OpenLMD, Multimodal Monitoring and Control of LMD processing

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ABSTRACT

This paper presents OpenLMD, a novel open-source solution for on-line multimodal monitoring of Laser Metal Deposition (LMD). The solution is also applicable to a wider range of laser-based applications that require on-line control (e.g. laser welding). OpenLMD is a middleware that enables the orchestration and virtualization of a LMD robot cell, using several open-source frameworks (e.g. ROS, OpenCV, PCL). The solution also allows reconfiguration by easy integration of multiple sensors and processing equipment. As a result, OpenLMD delivers significant advantages over existing monitoring and control approaches, such as improved scalability, and multimodal monitoring and data sharing capabilities.

Keywords: LMD, multimodal, monitoring, ROS, laser processing, virtualization, additive manufacturing

1. INTRODUCTION

Laser Metal Deposition (LMD) is a promising additive-manufacturing technique for repair or fabrication of near-net-shape (i.e. close to the target final shape) metallic parts. It allows direct manufacturing of parts from their 3D CAD model layer-by-layer, through the successive deposition of (partially) overlapped clad tracks – defined off-line based on the assumption of constant track width and layer height using laser cladding.

In laser cladding [1] a laser beam is used to melt metallic powder particles directly injected on the surface of the target part while the cladding system follows a predefined path. This process is very popular in industry for coating and repair of critical parts, such as turbine blades or stamping molds.

It has been traditionally assumed that no distortions affect the laser cladding process, and hence a set of fixed, predefined process parameters (e.g. speed, laser power, powder flow) can be used through the deposition of successive layers.

In practice, the complexity of laser cladding makes it challenging to obtain homogeneous layers with specific metallurgical or mechanical properties, because the characteristics of the deposited layers are affected by several factors. As a consequence, fabricated parts may suffer from clad defects and geometric distortions. Overheating and accumulation of residual thermal stresses (especially in large and complex parts) are the main causes of fabrication defects. To prevent all these problems, suitable LMD monitoring and control systems are required.

Recently, different closed-loop control systems have been proposed to improve the performance of laser cladding processes [2]-[4]. Such systems rely on a coaxial arrangement for monitoring melt pool geometry or temperature, acting on laser power to compensate the effects of thermal variations. A more complex setup [5] – with three off-axis CCD cameras – has demonstrated improvement of dimensional accuracy by controlling the melt pool height. Other approaches not focused on control, provide LMD dimensional monitoring [6].

However, existing solutions provide very specific monitoring approaches that focus on a single measure of interest (e.g. melt pool width, track height) acquired either co-axially or off-axis. As a result, these approaches do not provide a comprehensive monitoring and control solution to LMD processing, since different setups (coaxial or off-axis) are needed to measure different process magnitudes in a general situation.

Such a comprehensive solution requires the deployment of an integrated architecture capable to acquire on-line coaxial and off-axis information with a multimodal approach.

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With this end, we propose a cost-effective and flexible multimodal on-line monitoring solution with a software architecture built on ROS (Robot Operating System)\(^1\) [7]. The system is capable of performing data acquisition referred to a common time and coordinates reference, with no motion constraints. It provides a modular multiprocessing architecture that can be easily adapted to different existing industrial facilities at a low cost.

Moreover, our approach presents two major advantages, providing a solution able to overcome interoperability and deployment issues, and at the same time supports virtualization and visualization tools to synchronously reproduce the monitored process.

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 share as open source (OpenLMD\(^4\)).

2. ARCHITECTURE OVERVIEW

A common industrial laser cladding cell (Figure 1) consists of a solid-state laser fiber 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.

![Figure 1. Elements of a common industrial laser cladding cell and setup from AIMEN technology center.](image)

With the aim of being hardware compatible with a generic laser processing robot cell, we propose a modular solution built on ROS (Robot Operating System) and based on open-source tools. This approach provides a robot-independent solution based on a multiprocess architecture which can be easily adapted to different requirements, making straightforward the deployment of complex multimodal monitoring and control solutions.

The architecture (Figure 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.

\(^1\) http://www.ros.org
\(^2\) https://github.com/openlmd
\(^3\) http://zenodo.org/record/45664
\(^4\) http://openlmd.github.io/
asynchronously in the form of messages. A reusable and sustainable solution is pursued based on the use of standard messages for the orchestration of machines, sensing devices, and processing algorithms.

A ROS driver has been developed to integrate the cell in the OpenLMD architecture. This driver presents two nodes, the `robot_state` node publishes instantaneous joints positions of the robot (at 50Hz) 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.

