the architecture, which has the main objective of monitoring using a 2D dashboard and a CAD/CAPP/CAM environment for process planning, CAD/CAM programming, and 3D simulation of a Robotic Additive Manufacturing Cell using the LMD-Wire process. The following sections describe the domains of the architecture.

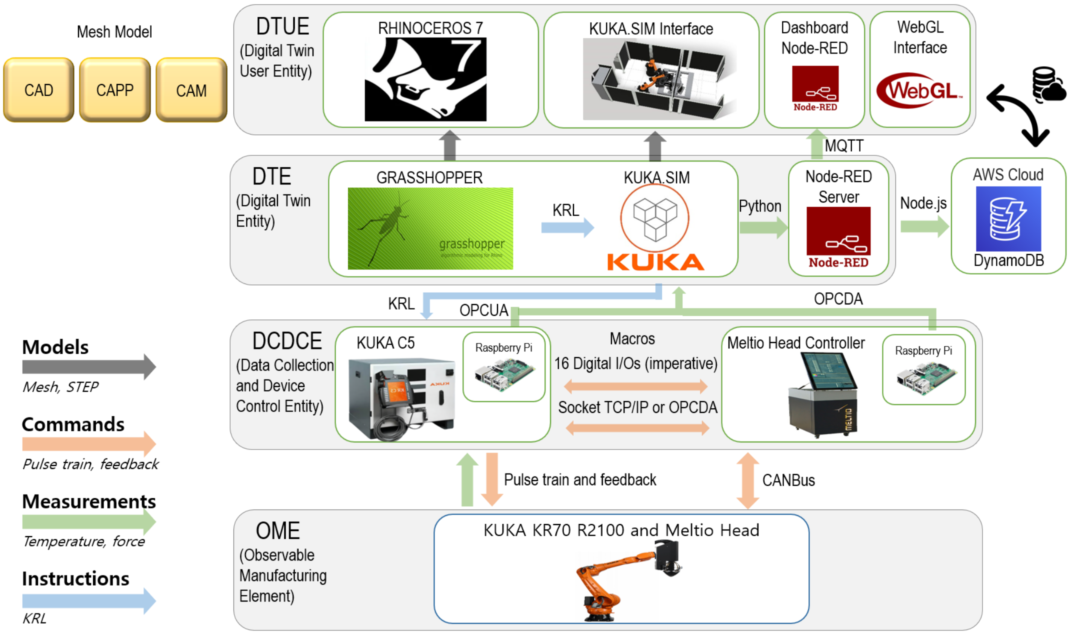

Figure 2. Digital twin architecture for parameterization of planar and non-planar additive manufacturing and robot life cycle simulation with ISO 23247 framework.

5.1 Observable manufacturing element - OME

The first layer, looking from bottom to top in Figure 2, corresponds to the domain of observable manufacturing elements/entities, where the Kuka KR70 R2100 Robot and the LMD-Wire Meltio Robots Engine are located, from which process data and machine status will be collected.

The Kuka KR70 R2100 Robot is integrated with the LMD-Wire Meltio Robots Engine, which uses the OPC-UA, OPC-DA, TCP Sockets, and CANBus protocols to obtain data from the machine. 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 obtain machine data or control any of the actuated devices.

The data/information transmitted by it will serve as the foundation of the Digital Twin (DT) and will flow through the other domains to compose the applications of a specific digital twin architecture. The developed functionality, such as monitoring, teleoperation, predictive maintenance, optimization, and simulation, among others, will be explored as a service offered in the Cloud/Edge, representing a new business model for the company. This approach is crucial for the ongoing digital transformation in Industry 4.0, as it enables greater efficiency, and informed decision-making, and creates new business opportunities.

5.2 Data collection and device control entity - DCDCE

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 microprocessor has been used as a data acquisition system integrated into the machine's structure and connected to it via Ethernet TCP/IP.

A server application has been developed using JavaScript technology in the Node.js runtime environment, which is embedded in the Raspberry Pi 2 computer. This application communicates with the machine via TCP/IP, sending the Meltio application protocol macro-commands to retrieve the desired data and making 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.

