3D vision system integration on Additive Manufacturing machine for in-line part inspection

Ambra Vandone*a, Stefano Baralda, Demetris Anastassioul, Andrea Marchetti, Anna Valente

*SUPSI, Institute of Systems and Technologies for Sustainable Production, Galleria 2, Manno 6928, Switzerland
†IRIDA Labs S.A. Innohub Patras, 26504, Rio-Patras, Greece

* Corresponding author. Tel.: +41(0)586666708; fax: +41(0)586666571. E-mail address: ambra.vandone@supsi.ch

Abstract

Laser based technologies enable major opportunities in performing quite heterogeneous deposition and subtraction processes characterized by very similar process dynamics. Hybrid machines integrating high power and ultra-short laser sources can efficiently exploit such technologies only when they embed a sensing system able to execute in-line inspection of partially manufactured parts. The current work presents an innovative configuration of Direct Energy Deposition hybrid machine equipped with a custom 3D vision system and software that allow: 1) the part shape measurement at every user defined checkpoint; 2) the acquisition of the temperature distribution onto this part surface; 3) the analysis of the data and the defect identification. The system is based on structured light technique and measures the spatial position of thousands of points belonging to the part surface. The measurements performed by a thermal camera are then associated to this point cloud and a dedicated software performs the comparison of the acquired geometry to the CAD model to detect over- or under-deposition areas and analyses the thermal distribution to detect potential defects. Corrective strategies can be generated for the layers that still have to be manufactured in terms of additional deposition or ablation. The benefits of the approach have been evaluated on experimental tests inspired by industrial scenarios.

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Peer-review under responsibility of the scientific committee of the ISEM 2020

Keywords: Metal Additive Manufacturing; Direct Energy Deposition; Vision Systems; Process Monitoring.

1. Introduction

Among all the metal-based Additive Manufacturing (AM) techniques, powder-based Direct Energy Deposition (DED) presents a unique flexibility in terms of part realization or restoration. This technology entails a mixture of carrier gas and metal powder particles blown out from a set of nozzles [1]. The particles intercept a laser beam that provides the necessary energy to fuse them and to form a melt pool [2], i.e. a drop of molten metal. While the deposition head advances, moving the nozzle and the laser beam according to the desired product geometry, the melt pool cools down, evolving into a solid metal track.

Unfortunately, heat build-up, complex tool path, cooling rates, powder flow dynamics and many other process conditions may yield unpredictable effects on the metal formed part that might present insufficient dimensional precision or surface roughness, low mechanical performances, presence of pores and residual stresses [3]. Thus, improvements in process monitoring and control still have to be done for the stable adoption of DED in the industrial field.

The scientific community has proposed, in the last years, a wide variety of methods to control the process at various levels. On one side, various approaches have been tested to characterize the process either empirically or numerically, to obtain reliable process recipes for various scenarios [4]. On the other side, many researchers have worked on real-time monitoring by various means (e.g. vision [5], thermography [6], acoustic emission [7]; see [8] for a survey) with the aim to
detect and control process fluctuations while the deposition is running [9]–[11].

A third option, proposed for example in [12]–[14], places itself somewhat in the middle of feed-forward and in-line control. In particular, the process is paused at a checkpoint, e.g. after the completion of few deposition layers, and a 3D scanner is used to acquire the geometry of the partially manufactured part. The reconstructed surface is then compared with the target partial geometry, and a new part program for the prosecution of the process is issued and executed, based on the detected discrepancies between the expected and measured geometry.

This approach may reach its full potential on the hybrid machine realized for the H2020 4D Hybrid project [15], described in Section 2, which allows applying both additive and subtractive corrections after inspections performed at few checkpoints.

In this work, we describe the technical solution adopted in the 4D Hybrid machine and the custom-made vision system that carries out geometric and thermal scanning. Moreover, we describe the data elaboration pipeline and present some results for real built parts, highlighting the potential of this system in the context of defect detection and consequent part program regeneration.