![Diagram of OpenLMD main architecture and on-line visualization and virtualization of LMD multimodal data.](image)

Thanks to this approach, the system can visualize the process and data acquired (e.g. tool pose, acquired 3D points) in a virtual environment by using RVIZ. Moreover, the system is also capable to record all the generated process information through ROS bags. Stored bag files can be reproduced later to recreate all the topics at the same time. Therefore, 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 employed to implement the system.

### 3. MULTIMODAL MONITORING

Multimodal information is provided by different sources coupled to the laser head (Figure 3) in two arrangements:

- **Coaxial arrangement:** A CMOS sensor covers the visible and near infrared range (0.4-1µm) at 30Hz and an uncooled PbSe sensor covers the middle wavelength infrared range (1-5µm) at 1kHz sampling rate, both to monitor melt pool geometry, thermal distribution, and surface dynamics.

- **Off-axis arrangement:** A CMOS sensor coupled to a laser stripe for triangulation acquires 3D profiles of the surface at 30Hz.

The coaxial arrangement pursues the process monitoring (i.e. thermal data and surface inspection) while the off-axis arrangement provides 3D geometrical information (i.e. point cloud data). Moreover, this setup provides a solution that can be extended for other laser processes (e.g. laser welding, laser cutting).

Besides the multimodal nature of data acquired, different feature extraction techniques (e.g. melt pool width, shape, texture dynamics, speed, thermal gradient, 3D shape) are being tested under the proposed architecture.

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3.1 Multispectral coaxial monitoring

Each camera in the coaxial configuration must be calibrated and aligned (Figure 4) to get real measurements and for the multispectral data fusion. The calibration procedure provides a flexible setup that can be adapted to different process requirements, and avoids the need for accurate mechanical positioning parts. In this way, the system can be easily adapted to work with different laser heads and setups, as required for different industrial facilities and processes.

The cladding nozzle is well centered with the laser beam, ensuring coincidence between the laser beam and the vertex of the powder cone. Moreover, this vertex has to match the working distance of the laser – defined by the focal length of the lens inside the laser head. This working point is registered as Tool Center Point (TCP) and defines the exact location of the laser cladding head in relation to the workpiece. Since the image sensors are attached to the laser head – coupled to the robot wrist –, their relative position and orientation to the TCP remains fixed. Therefore, the melt pool and the surrounding area remain within the field of view.

Besides the working point of the laser head, the TCP defines the plane where the cameras should be calibrated to observe the process. Since the cladding track typically has a height lower than 1mm, the calibration of 2D coaxial images can be done as a generalized homography transformation without significant loss of accuracy in transverse coordinates.

The homography transformation (Eq. 1) is estimated from 4 known point in the space, providing a direct transformation where \((u, v)\) are the coordinates of each image pixel and \((X, Y)\) the real coordinates in the space.
\[
\begin{pmatrix}
  s \cdot X \\
  x \cdot Y \\
  s
\end{pmatrix} =
\begin{pmatrix}
  h_{11} & h_{12} & h_{13} \\
  h_{21} & h_{22} & h_{23} \\
  h_{31} & h_{32} & h_{33}
\end{pmatrix}
\begin{pmatrix}
  u \\
  v \\
  1
\end{pmatrix}.
\]

To address the multimodal coaxial calibration (Figure 5), three operations are required: 1) optical adjustment to focus the image on the TCP plane to image the targeted plane; 2) light source placement – on the working distance - opposite the nozzle and image capture with both cameras; 3) homography estimation from image to TCP plane to transform pixels to actual surface positions scaled in millimeters.

![Calibrated images after homography transformation.](image)

**3.2 3D geometrical monitoring**

The off-axis triangulation system works on-line providing a 3D point cloud that is registered in real-time in robot coordinates (mm) based on the instantaneous robot position – with independence of the robot movement -. This system was developed in a previous work \[7\] and enables different setups and configurations with a simple offline calibration procedure. Such calibration is made with a printed chessboard pattern with squares of 10mm side each and several images acquired from different robot poses to ensure a maximum accuracy in the point cloud calibration.

![3D point cloud registered on-line to locate a part free placed onto the working area.](image)

When the laser stripe is projected onto the scene, an illuminated point in the 3D space corresponds to a pixel in the captured image. The coordinates of each illuminated point (3D profile) are computed by triangulation in the camera coordinate system. Then the 3D point cloud is registered following the robot movement based on the instantaneous robot position and the camera location.
4. EXPERIMENTAL RESULTS

4.1 Experimental setup

The proposed system has been integrated in a typical industrial laser cladding cell (Figure 1). A WT03 laser head from Permanova has been mounted on a 6-axis IRB4400 robot manipulator from ABB. A 1.5kW fiber laser from Rofin and a powder feeder from GTV, which delivers the metallic powder through a coaxial nozzle from Fraunhofer IWS – attached to the WT03 – completes the laser processing equipment.