An MQTT broker receives the machine data, formats it, and makes it available to any MQTT subscriber interested in this data. We also have a Node-Red service running on the Raspberry Pi 2 gateway, programmed as an MQTT subscriber to retrieve the data from the MQTT broker in Node.js and send it directly to the AWS cloud for storage and visualization.

5.3 DT domain

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

It should be emphasized that there are more complex DT functionalities that require a higher degree of development maturity. The two implemented functionalities are described by the ISO as services of the DT domain, although they have low complexity compared to AI-based Predictive Maintenance services or closed-loop manufacturing with feedback based on dimensional or geometric inspection data.

These services are supported by process data and machine status data associated with the three different data streams developed:

- (1) one stream based on MQTT and the Node-Red graphical programming environment, where the latter is directly connected to the AWS Cloud using token-based authentication to enable data storage and visualization, as well as monitoring on a 2D dashboard created within the Cloudant platform itself;
- (2) a second stream based on MQTT feeding into a 3D simulation environment using Kuka.Sim, which includes the 3D model of the LMD-Wire Meltio Robotic Additive Manufacturing Cell;
- (3) a stream based on OPC-UA, OPC-DA, TCP socket/7000, and CANBus protocols, where the Cell data can be consumed by reading and writing messages to variables such as Robot TCP position, pose, velocity, monitoring, IO, among others.

5.4 DT user domain

In this domain, we have the stakeholders interested in consuming the services provided in the DT domain, which can be individuals or systems. In this case, the users are the people who are members of the LaDPRER laboratory at the University of Brasília, who make use of the machine.

The Grasshopper-Rhino 3D software is used as a CAD/CAPP/CAM system, where a mesh model of the part to be printed is opened, and the printing parameters such as layer height, laser power, robot speeds, Wire feed rate, substrate dimension, among others, are configured. The CAPP/CAM system performs the process planning and generates the KRL program for the Kuka Robot. Next, the program is sent to Kuka.Sim, which performs the simulation of the printing process, validating the generated KRL code.

The monitoring of process variables is presented on a 2D dashboard through web interfaces using HTTP and MQTT protocols, implemented with Node-RED. The process variables are stored in a cloud-based database (AWS) for later use in data analytics algorithms, such as predictive maintenance.

6. IMPLEMENTATION DESCRIPTION AND RESULTS

The experimental setup of the work consists of the Kuka KR70 R2100 robot and the LMD-Wire Meltio head, connected to the Raspberry Pi 2 board via Ethernet TCP/IP. The Raspberry Pi 2 is running the Raspberry Pi OS as its operating system. A Node.js server application has been deployed as a service on the Raspberry Pi 2, which includes a serial communication module for sending macro-commands to the machine to retrieve its status data.

6.1 CAD/CAPP/CAM using Rhinoceros and Grasshopper

An algorithm was developed in Grasshopper for CAD/CAPP/CAM, which is associated with programming, simulation, and generation of programs in KRL (Kuka Robot Language) format for material deposition strategies. The algorithm supports the contour deposition of parts with either one, two, or three material deposition beads. It enables the slicing of the hollow part to be created by using deposition beads associated with the part's contour through planar slicing. The URL (`https://youtu.be/UsXkto9vljg`) provides a video demonstrating the algorithm in action and the simulation in Rhinoceros (Alvares and Lacroix, 2023a). 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 tool orientations (A, B, C). Depending on the input object, the file format of the part (BRep, Curve, or Mesh), the following workflow needs to be followed: BRep => Curves => Polylines => Points/Vectors => X, Y, Z, A, B, C (Cuevas and Pugliese, 2020).

Figure 3 presents the CAD/CAPP/CAM algorithm developed in Rhino3D-Grasshopper. The left side of the figure represents the DT of the Cell displayed in Rhinoceros, and the right side shows the CAPP/CAM algorithm developed in the Grasshopper environment using the Robots add-on, among others, which allows the generation of KRL code compatible with Kuka robots. In the URL (`https://youtu.be/UsXkto9vljg`), a video is provided demonstrating the use of the CAD/CAPP/CAM algorithm (Alvares and Lacroix, 2023a), showcasing development details.