2. Machine description

The 4D Hybrid solution is a 5-axis machine (three linear orthogonal axes and two rotary axes on the machine table) that drives a powder deposition head for DED. The machine is hybrid, meaning that it is equipped for performing not only laser-based metal deposition, but also material removal – a feature that the vast majority of commercially available solutions integrates by contact machining [16]. In fact, the machine laser optical chain comprises two laser sources (Fig. 1): a 1 kW continuous wave (CW) laser source (1) used for deposition and a 100 W pulsed wave laser source for ablation (3). The CW source is connected to a laser switch (2) which allows the selection of the beam spot size between the values of 0.16 or 1 mm in diameter, according to the geometrical part complexity. The three fibers are plugged into a laser beam combiner (4), a device capable of selecting the desired beam by a moving mirror. The laser optical chain is completed by a 2-axis RAYLASE laser scanner (5), equipped with an F-Theta lens (6), which allows operating laser ablation with a spot of 0.1 mm at high speed (18 m/s) on small patches (9x9 mm²) of target surface placed on a specific focal plane. A camera adapter (7) allows integrating in the optical chain different vision-based sensors, like cameras or pyrometers.

As mentioned before, the machine kinematic chain is composed of five axes, thus enabling to perform very complex tool paths and to realize parts with cavities and overhangs without the need of supporting material within a working volume of 800x800x1200 mm³.

A custom 3D vision system (8), which will be called in the following Vision Box (VB) and described in details in Section 3, is mounted close to the deposition head (9) and used to inspect the built part whenever the process is paused. The VB (Fig. 2) is connected to an external PC that manages the inspection triggering and data processing, as well as the communication with the machine PLC for synchronizing the machine poses with the part geometry acquisition (see Section 3 for further details).

The PLC-CNC solution used to control the machine is OPENControl by Prima Electro.

3. 3D vision system for part inspection

The designed 3D vision system that performs inspections of the semi-built part at certain user-defined checkpoints is based on structured light technique. This technique consists in projecting a known pattern, usually grids or parallel bars, onto a scene. The deformation of these patterns on 3D surfaces is captured by the cameras, allowing for the reconstruction of the shape of the objects in the scene [17]. Its main advantages with respect to other shape measurement techniques are: the non-contact fashion, which is favorable considering the process high temperatures and presence of powder; the fast acquisition of information, since it acquires the positions of thousands of surface points in a field of view of tens of centimeters with a single scan; and the high accuracy in the order of few microns.

3.1. Hardware

The vision system is composed of the VB system, and a remote control unit (called Vision PC).

The VB comprises (Fig. 3):

- Two monochromatic cameras with 5 MPix sensors, mounted slightly angled one with respect to the other to perform stereoscopic image acquisition running at 20 Hz. Both cameras are equipped with a 16 mm focal length lens.
with iris range F1.4-16, to assure a good 2D spatial resolution (in the order of magnitude of tens of microns) for an object placed approximately at a distance of 200 mm. Both cameras have been calibrated and registered by means of a chessboard calibration plate [18] to correct lens distortion and perspective. The communication with the vision PC is performed via GigaEthernet connections.

- **A DLP projector** connected to a dedicated driver board that controls the projection of patterns. It is placed between the two cameras and its USB connection is managed by a USB server that delivers the signal to the vision PC via Ethernet.

- **An infrared camera** with VGA resolution (640x480 pixels), acquiring temperatures in one of three possible ranges (-20 °C - 100 °C, 0 °C - 250 °C and 150 °C - 900 °C), with accuracy of ±2% degrees. The IR camera has been registered to the stereoscopic system using a custom calibration plate made by two different materials (aluminium and silicone) exploiting their different thermal radiation emission. This registration allows for the projection of the acquired thermal map onto the reconstructed 3D surface. The thermal camera is connected to the vision PC by the same USB server used by the projector.

The vision PC manages the collection and the elaboration of data coming from the different devices, and the communication with the machine CNC.

### 3.2. Operating principle

To provide information about the geometry and the temperature distribution on the piece inspected, the vision system performs the following steps:

1. **Fringe projection and stereo image acquisition**: a sequence of 24 patterns represented by parallel bars with different widths and oriented in two perpendicular directions are projected onto the inspected part. Images of the distorted patterns are acquired in stereo mode by the two visible cameras (Fig. 4a, 4b). Gray code and phase shifting algorithms [19] are exploited to elaborate these images to provide information about the spatial position of thousands of points captured in the scene, to form a point cloud.

2. **Temperature measurement**: a thermal image is acquired right before the fringe projection (Fig. 4c). It is then projected onto the generated point cloud, thus associating the value of a scalar field (the temperature) to each point.

3. **Multiple poses**: to acquire the overall 3D surface of a part, it is essential to capture images from different points of view. This avoids occlusions and allows for exploring the sides and holes of complex geometries. This is achieved by moving the machine into different poses and repeating the aforementioned steps.

