Towards Vision-based Closed-loop Additive Manufacturing: A Review

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***Abstract*—The use of additive manufacturing technology has grown considerably in the last decade. Starting from a futuristic idea, additive manufacturing has shown to be a great tool for rapid prototyping and has found its way into industry as a set of techniques for manufacturing highly customized parts. However, a great number of challenges remain if we are to have efficient and general additive manufacturing systems with high precision, low failure rates, and good strategies for detecting and dealing with part failures. In this paper, the current state-of-the-art on online monitoring and closed-loop control in fused filament fabrication and directed energy deposition with camera and laser scanning is presented. A discussion on the challenges and possible ways of enabling full online part geometry monitoring in AM with articulated manipulators and multi-axis deposition is also provided.**

***Index Terms*—Three-dimensional printing, Closed loop systems, computer vision.**

I. Introduction

Additive Manufacturing (AM) is an umbrella term for a set of techniques where physical objects are built by incrementally adding or joining material based on a virtual 3D model representation [1]. This is usually done with a Cartesian robot depositing material in a layer upon layer fashion on top of a suitable build platform. A synonym of AM that is used extensively in the consumer market is 3D printing. However, the meaning of this term is less broad than AM and is usually used when thinking of commercial off-the-shelf plastic AM machines for the consumer or hobby market.

Compared to conventional manufacturing techniques like subtractive manufacturing (milling, grinding, drilling, etc.), AM is thought to generally lead to less material waste, since parts are built by adding just enough material bit by bit to get the right geometric properties, and not by removing material from a block larger than the product. AM also enables the creation of single part objects with inner cavities, which is hard or impossible to do with subtractive techniques or molding. AM is a good technique for fast prototyping, reducing the time from design to market [2], [3]. AM also has the ability that products can be produced closer to the point of use, when they are needed, making AM ideal for spare part production [2].

There are also several drawbacks to AM compared to subtractive manufacturing and molding. For instance, AM is slow for mass production when compared to molding and slow in the production of large components. In addition, the surface finish of AM parts is usually quite rough. If a smooth surface finish is needed, some sort of subtractive post-processing must be performed [3]. Another issue with AM is that of part strength. If the layers do not properly bond together, a part may have severely reduced strength and may break during use. For products with particular mechanical requirements, the ability to do in-depth quality inspection is important.

There are seven main methods used in additive manufacturing [1]. In this paper we focus on AM with robot manipulators, mostly articulated and Cartesian. As a result, we only consider two of the seven main AM methods, namely Material Extrusion (MEX), otherwise known as Fused Filament Fabrication (FFF), and Directed Energy Deposition (DED). The other five methods are powder bed fusion, vat photopolymerization, material jetting, binder jetting and sheet lamination. In FFF methods, a heated nozzle is used to deposit material layer-by-layer on a build platform. This is the most common method for plastic AM. In DED methods, focused thermal energy, in the form of a laser, an electron beam or a plasma arc, is used to fuse deposited material powder or filament by melting. For an overview and a more in-depth explanation of the different methods in AM, see [2], [4].

Closed-loop control is used purely for positioning the deposition head relative to the build area in AM systems, and few existing AM systems today use feedback of the geometric information or bonding method to improve the build process. With this view, nearly all AM systems work in an open-loop configuration and are blind to disturbances and changes in the build volume. For instance, most commercial AM systems will happily continue to deposit material, even if parts of the build have collapsed. Even small corrections to the build path and extrusion speed in case of variable layer height and material warping is impossible without some form of feedback from the so-far printed part geometry. An illustration of closed-loop control in AM is shown in Figure 1.

Despite being open-loop, AM systems are performing quite well. With well-designed machines, materials designed for

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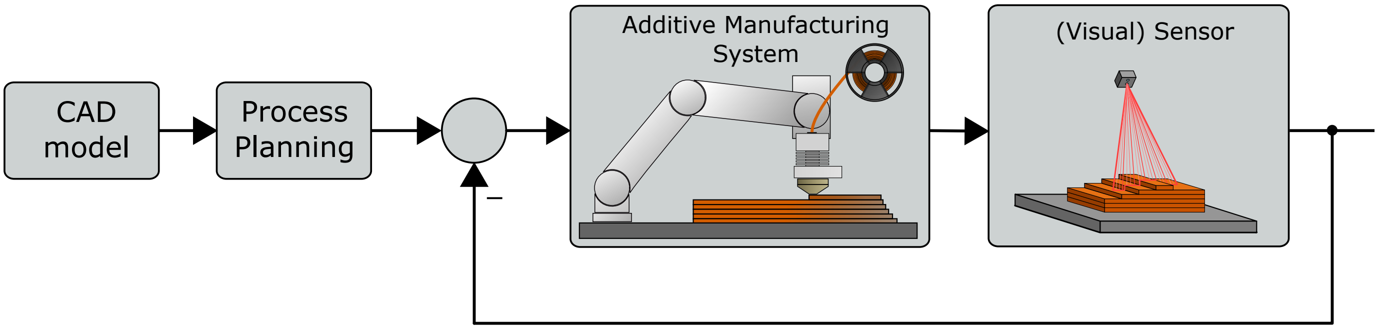

