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An integrated and interoperable AutomationML-based platform for the robotic process of metal additive manufacturing

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Abstract

Increasingly, industry is looking to better integrate their industrial processes and related data. Interoperability is key since the organizations need to share data between them, between departments and the different stages of a given technological process. The problem is that many times there are no standard data formats for data exchange between heterogeneous engineering tools. In this paper we present an integrated and interoperable AutomationML-based platform for the robotic process of metal additive manufacturing (MAM). Data such as the MAM robot targets and process parameters are shared and edited along the different sub-stages of the process, from Computer-Aided Design (CAD), to path planning, to multi-physics simulation, to robot simulation and production. The AutomationML neutral data format allows the implementation of optimization loops connecting different sub-stages, for example the multi-physics simulation and the path planning. A practical use case using the Direct Energy Deposition (DED) process is presented and discussed. Results demonstrated the effectiveness of the proposed AutomationML-based solution.

Keywords: Interoperability; AutomationML; Additive Manufacturing; Data

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1. Introduction

The digitalization of industry has been growing through the course of the last decades, transforming data management into one of the main topics of the industry 4.0 concept [12]. Data exchange between heterogeneous engineering tools have been considered a bottleneck in production, reducing the efficiency and flexibility of the production systems. In such a scenario, it is important to have an efficient data flow between the different stages and tools involved in a given production system [9, 20].

Traditionally, data are exchanged manually from one system to another via heterogeneous data files [22]. Such data files present different formats, structures or types, making data exchange a challenging and in many cases impractical task. This is a time consuming and prone to human error process where data editing is hard to manage and keep in memory, often causing loss of important information.

The metal additive manufacturing (MAM) data flow involves a wide range of file types generated along the different sub-stages of the process. Proprietary file types are usually specific for a given software making interoperability difficult [23]. Standard file formats can be used to overcome this issue, for example, the stereolithographic (STL) files to specify 3D surfaces at the design sub-stage or the slicing software at the path planning sub-stage. Nevertheless, there is no standard nor machine independent file formats linking the different stages of the process. Commonly, each equipment/software has its own specific file format and specific data structure.

This paper addresses the above challenges by updating a neutral data format based on AutomationML [2, 16], allowing to exchange and edit MAM process data between the different heterogeneous tools used in both offline and online stages. The offline stage includes part CAD design, topology analysis, path planning, simulation and the testing of the part in a virtual environment. The online stage addresses the effective production of

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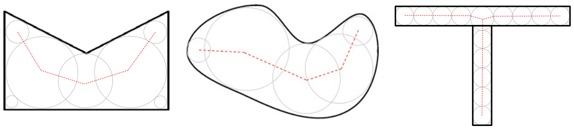


Fig. 1. MAT of different shapes using loci of centers. The dash lines represent the medial axis.

the part and the non-destructive testing. Results are illustrated with a real use case.

2. AutomationML

A number of flagship companies in manufacturing and automation domain joined efforts to identify data exchange issues of modern productions systems, conducting to the development of Automation Markup Language (AutomationML) [13]. The main objective was to create a system where different components are integrated together (physical manufacturing plants, components and software), resulting in a more efficient management of manufacturing resources. The AutomationML format is based on extensible markup language (XML) format, standardized in IEC 62714, combining pre-existing neutral data formats such as computer aided engineering exchange (CAEX), COLLAborative design activity (COLLADA) and PLCopen XML. It merged the best properties of each of them into a single format, AutomationML [4]. The central part of an AutomationML file is a CAEX structure, allowing to store data as a hierarchical structure of plant objects [3]. Data are stored in instance hierarchies where nodes represent individual objects (internal elements), and in its turn, the internal elements within an instance hierarchy can be composed of other internal elements resulting in a hierarchical structure [18]. The objects (classes and instances) are stored in the CAEX structure. There are auxiliary data formats which compose the AutomationML file, for example, COLLADA [19] and PLCopen XML [10]. The relationship between object hierarchies can be setup for the programming of CAEX documents, where the relationship between a System Unit Family Class and a Role Class are established using AutomationML Engine [2, 9].