4. **Merging data**: point clouds arising from different poses are merged together to represent the entire part geometry (Fig. 4d). Merging data is a straightforward step since all the clouds share the same reference system thanks to the calibration procedure described in Section 4.1. Nonetheless, it is possible that calibration or acquisition errors and inaccuracies introduce offsets between the different poses. Thus, a subsequent fine alignments step is performed by using Iterative Closest Point method [20].

An example of the vision system outcome is illustrated in Fig. 4.

The scanning process takes approximately one second for the projection of all the patterns and the concurrent image acquisition, and few seconds to move the machine from a position to another. The more the poses planned in the part program, the longer the scan process and the cloud merging step. Generally, for simple parts seven poses are realized (a top view and six tilted views rotated of 60° each), and results are provided in five to ten minutes.

### 4. Integration of the VB into the hybrid machine

#### 4.1. Calibration between VB and machine reference frames

The 3D reconstruction of the part geometry is provided by the VB system according to its specific reference frame. To be able to compare this geometry to the nominal one and to correct the differences in the machine work space, it is necessary to compute the transformation between the VB and the machine coordinate system.

The positions of machine axes with respect to the VB reference frame are estimated by placing a target with easily detectable markers on the rotary table and by capturing images of different translated and rotated configurations of the
calibration target. Translation movements allow defining the directions of machine linear axes with respect to the camera reference frame, simply by fitting lines through the positions of the markers in different translated configurations. Rotations allow to detect the directions of the two rotary table axes; they are obtained by fitting 3D circles through the different positions assumed by each marker, and by subsequently fitting an axis through the circle centres (exploiting the pivot calibration method [21]).

Once the axes orientations are known with respect to the VB coordinate system, actual axis positions and the machine direct kinematics allow transforming the coordinates of point clouds acquired by the VB to coordinates in the workpiece reference system.

4.2. Scan sequence - machine positioning synchronization

As anticipated in Section 3.2, a complete part scan is generated by assembling point clouds acquired from different views, i.e. by setting the machine to different poses. Moreover, a single point cloud is generated by acquiring a sequence of stereoscopic images of the patterns projected onto the part. The whole process is completed by projecting the thermal image on the reconstructed global point cloud. In the following, we detail the steps required for generating the complete scan in a fully automated way.

The vision PC communicates with the machine PLC via UDP, by exchanging numerical information and synchronization signals directly over a set of PLC variables shared with the CNC. This allows for performing the following scanning sequence:

1. The vision PC is in waiting state, continuously reading the task start flag from the PLC.
2. When the part program reaches a checkpoint, the PLC set the “Start scan sequence” flag.
3. The machine moves to a new position for performing the geometry and thermal profile acquisition.
4. The PLC set the “machine in position” flag. Moreover, it provides to the vision PC the actual coordinates of the machine.
5. The vision PC triggers the stereoscopic system (projector and cameras) to perform the 3D scan. Moreover, the thermal camera acquires a thermal map.
6. The pictures acquired from all the cameras (visible and thermal) are sent to the vision PC for creating a point cloud of this pose (see Section 3.2).
7. The “machine in position” flag is reset, as a signal for the PLC to proceed to the next pose.
8. If more poses must be acquired, repeat from step 3. Otherwise, the PLC reset the “Start scan sequence” flag.
9. The vision PC performs the registration of all the poses in a single point cloud, by using the machine coordinates associated to each one of them, and provides an integrated point cloud to the on-line CAM module.

5. Test cases

In this section, we present some tests performed onto the 4D Hybrid machine.

5.1. VB metrological qualification

First of all, acquisitions of different certified gauge blocks (nominal dimensional tolerance of tens of microns) have been performed in order to evaluate the VB performances in terms of:

- **Precision \ acquisition noise:** evaluated as the dispersion of the acquired points with respect to the corresponding theoretical geometry.
- **Accuracy:** estimated by comparing the certified object dimensions to the ones obtained from primitives fitting the acquired points.
- **3D reconstruction accuracy:** computed comparing nominal block CAD to merged point cloud.

5.1.1. Precision evaluation

The top surface of a 5 mm squared block has been acquired and the deviation of each point to the reference planar surface has been calculated. The standard deviation of this data has been used to estimate the acquisition noise, finding a value around 15 µm (see Fig. 5).