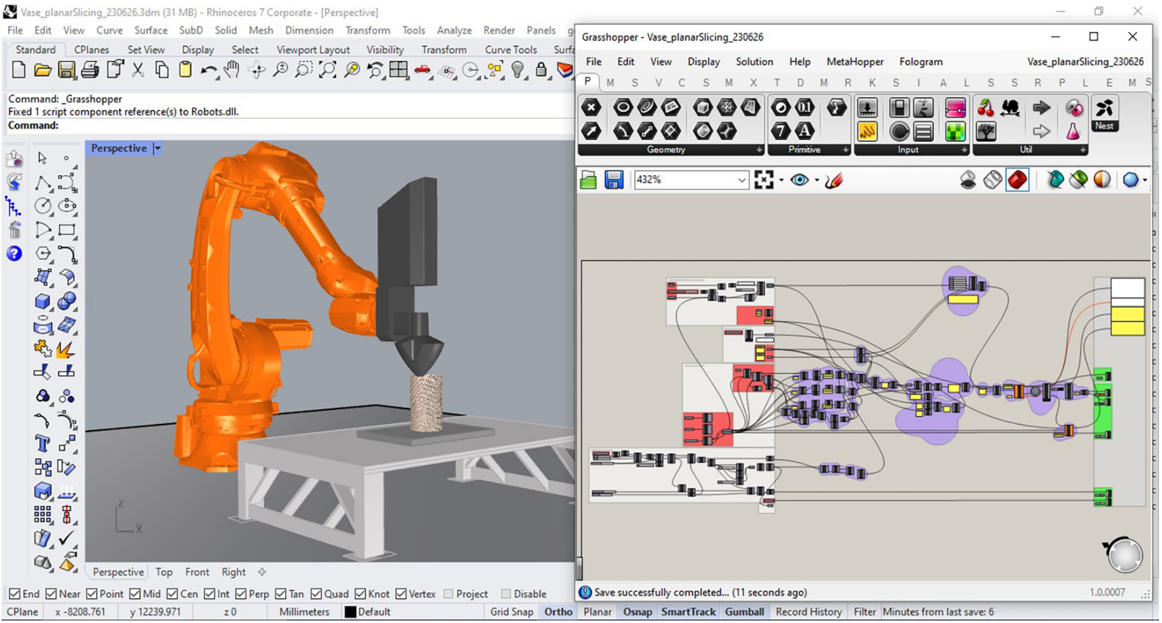

Figure 3. Algorithmic CAD/CAPP/CAM Rhinoceros-Grasshopper to contour hollow parts.

6.2 Simulation with Kuka.Sim

Figure 4 shows 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 using planar slicing for contour parts (hollows), 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 (Alvares and Lacroix, 2023a).

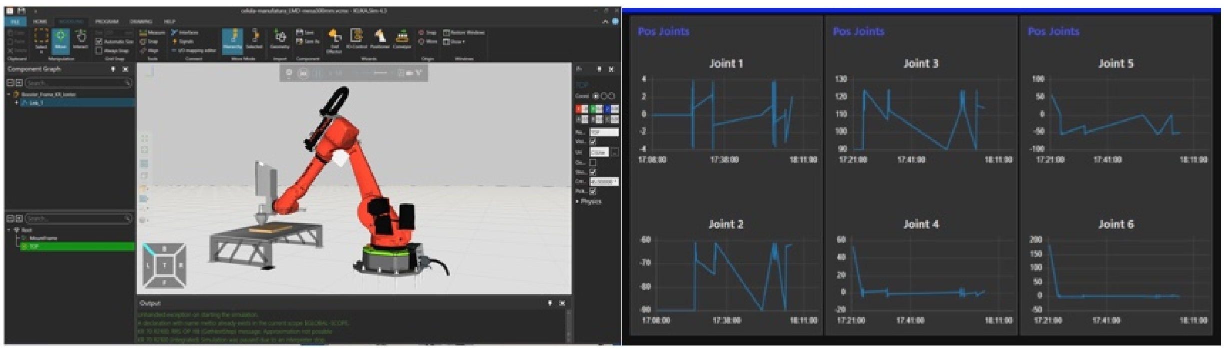

Figure 4. Simulation with Kuka.Sim to contour hollow parts and 2D dashboard generated by the Node-RED platform using the MQTT protocol.

