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OpenLMD, an open source middleware and toolkit for laser-based additive manufacturing of large metal parts

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ABSTRACT

We describe OpenLMD, a novel open-source toolkit for on-line multimodal monitoring and process control of Laser Metal Deposition (LMD). Building on existing open-source libraries (e.g. ROS, OpenCV, PCL), it enables the orchestration and virtualization of a robot cell for LMD and laser materials processing in general. It allows fast and intuitive process programming and planning, easy integration of multiple sensors and equipment, real-time process control, process virtualization and advanced visualization, and web-based interoperability. The approach adopted presents clear advantages in terms of scalability, and multimodal monitoring and data sharing capabilities. OpenLMD speeds up the deployment of laser metal deposition cells that feature CAD-based programming, advanced monitoring and control functionalities, and high interoperability. Its adoption allows focusing on a specific problem, without giving away functionalities that are important for performance demonstration. It facilitates collaborative research and the creation of datasets and benchmarks, in close-to-industrial settings. The ultimate goal is to enable working solutions for fully automated 3D printing of large metal parts, the challenging objective of many recent efforts on process modelling, monitoring, and control.

1. Introduction

Laser metal deposition (LMD) is an additive manufacturing technique based on laser cladding, in which a laser beam melts metallic powder particles directly injected over a predefined track path onto the surface of a base material or previously built tracks [1]. This process has been adopted by industry for coating and repair of critical parts, such as turbine blades or stamping molds. However, what makes LMD process most interesting is the promise of enabling additive-manufacturing of near-net-shape large metallic parts [2,3]. It allows in principle direct manufacturing of parts from their 3D CAD model layer-by-layer, through the successive deposition of (partially) overlapped clad tracks. However, the complexity of laser cladding makes it challenging in practice to obtain homogeneous layers with specific metallurgical and mechanical properties. Energy and mass inputs are key parameters that drive heat transfer dynamics, affecting heat flow, temperature distribution, and melt pool geometry, and eventually producing stress and deformations or failure of the manufactured parts [4]. Moreover, this dynamics changes from one layer to another and is highly dependent on the geometry of the sub layers [1,5,6]. This has motivated increasing efforts on modeling [5,7], process planning [8], and process monitoring and control [9] during the last years.

Therefore, novel technology is required that fills in the gaps of process modeling and planning and process control, in order to enable the practical use of LMD as a fully automated technique for 3D printing of large metal parts. With the aim to facilitate a collaborative approach to this development effort, we propose OpenLMD as a middleware and a set of tools that facilitate the deployment of a flexible LMD robot cell with state-of-the-art capabilities on process planning, process monitoring and control, and data gathering.

With this aim, we adopt a cost-effective and flexible multimodal on-line monitoring approach with a software architecture built on ROS (Robot Operating System).[1] The system is capable of performing data acquisition of very different sources (e.g. sensors, robot, laser) referred to a common time and coordinates reference, with no motion constraints. It provides a modular multiprocessing architecture easy to integrate in an existing robot cell at a low cost. Besides, it is agnostic as to the robot or machine brand and language. It allows to reuse and develop novel path planning approaches and to apply them with different machines. The only requirement is that the machine can

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[1] http://www.ros.org.

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accomplish such tasks and that a simple driver to integrate the machine is available.

This approach presents two major advantages. On one hand, it provides a solution that overcomes interoperability and deployment issues and facilitates the acquisition of exhaustive data on the process that can be used both as measurements or as labels for the development of e.g. supervised learning systems and the integration in more complex automation schemes. This aligns with the promise of smart factories as enablers of future manufacturing [10], characterized by a much higher flexibility of automated processes [11]. On the other, it supports virtualization and visualization tools to synchronously reproduce the monitored process.

OpenLMD as a middleware does not impose any inherent limit on size or accuracy. Such limits will be imposed mainly by the movement system used (i.e. robot and external axis) as well as the laser processing head properties (laser beam shape and powder flow stability). Moreover, the use of 3D measurement systems that correct the robot trajectories—as supported by OpenLMD—may have a significant impact, adding one more source of accuracy. The adequacy of OpenLMD for large parts is inherent to the fact it is designed to deploy LMD processing on industrial robot cells with workspaces much larger (up to several meters) than more extended conventional laser processing (e.g. SLM) machines.

A first implementation has been validated in an industrial LMD cell on an operational environment, demonstrating that on-line multimodal measurements can be easily carried out while achieving a good enough accuracy and control performance. Furthermore, code[2] and data[3] acquired are made publicly available and shared as open source (OpenLMD[4]).