![Fig. 5. Precision evaluation: point cloud acquired (a) and deviation from a planar reference surface (b).](image)

5.1.2. Accuracy

The accuracy of the VB system is intended as the bias between the reference dimension and the one measured from the acquired cloud. Five blocks of certified thickness have been placed on a rectified planar surface and a top view scan has been performed (Fig. 6). Points belonging to each top surface block have been fitted with five planes and the distances with respect to the substrate plate (also fitted with a planar surface) have been computed. The results, reported in Table 1, show that the block thickness is generally slightly underestimated (mean distance equal to 24 µm).

<table>
<thead>
<tr>
<th>Block number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>Nominal thickness [mm]</td>
<td>1.00</td>
<td>1.01</td>
<td>1.10</td>
<td>1.50</td>
<td>2.00</td>
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<tr>
<td>Measured thickness [mm]</td>
<td>0.97</td>
<td>0.99</td>
<td>1.08</td>
<td>1.50</td>
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<tr>
<td>Deviation [mm]</td>
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5.1.3. 3D reconstruction accuracy

The quality of the outcome of the VB system is influenced by the registration and merging of the clouds acquired from different poses. This 3D reconstruction accuracy has been assessed by comparing the merged point cloud representing the entire block shapes to their CAD models. An example is reported in Fig. 7, where seven clouds acquired from different poses have been registered and merged together. The distance of each point of the final cloud from the block model is computed and results show an overall mean deviation of approximately 70 µm. It can be noticed that the points acquired from the top view are the most reliable ones.

5.2. Part inspection

In this section, we report the outcomes for the inspection process onto two additive manufactured pieces. In the first case, the attention is addressed to the geometrical characteristic, i.e. to the comparison to the nominal CAD model. In the second one, the focus is addressed to the thermal aspect.

5.2.1. Geometry reconstruction and CAD comparison

Starting from the nominal shape shown in Fig. 8a, the part has been manufactured (Fig. 8b) and consequently inspected. The points measured onto the part surface, obtained by performing few scans from different perspectives, are merged together to realize the final cloud (Fig. 8c). Distances between the measured points and the reference geometry are in the order of magnitude of 0.8 mm (Fig. 8d green points) with few points reaching a distance of approximately 2 mm (Fig. 8d orange points) due to the visible imperfection in the up-left corner. In accordance with these results the user might select whether to use ablation to get rid of the undesired points, discard the entire part or adjust the part program for the remaining layers if the case.

5.2.2. Thermal map

Fig. 9 shows two similar pieces realized by the 4D Hybrid machine. At the end of the 15th layer, right after switching off the laser source, the inspection started. The 3D point cloud representing the part surface has been enriched by the temperature information captured by means of the thermal camera inside the VB. Warm areas are located corresponding to internal holes that, as expected, entrap the heat. They are highlighted in red color, indicating that the temperature locally reaches almost 100 °C. It can be noticed that also the region between the two pieces is quite warm (around 70 °C) since the heat dissipation is weaker than in the outer directions, where the temperature of the substrate decreases gradually moving away from the deposition area. Part of the clamping system is visible too, presenting a temperature close to the environmental one (approximately 30 °C). The comparison between this thermal map and the temperature field obtained by thermo-mechanical simulation could be useful to detect defects inside the piece such as pores, cracks or cavities that usually acts as heat sinks.

6. Conclusions

The developed 3D vision system is capable of measuring metal AM parts, without the need to remove them from the work table fixturing. The presence of such inspection system fully integrated with the hybrid machine allows assessing the part quality in-line with the process, enabling the possibility to react to undesired process outcome performing corrective actions in terms of material removal by ablation or deposition.
strategy adjustment for the remaining layers. This way, scraps and wastes in time and material can be considerably reduced.

The geometric accuracy yielded by the system (<0.03 mm) is well-suited for detecting process deviations in DED, where process uncertainty can lead to deviations of few tenths of millimetres even for a single layer. Moreover, the surface thermal map is overlaid on the acquired point cloud, thus enabling more advanced diagnostics of the quality of the deposition in progress.

Future works will focus on the evaluation of the vision system performance and robustness, by testing parts differing in material, superficial properties or geometrical complexity. Moreover, the authors’ group will continue in the realization of the CAx adaptation chain platform [12] that will be able to suggest in a completely automatic way the most suitable corrective strategy according to the inspection results and a previously built database.

Acknowledgement

This work has been partially funded by EU H2020-FOF-2016 project 4D Hybrid - Novel ALL-4N-ONE machines and systems for affordable, worldwide and lifetime Distributed 3D hybrid manufacturing and repair operations. Contract 723795.

References