3. Metal additive manufacturing data management

Additive manufacturing has been growing in the last few years [1]. The engineering community is developing strategies to apply AM on engineering projects using composites (e.g. fiberglass and carbon fiber) and metals (e.g. steel and titanium alloys) [15]. When it comes to DED, aerospace and automotive industries appear to be leading the way, seeking opportunities to reduce manufacturing lead-times, component weight and lower production costs [7].

In this paper we study two different DED processes, the wire arc additive manufacturing (WAAM) and laser metal deposition (LMD). WAAM is an arc-based process featuring a high deposition rate [25, 24, 14]. Recently, WAAM-based solution have been proposed for the manufacturing of structures containing thin walls applied in aerospace industry [6]. LMD uses a laser beam to deposit metallic material, added in the form of powder or wire, by melting them on the surface of a substrate. The main advantage of LMD is the relatively low heat input, reducing defects (distortions and cracks) in the final produced part [17].

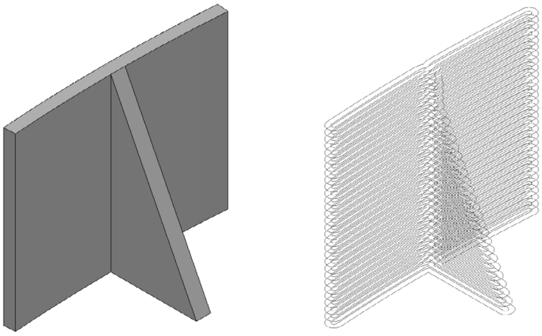


Fig. 2. CAD part (left) and the generated path using MAT strategy (right).

DED technology allows to produce parts with complex shapes at a relatively low cost. However, considering for instance the LMD process, the process parameters (laser power, deposition speed, path strategy, dwell time, among others) require fine adjustment and vary from part to part.

Typically, the a MAM process requires the conjugation and integration of efforts from different departments, from the CAD design to the final production and testing of the part [26]. In such heterogeneous landscape data exchange is more difficult. Neutral data format files such as AutomationML might be very helpful to make this process more efficient.

There are several possible solutions for AM path planning. However, only a few of them are suitable for DED. When implementing the path planning strategy, a key challenge is to develop robust algorithms to slice a CAD model and to obtain a path that ensures a defect free part with minimum support structures and collision free deposition. Ding et al. enunciate a list of path patterns for the AM process such as raster, zigzag, contour, spiral, among others [8]. Nevertheless, for the WAAM and LMD process these patterns are not suitable. A possible solution for DED path planning is based on the medial axis transformation (MAT) [8]. MAT was first introduced by Blum to describe shapes with medial axis defined as loci of centers of locally maximal spheres inside an object [5]. In two dimensions (2D) the MAT would be the loci of centers of locally maximal circles inside the region of a 2D shape, Fig. 1. The path planning strategy is based on filling the part from inside towards outside, reducing imperfections like pores and gaps. Fig. 2 shows a path example applied to our use case part based on MAT strategy for DED.

Our approach imports to an AutomationML file the data from a path generator and combine it with the process parameters data. We used Autodesk PowerMill Ultimate CAM software as path generator. Once the paths are created, Fig. 2