2. Architecture overview

A common industrial laser cladding cell (Fig. 1) consists of a solid-state laser fibre coupled to a cladding head, a powder feeder with a coaxial nozzle, and a motion system based on an anthropomorphic industrial robot. The field bus integration of this equipment—configuring the robot as master controller—is a traditional option to enable the operation of the whole system from the robot routine.

With the aim of being hardware agnostic—i.e. compatible with a generic laser processing robot cell—we propose a modular and open-source solution built on ROS (Robot Operating System) and additional on open-source packages. This approach provides a solution not dependent on the specific model or brand of robot. Besides, we adopt a multi-process architecture that can be easily adapted to different requirements, making straightforward the deployment of complex multimodal monitoring and control solutions.

The architecture (Fig. 2) has been designed to be modular and fully asynchronous, based on the use of timestamps to correlate information over time.

It presents two main elements: nodes and topics. Each node (e.g. sensor or robot drivers, feature extraction routines, process control routines) publishes through or subscribes to ROS topics to share information asynchronously in the form of messages. A reusable and sustainable solution has been pursued through the use of standard messages for the orchestration of machines, sensing devices, and processing algorithms.

A simple ROS driver integrates the robot cell in the OpenLMD architecture. This driver presents two nodes, the *robot_state* node publishes instantaneous joints positions of the robot (at 50 Hz) and the *robot_server* subscribes commands to control the robotized cell. As a result, the instantaneous robot position is determined on-line to reconstruct the virtual representation of the robot through the TF ROS library.

Therefore, replacing the movement system only requires the implementation of this driver for the new robot. Provided that joints positions are available, that the robot programing language allows to control movement using variables that can be modified externally through a robot server, and that a kinematic model of the robot is also available, then this driver can be easily developed.

Similarly, sensors and measurements are easily added through specific drivers. While sensor drivers present a node that publishes the acquired data with a timestamp, measurements typically feature a node that subscribes to one or more topics from sensors and a node that publishes the derived measurements or estimations as a new topic.

Thanks to this approach, the system can jointly visualize all the process parameters, data acquired, and derived measurements (e.g. tool pose, acquired 3D points) in a single virtual environment by using RVIZ.

Moreover, the system is also capable to record all the generated process information within ROS bags. Stored bag files can be reproduced later to recreate all the topics at the same time. This brings a twofold benefit. On one hand, additional measurements and estimations may be derived and tested without the need to repeat the process. On the other, full process virtual visualization is possible using again RVIZ to represent all the recorded data synchronously—thanks to the use of timestamps—in a 3D environment. Several open source tools for computer vision and robotics (e.g. OpenCV, PCL, ROS, RVIZ) and Python packages (e.g. Numpy, Pandas) have been used to implement the system.

The Industry 4.0 paradigm seeks a connected factory with processing and communication capabilities. This does not only imply the machine-to-machine interaction and communication but also suggests the interplay of humans and technology [12]. OpenLMD facilitates handling and processing a large number of image and process related data, and aims to operate as a Cyber Physical (CP) entity that supports the communication between different users (e.g. engineers, operators, managers) within the factory.

To accomplish this, a web-based Human Machine Interface (HMI) has been developed and integrated in OpenLMD's architecture under the context of this paper. As a web-based development the architecture of the HMI corresponds to a server-client side logic which displays the information on a website optimized for mobile devices use. To this end, an application has been built in Java while for the web server set up 'Apache Tomcat 7.0'[5] was used. As far as it concerns the front-end development, we used the 'Bootstrap Framework v3.3.7'.

Due to the ROS-based solution followed in the OpenLMD system, special focus is given to the communication of the web server with the LMD controller. Specific ROS libraries with client side tools for the web app visualization were implemented in the server side code supporting the different HMI's functionalities. Indicatively:

- Rosbridge for visualization of real measurements and process parameters values.
- Mjpegcanvasjs library for video streaming of the raw and processed data.
- Ros3Djs and ROS web_video_server for visualization of the robot movements.
- Rwt_plot ROS library for graphs visualization.

3. Process planning

OpenLMD features an adaptive path planning generation system. This system calculates a filling path based on a surface from a point cloud or from a CAD model. It allows to put in place different filling in

[2] https://github.com/openlmd.
[3] http://zenodo.org/record/45664.
[4] http://openlmd.github.io/.
[5] https://tomcat.apache.org/ https://tomcat.apache.org/.