The 6-axis robot moves the laser beam along the target paths and sets all the process parameters (e.g. laser power, powder flow) via Proﬁbus. An IDS µEye industrial camera with a 1.3Mpixel CMOS NIR sensor is used in the triangulation system, while a TACHYON 1024 microCORE from New Infrared Technologies and other µEye NIR is used in the coaxial system. These cameras complete the hardware available in the LMD cell available in the AIMEN Technology Center.

The OpenLMD software components have been deployed in a PC with an Intel I7 Quad Core processor working at 3GHz and 8GB of RAM, running ROS Indigo under Ubuntu 14.04. The corresponding code has been mostly written in Python and it is available on GitHub.

4.2 3D path planning

An adaptive path planning generation system has been developed for the geometrical control of LMD robotized processing. The software calculates the next path required for an adequate execution of the geometry in function of the 3D scanning information recorded during the process.

At a first step, the automatic coating of surfaces has been demonstrated in our workflow, removing tedious programming tasks.

Placed the part inside the working space, the part can be located using the off-axis triangulation system and the robotic cell automatically programmed to performa coating repair job. The region where the part was placed is scanned and the 3D point cloud acquired. Then, the point cloud information is projected on the plane Z=0 – the Zmap is obtained – and used to select the surface to be repaired directly in the graphical interface. That selection feeds the path planner to automatically generate the filling path with high accuracy.

The algorithm implement to process the acquired point cloud and generate the robot routine can be described as follows:

1. The 3D point cloud is 2D projected
2. The surface is selected in the 2D image

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*https://github.com/openlmd*
3. The Zmap image is segmented
4. Contours are calculated from that segmentation
5. Contours and the Zmap feed the path planner
6. A new path is automatically calculated from such information

Finally, the path is automatically parsed to send the commands required by the ROS robot driver, which executes the robot movement point by point following the trajectory defined by the path.

4.3 Real-time process control

The high performance offered (1000fps) by the TACHYON 1024 microCORE makes it particularly suitable for closed-loop process control at a low cost. Moreover, the sensitivity in the MWIR band (1-5µm) makes this sensor a valuable detector for thermal monitoring of high energy processes.

Following the same approach described in [8], but taking advantage from OpenLMD architecture and Tachyon detector, a closed-loop control system able to compensate the process heating acting on the laser power was implemented.

MWIR images are acquired and processed on-line to measure the melt pool geometry using an elliptical approximation. The melt pool width calculated with such approximation feeds a PI controller to adapt the laser power, significantly reducing geometrical distortions (Figure 7).

Figure 7. Heating accumulation effects (up) and control compensation (bottom) on a wall construction.

This better thermal control enables a better microstructure, leading better mechanical properties and minimizing uncertainty and variability. Moreover, this improves the dimensional accuracy resulting in significant reduction of finishing work and costs.

5. CONCLUSIONS

The OpenLMD architecture was introduced and a multimodal on-line monitoring system was presented. It provides an efficient, cost effective, and flexible solution, capable of working with different cell configurations and operating conditions. Moreover, the open source approach based on ROS ensures a hardware transparent solution (e.g. independent on robot brand), which is modular, reusable, and sustainable.

With the specific implementation tested, the monitoring system generates spectral images of the process and 3D point clouds of the surface in robot coordinates without imposing constraints to the movement of the robot, achieving a 3D resolution better than 0.5mm. Another significant feature from an industrial perspective is the ability of the system to work with large parts, in the range from centimeters to several meters large.

Overall, the system provides multimodal monitoring capabilities and supports the acquisition and analysis of big amounts of process data, all referred to common temporal and spatial reference systems. This enables the adoption of modern machine learning approaches to feature extraction and image analysis like deep learning and its application to process control and readjustment in the context of such a complex material processing technique like LMD. Ongoing work deals with the acquisition of partially labeled data from large test series with the aim of setting up detection and measurement benchmarks.
The capability to acquire images at a high speed and in different spectral bands has been observed to improve sensitivity to thermal phenomena. Besides, the different magnitudes monitored will facilitate a comprehensive approach to monitoring. Finally, the modularity and interoperability of the developed architecture facilitates the implementation of specific parts under an embedded approach. Ongoing work is dealing with the implementation of coaxial image acquisition and analysis using a compact and embedded system with real-time processing capabilities for high-speed closed-loop control.

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