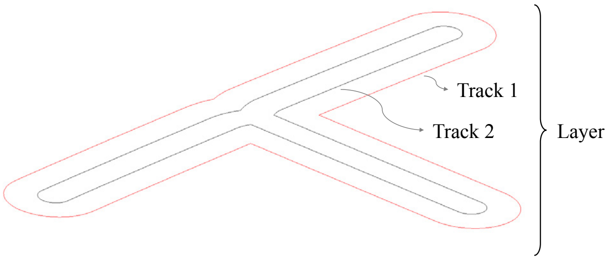
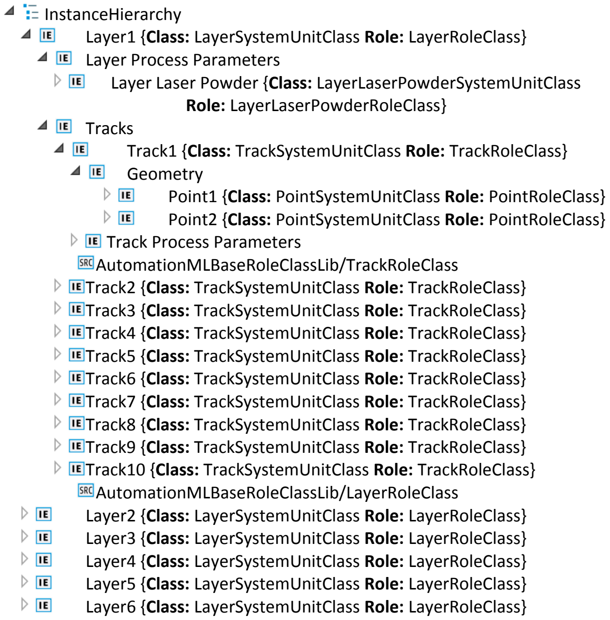


Fig. 3. Layer and two closed tracks.



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◢ InstanceHierarchy
  ◢ IE  Layer1 {Class: LayerSystemUnitClass Role: LayerRoleClass}
    ◢ IE  Layer Process Parameters
      ▷ IE  Layer Laser Powder {Class: LayerLaserPowderSystemUnitClass
                       Role: LayerLaserPowderRoleClass}
    ◢ IE  Tracks
      ◢ IE  Track1 {Class: TrackSystemUnitClass Role: TrackRoleClass}
        ◢ IE  Geometry
          ▷ IE  Point1 {Class: PointSystemUnitClass Role: PointRoleClass}
          ▷ IE  Point2 {Class: PointSystemUnitClass Role: PointRoleClass}
        ▷ IE Track Process Parameters
         SRC AutomationMLBaseRoleClassLib/TrackRoleClass
      ▷ IE Track2 {Class: TrackSystemUnitClass Role: TrackRoleClass}
      ▷ IE Track3 {Class: TrackSystemUnitClass Role: TrackRoleClass}
      ▷ IE Track4 {Class: TrackSystemUnitClass Role: TrackRoleClass}
      ▷ IE Track5 {Class: TrackSystemUnitClass Role: TrackRoleClass}
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      ▷ IE Track8 {Class: TrackSystemUnitClass Role: TrackRoleClass}
      ▷ IE Track9 {Class: TrackSystemUnitClass Role: TrackRoleClass}
      ▷ IE Track10 {Class: TrackSystemUnitClass Role: TrackRoleClass}
         SRC AutomationMLBaseRoleClassLib/LayerRoleClass
  ▷ IE  Layer2 {Class: LayerSystemUnitClass Role: LayerRoleClass}
  ▷ IE  Layer3 {Class: LayerSystemUnitClass Role: LayerRoleClass}
  ▷ IE  Layer4 {Class: LayerSystemUnitClass Role: LayerRoleClass}
  ▷ IE  Layer5 {Class: LayerSystemUnitClass Role: LayerRoleClass}
  ▷ IE  Layer6 {Class: LayerSystemUnitClass Role: LayerRoleClass}
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Fig. 4. CAEX structure from the AutomationML file.

(right), with the help of a PowerMill Post Processor is possible to generate a customized numerical control file(NC) containing all the points of the path. Postliminary, the points can be extracted from the NC file and stored as a CAEX tree structure in an AutomationML file by means of the Integradde Build file Software (IBFS).