6.3 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 (DynamoDB) 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. 2), using Python programming and Node-red 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. 4) displaying the graphs of each monitored variable. Additionally, the data is stored in the AWS database. The following real-time measurements are monitored: Axis position: Indicates the positions of 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.

The URL `https://youtu.be/lTZk7mai2Js` presents a video showing the Node-RED Dashboard, the Python program retrieving data from the Kuka.Sim platform's joints, and publishing it to Node-RED using MQTT, as well as to the AWS database. The 3D visualization of the simulation can also be performed using an App called Visual Components Experience, which is available for Android and Apple devices. This app allows users to view the simulation in WebGL format.

7. CONCLUSIONS

This article describes a Robotic Additive Manufacturing Cell using the LMD-Wire process. 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 Brasilia is nearing completion and is expected to be operational in September 2023. The case studies presented refer to programming, simulation, and monitoring without the actual printing of parts.

The main contribution of this research is to present the solutions and challenges of Robotic Additive Manufacturing using LMD-Wire. The development of solutions and approaches that can serve as guidelines for other implementations, serves 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.

8. ACKNOWLEDGMENTS

The authors would like to express their gratitude to CNPq (National Council for Scientific and Technological Development) and FAPDF (Foundation for Research Support of the Federal District) for their financial support in the development of this work.

9. REFERENCES

Alvares, A.J. and Lacroix, I., 2023a. "CAD/CAPP/CAM with Grasshopper to Robotic Adittive Manufacture". `https://youtu.be/UsXkto9vljg`. [Online; accessed 19-Juny-2023].

Alvares, A.J. and Lacroix, I., 2023b. "Simulation with Kuka.Sim to Robotic Adittive Manufacture". `https://youtu.be/ukc_CrEFBRE`. [Online; accessed 28-Juny-2023].

Biegler, M., Graf, B. and Rethmeier, M., 2018. "In-situ distortions in lmd additive manufacturing walls can be measured with digital image correlation and predicted using numerical simulations". *Additive Manufacturing*, Vol. 20, p. 101 – 110.

Bremer, J., Gasser, A. and Schleifenbaum, J.H., 2019. "Measurement of robotic path deviations and its influence on additively manufactured components". In *CAMX 2019 - Composites and Advanced Materials Expo*.

Cabral, J.V.A., Gasca, E.A.R. and Alvares, A.J., 2023. "Digital twin implementation for machining center based on iso 23247 standard". *IEEE Latin America Transactions*, Vol. 21, No. 5, pp. 628–635.

Cuevas, D. and Pugliese, G., 2020. *Advanced 3D Printing with Grasshopper, Clay and FDM*. Independently published. ISBN 9798635379011.

Feng, A., Chen, C., Wu, C., Wei, Y. and Wang, Y., 2022. "Modeling of laser melting deposition equipment based on digital twin". *Metals*, Vol. 12, No. 2.

Garmendia, I., Pujana, J., Lamikiz, A., Madarieta, M. and Leunda, J., 2019. "Structured light-based height control for laser metal deposition". *Journal of Manufacturing Processes*, Vol. 42, p. 20 – 27.

Glaessgen, E. and Stargel, D., 2012. "The digital twin paradigm for future of NASA and U.S. air force vehicles". In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*.

Gu, H. and Li, L., 2019. "Computational fluid dynamic simulation of gravity and pressure effects in laser metal deposition for potential additive manufacturing in space". *International Journal of Heat and Mass Transfer*, Vol. 140, p. 51 – 65.

Hankel, M., 2015. "The reference architectural model industrie 4.0 (rami 4.0) - bosch rexroth".

Huang, Z., Shen, Y., Li, J., Fey, M. and Brecher, C., 2021. "A survey on ai-driven digital twins in industry 4.0: Smart manufacturing and advanced robotics". *Sensors*, Vol. 21, No. 19. ISSN 1424-8220.