Fig. 1. General illustration of closed-loop control in AM.

the purpose, and calibration routines, commercial printers are precise enough for hobby and prototyping use and can run for hours and hours without producing significant faults if they are tuned correctly. However, the adoption of AM in industry for the creation of high-quality custom parts and the industrial requirements for precision have led to a considerable interest in methods for post quality control and tolerance of AM created parts. In this paper, we will not go into detail on post quality control and tolerancing, but interested readers are referred to [5], [6]. It should be mentioned that some of the methods and ideas in part quality inspection may also be interesting in online monitoring and control. However, for online monitoring, methods should be able to run in real-time and in-situ.

The underlying processes parameters and sensors available differ greatly between different methods of additive manufacturing, e.g. wire arc welding can use current measurements, whereas plastic filament deposition does not. This article focuses on camera sensors and laser scanners which are more likely to give closed-loop control algorithms that are applicable across a larger spectrum of the different AM methods.

According to Leach et al. [6], in-process monitoring and control of metal AM processes is one of the most important avenues of investigation for the development of increasingly advanced and robust AM processes.

In this paper, a review on the use of camera sensors and laser scanners to achieve different kinds of closed-loop control in additive manufacturing is presented in section II. A discussion on possible challenges and possible approaches to enable feedback from part geometry is presented in section III.

II. State-of-the-Art

In the literature, we find several demonstrations of the use of cameras and laser scanners for online monitoring and closed-loop control in AM. The findings can, for the most part, be divided into three main categories. They are

- online part defect detection,
- online control of layer height, layer width and deposition head to layer distance (standoff distance),
- thermal online monitoring and/or control.

In this section we will review some of these online monitoring and closed-loop methods demonstrated for AM in the literature. We first take a look at methods demonstrated for fused filament fabrication (FFF), then we look at direct energy deposition (DED). An overview can be found in Table I.

A. *Closed-loop in FFF*

L. Rebaioli et al. [7] demonstrate an online layer height control (OLHC) method where the printhead-to-layer distance is adjusted according to the deviation from desired layer height, as well as an online re-slicing algorithm, where the path the printhead is to follow is adjusted according to the cumulative layer height error measured. The algorithms were demonstrated on an articulated 6 DOF manipulator with a laser sensor attached to a plastic extruder. The laser measurement provides the mean layer height as an input parameter for the online re-slicing algorithm, and deviation from the desired current layer height as input to the OLHC algorithm. Proportional control is applied to modify the robot trajectory to converge to the desired current layer height. The core benefit of the work is a method to actively adjust the layer height to obtain better adhesion between layers. The method, in its current iteration, is limited to planar slicing and does not utilize the full 6 DOF capabilities of the manipulator.

C. Liu et al. [8] demonstrate an online image-based closed-loop quality control system for automatic detection and mitigation of under-fill and over-fill during fused filament deposition. The system was demonstrated on a Cartesian 3DOF platform (Hyrel 30M 3D printer) with ABS filament. An experimental design study was first conducted in order to connect machine parameters and defects, a textural analysis-based image classification algorithm was used for defect detection, and a PID-based feedback controller was implemented to control the machine parameters. The case study shows that the proposed method is effective at removing under-fill and over-fill defects.

F. Wang et al. [9] propose a method for controlling the between layer cool-down time using thermal images from a FLIR camera, during manufacturing with the Thermwood Large Scale Additive Manufacturing machine and polycarbonate resin containing carbon fiber as the filament. They argue that an important factor for determining the resulting strength of the printed part is the print surface temperature. With too high temperature, warping may occur, and with too low temperature bonding may not be achieved. Based on the real-time thermal imaging data, a regression model was built with the purpose to predict the temperatures at a set of points on the surface. This enables the machine to start printing the next layer when the surface temperature of the previous layer has reached a suitable level, where the risk of deformation or bad bonding between the layers is low. According to the authors, the presented control approach led to a significant reduction in total build time without sacrificing print quality.

W. Lin et al. [10] propose a method for geometrical defect detection by scanning the upper layer of the printed part using a laser scanner mounted on the print-head at a specific layer interval. The method was tested on a custom Cartesian 3DOF platform with automatic tool switching. After 15 layers are printed, the system switches from printing mode to scanner mode and moves the laser scanner over the print, and a point cloud of the part is captured. After pre-processing, a model of the upper layer is extracted and compared with the ideal surface extracted from the CAD model in order to detect defects. If a severe defect is detected, the 3D printer can shut down in order to reduce time and material waste. This forms an intermittent feedback control that allows for simple failure detection during print and may alert workers when a print has failed.