The IBFS imports and stores data from the NC file to the AutomationML file. Such data are later provided to a robot post-processor that includes path discretization functionalities [28, 29]. Every line from the NC file represents a single point of the path. Each point has the information of its Cartesian coordinates and orientation, and the type of robot movement, which can assume values as APP for approach movement, RET for retraction movement, LLNK for link movement and ADD for material deposition movement. The points from the NC file are saved into a variable named Points[], where it is conducted an iterative process in order to organize the points into layers and tracks. The output from this step is the variable Points[], in which every point has an indication to which layer and track it belongs. Also, it is attached to them the Cartesian coordinates and the orientation. The IBFS uploads the points from the paths and has the ability to group them into tracks and layers. A track is a sub element of a layer representing the points associated to the deposition of material. The criteria to identify one track from another consists on analysing when occurs an interruption in material deposition, this is, when the extruder stops the deposition on a track to move and start deposition on another one. On the other side, a layer is a group of tracks that constitute one slice of a part, Fig. 3. Having the AM path separated into tracks and layers allows a better control on the manufacturing process, making the process more flexible and allowing to edit the parameters at layer or track level. This may conduct to the fabrication of better-quality parts, for example by locally controlling the thermo-mechanical properties and by this way reducing the defects and the structural failures on the manufactured part such as pores, cracks and distortion [27].

4. AutomationML file generation

The IBFS features regarding the generation of the AutomationML file were developed with the help of AutomationML Engine and mirrors the XML data model of CAEX hierarchies through a C# class model. Moreover, it has an automatic generating process that allows to manipulate object data, to add or remove children in the CAEX hierarchies, and to change CAEX objects like instances or classes. AutomationML Engine is used as a tool to simplify the programming process and relieves the programmer from directly managing XML code, avoiding human programming errors. The IBFS is operated on a class level, while AutomationML Engine creates the correct CAEX schema [9], Fig. 4.

5. IBFS input files

The IBFS is equipped with tools that allow to upload NC files with both data regarding AM paths as well as welding paths. Concerning AM, it is possible to import to the IBFS a wide range of different paths. Depending on the chosen path planning strategy for the manufacturing process, the AM files are divided into three categories according to the base type of the model. The first type is Planar Base, the second is Cylindrical Base and finally the third one is the Arbitrary Base. For the welding paths, the IBFS includes two options, Spot Welding and standard Welding (single or multi-bead welding). When the data are extracted from the NC file and stored in the AML file, the IBFS software has the option to include only the tracks of the AM or Welding Path which have material deposition and ignore the remaining ones, that is, the approach, retraction and link movements. This is particularly useful when it is required to have information in the AML file that is exclusively associated to the tracks with material deposition. When it is required to transfer data to a robot simulator/controller the user has the freedom to simulate the paths as desired. We also developed a module for the IBFS to add process parameters data to the AML file. This step enables the user to choose the DED method and to add manually process information (laser power, deposition velocity, dwell time, etc.) at layer or track level. Fig. 5 shows

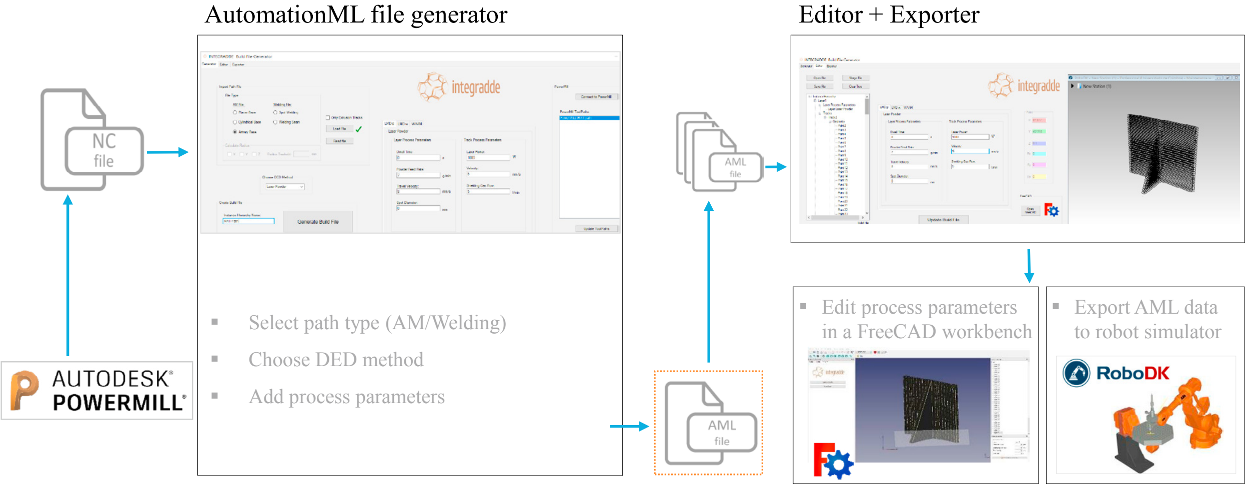


Fig. 5. IBFS complete workflow.