ISO 23247-1, 2021. "Automation systems and integration — digital twin framework for manufacturing — part 1: Overview and general principles".

Jan, Z., Ahamed, F., Mayer, W., Patel, N., Grossmann, G., Stumptner, M. and Kuusk, A., 2023. "Artificial intelligence for industry 4.0: Systematic review of applications, challenges, and opportunities". *Expert Systems with Applications*, Vol. 216.

Kerin, M., Pham, D.T., Huang, J. and Hadall, J., 2023. "A generic asset model for implementing product digital twins in smart remanufacturing". *The International Journal of Advanced Manufacturing Technology*, Vol. 124, No. 9, pp. 3021–3038.

Kubota, T., Hamzeh, R. and Xu, X., 2020. "Step-nc enabled machine tool digital twin". *Procedia CIRP*, Vol. 93, pp. 1460–1465. ISSN 2212-8271. 53rd CIRP Conference on Manufacturing Systems 2020.

Lettori, J., Raffaeli, R., Bilancia, P., Peruzzini, M. and Pellicciari, M., 2022. "A review of geometry representation and processing methods for cartesian and multiaxial robot-based additive manufacturing". *The International Journal of Advanced Manufacturing Technology*, Vol. 123, No. 11, pp. 3767–3794.

Liu, C., Le Roux, L., Körner, C., Tabaste, O., Lacan, F. and Bigot, S., 2022. "Digital twin-enabled collaborative data management for metal additive manufacturing systems". *Journal of Manufacturing Systems*, Vol. 62, p. 857 – 874.

Liu, C., Vengayil, H., Lu, Y. and Xu, X., 2019. "A cyber-physical machine tools platform using opc ua and mtconnect". *Journal of Manufacturing Systems*, Vol. 51, pp. 61–74. ISSN 0278-6125.

Lu, Y., Liu, C., Wang, K.I.K., Huang, H. and Xu, X., 2020. "Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues". *Robotics and Computer-Integrated Manufacturing*, Vol. 61, p. 101837. ISSN 0736-5845.

Luo, W., Hu, T., Ye, Y., Zhang, C. and Wei, Y., 2020. "A hybrid predictive maintenance approach for cnc machine tool driven by digital twin". *Robotics and Computer-Integrated Manufacturing*, Vol. 65, p. 101974. ISSN 0736-5845.

Pires, J.N., Azar, A.S., Nogueira, F., Zhu, C.Y., Branco, R. and Tankova, T., 2022. "The role of robotics in additive manufacturing: review of the am processes and introduction of an intelligent system". Vol. 49, No. 2, pp. 311–331.

Qiao, Q., Wang, J., Ye, L. and Gao, R.X., 2019. "Digital twin for machining tool condition prediction". *Procedia CIRP*, Vol. 81, pp. 1388–1393. ISSN 2212-8271. 52nd CIRP Conference on Manufacturing Systems (CMS), Ljubljana, Slovenia, June 12-14, 2019.

Shao, G. and Helu, M., 2020. "Framework for a digital twin in manufacturing: Scope and requirements". *Manufacturing Letters*, Vol. 24, p. 105 – 107.

STEP Tools, I., 2016. "Digital Thread and Digital Twin Demonstrations at Future of Flight, https://www.steptools.com/blog/, Acesso em: 17 nov. 2022".

Tong, X., Liu, Q., Pi, S. and Xiao, Y., 2020. "Real-time machining data application and service based on imt digital twin". *Journal of Intelligent Manufacturing*, Vol. 31, p. 1113–1132.

Xu, X., 2017. "Machine Tool 4.0 for the new era of manufacturing". *The International Journal of Advanced Manufacturing Technology*, Vol. 92, No. 5-8, pp. 1893–1900. ISSN 0268-3768.

Yan, L., Chen, Y. and Liou, F., 2020. "Additive manufacturing of functionally graded metallic materials using laser metal deposition". *Additive Manufacturing*, Vol. 31.

10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.