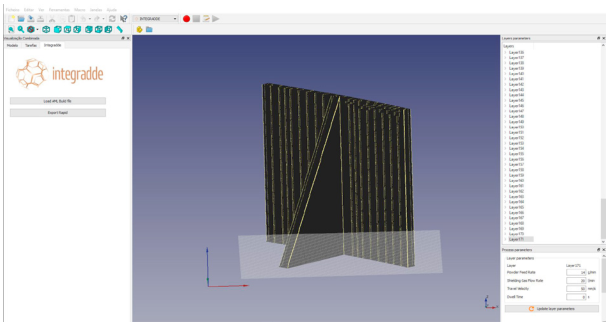


Fig. 6. FreeCAD-based custom workbench.

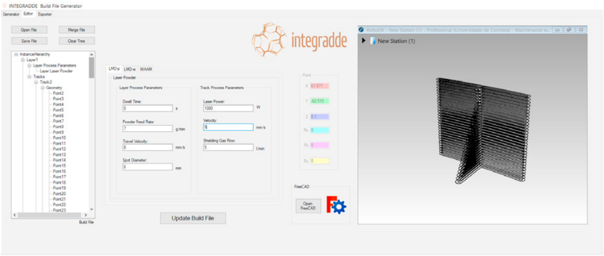


Fig. 7. IBFS Editor and Exporter.

the complete workflow of the IBFS software, starting with the generation of the AutomationML file up to connecting this file with external software programs.

6. FreeCAD-based editor

The layers, tracks and the process parameters from AutomationML file can be visualized in a CAD environment using our proposed FreeCAD-based custom workbench. The AutomationML file is the only input for this workbench and it allows the user to modify the process parameters intuitively. Such a CAD environment was created in FreeCAD software [11], offering the possibility to create a workbench with custom features programmed in Python and C++ language by means of Qt libraries. The workbench provides functionalities to select and edit a given layer or track, Fig. 6. Such a characteristic is especially useful for complex part geometries where we could anticipate eventual local problems on the manufacturing of the part and then strategically modify the parameters on the desired track or layer. As the parameters are changed the AutomationML file is also updated.

7. IBFS Editor

The IBFS software was designed to increase the interoperability between different software tools and files. It includes the ability to connect CAM software and Robot Simulation software. Besides the FreeCAD workbench, the IBFS also provides an integrated AutomationML file editor with the option to edit and visualize the data from an AutomationML file, Fig. 7. Owing to the large size of AutomationML files (depending on the part geometry and the chosen strategy to generate the DED path), it may be convenient to divide the data into multiple AutomationML files. With the proposed editor the user has the ability to merge those AutomationML files and combine them in order to rebuild the full part.

8. Robot simulation and part manufacturing

Regarding the offline stage, the AutomationML file contains all the information to build the part and therefore to simulate the building strategy in a robot simulation environment or in a structural simulation environment. RoboDK software has been used for off-line robot programming since it contains an extensive library of industrial robot arms and external axes. Once the AutomationML file is completed with all the data necessary to build the required part, then it is possible to proceed to

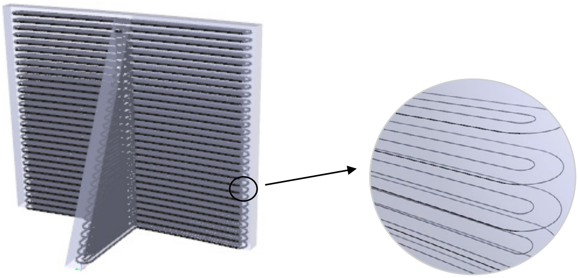
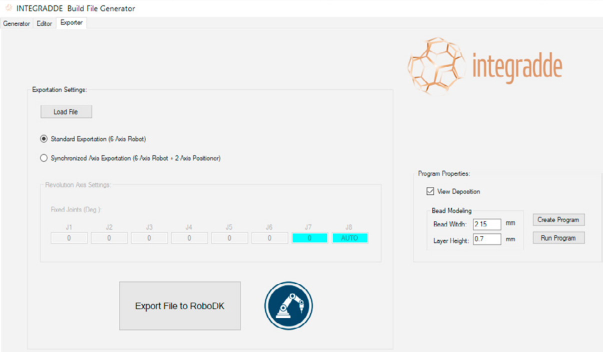


Fig. 8. Additive manufacturing paths imported to the robot simulator software (RoboDK).



Exportation Settings:

● Standard Exportation (6 Axis Robot)

○ Synchronized Axis Exportation (6 Axis Robot + 2 Axis Positioner)

Revolution Axis Settings:

Fixed Joints (Deg.):

J1	J2	J3	J4	J5	J6	J7	J8
0	0	0	0	0	0	0	AUTO

Program Properties:

☑ View Deposition

Bead Modeling

Bead Width: 2.15 mm

Layer Height: 0.7 mm

Fig. 9. IBFS Exporter GUI.

the next stage which is exporting the data from the AutomationML file to the robot simulator, Fig. 8. To reach this goal we developed for IBFS a module linking data from the AutomationML file and the robot simulator software (RoboDK). It enables the user to load the AutomationML file data directly to a robotic cell and it provides two exportation options. The first one, Standard Exportation, enables to choose a robotic cell with a 6-axis industrial robot from the RoboDKs library. The second one, Synchronized Axis Exportation, enables the user to export the AutomationML data to an 8-axis robotic cell, this is, 6-axis industrial robot plus a 2-axis positioner, Fig. 9. Follows the simulation analysis in order to confirm that the part can be successfully produced, Fig. 10. After successfully simulating the path with the robot simulator software it is possible to proceed to the final step, which is robot code generation. To generate the robot code, it was used a suitable robot post-processor from RoboDK, which allowed the production of the part, Fig. 11.

9. Conclusion

This paper proposed an integrated approach for data exchange between heterogeneous engineering tools for metal additive manufacturing based on AutomationML technology. AutomationML demonstrated to be a reliable and easy to use interoperable format, allowing process data to be shared and edited along the different sub-stages of the process, from CAD design, to path planning, to multi-physics simulation, to robot simulation and production. The AutomationML neutral data format allowed the optimization loops connecting different sub-stages, for example the multi-physics simulation and the path planning. In the sequence of this work, the AutomationML Engine demonstrated to simplify significantly the programming efforts and the data exchange through the complete digital thread. It was successfully validated in a real use case.

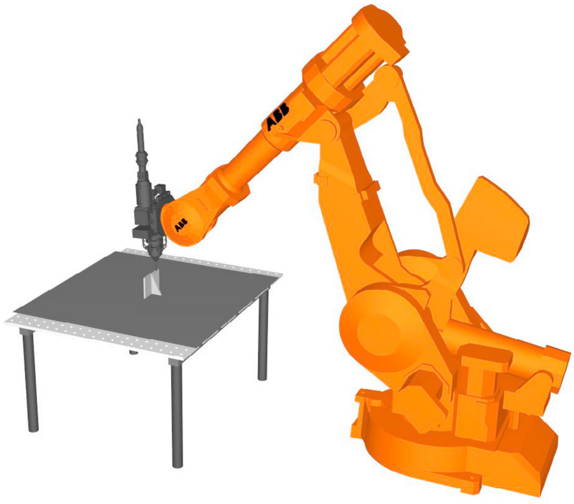


Fig. 10. Robotic simulation cell in RoboDK.

Fig. 11. Manufactured part using DED process.

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