Achieving a somewhat similar level of feedback control, F. Baumann and D. Roller [11] use a camera on the side of the build plate, showing the side of the printed objects, to detect missing material flow from the nozzle and print detachment from the build plate by using simple image processing techniques. If errors are detected, the system can alert users through a web interface. Although there were problems with some false positives and a few undetected errors, it presents a simple approach to defect detection modifications for a commercial FFF 3D printer.

Working on AM construction for tensile surface installations with few layers, e.g. two, S. Sutjipto et al. [12] demonstrate an online technique for building a two-dimensional occupancy grid (OG) map of the print using an extruder mounted RGB camera. Segmenting the captured images into background and filament areas, the images are probabilistically fused into the occupancy grid map, making use of the articulated robot's end-effector position. The map was further used to detect intersection points and for quality inspection of the deposited filament thickness and layer alignment. Further, the authors presented their thought on using intersection point detection to enable the triggering of pre-programmed localized actions, such as pressing the deposited material together at intersections, which would be useful for the construction of tensile meshes. However, no actual closed-loop control was demonstrated. It should be noted that this online measurement technique is limited to tensile mesh structures with few layers since it ultimately segments into background and foreground and has no method of distinguishing between layers.

B. Closed-loop in DED

S. Radel et al. [13] present a fully automated point-by-point method to build skeletal free-form structures with a wire arc additive manufacturing (WAAM) torch mounted on a 6DOF articulated manipulator. A camera fixed to the torch is used to monitor the deposition area and calculate the standoff distance between the torch and position of the last deposit in order to optimally place the torch before the next deposition.

T. Felsch et al. [14] present a hardware and software setup for laser metal deposition. They used a laser distance sensor mounted to the laser deposition head to measure and control the standoff distance between the deposition head and part surface. A 6DOF articulated manipulator was used to move the deposition head and the build surface was situated on-top of a 2DOF turn-tilt table, enabling the printing of objects with overhang. The system takes G-Code that describes the sliced version of the 3D object and generates robot native code. A pre-processing module analyzes the robot native code and includes the scanning functionality.

J. Xiong et al. [15] present a closed-loop control method that uses an optical camera to increase stability in the gas tungsten arc (GTA) metal AM technique with a 6 DOF articulated manipulator. To control the layer height, a PID controller with integral separation was used to regulate the distance between the GTA torch and the top layer to a desired value. Wire feed speed was used as the controlling variable. Image processing was used for finding the top surface and calculate the GTA torch to top layer distance.

T. Font comas et al. [16] demonstrate a method and calibration routine for monitoring the melt pool surface in a plasma arc welding (PAW) system with a low-cost camera and well-known image processing algorithms. A case study demonstrating how the system could be used to track the width of the melt pool was presented. It was proposed that this method could be used for feedback control of the process parameters of the PAW technique, but no feedback control scheme was presented.

I. Garmendia et al. [17], [18] use a structured light-based 3D scanner to measure the height profile of the part from a fixed position relative to the build platform, arguing that this measurement method would be more precise than strapping a sensor to a robot moving over the part surface in a scanning pattern. A depth image was captured in-situ after a pre-set number of layers were built and a control strategy that added or deleted layers, based on current build height and information from the CAD model, was used. A set of experiments showed that this control strategy effectively reduced geometrical errors in the height direction.

Exploring the use of data fusion and knowledge-based process control strategy in AM, A. Vandone et al. [19] proposes a data-driven modeling and control approach that makes use of, not only on-line monitoring and machine tracing data, but also off-line inspection data (i.e. 3D geometry and surface inspection). Utilizing a dichroic mirror, a camera was set up to capture the geometry of the melt pool from the direction of the laser beam. By additionally tracing the deposition head position and laser power, and doing offline 3D scans with high precision, data can be associated through time and space, enabling data-driven modeling for use in closed-loop control.

A. Heralić et al. [20] use a modified seam tracker setup comprised of a laser-line projector and two cameras to enable online closed-loop control of bead height and width when building thin-walled structures with a robotized laser metal-wire deposition (RLMwD) system. The bead height is measured by laser triangulation with the laser-line projector and camera number one. While the bead width is measured by camera number two looking at the melt pool from directly above, the same direction as the heating laser enters the melt. A feed-forward compensator and a PI-controller was respectfully used for controlling the bead height and width to the desired values by adjusting wire feed rate and laser power.

Similarly, S. Takushima et al. [21] use a laser-line projector mounted to the side of a laser metal-wire deposition head and a camera looking down the laser processing head to monitor the melt pool and measure the nozzle-to-layer height by triangulation. An overview of the system can be seen in Figure 3. The nozzle-to-layer height was measured at a distance of 4 mm in front of the melt pool, which has the benefit of more correct and robust height measurements when depositing material while turning, as shown in Figure 2.

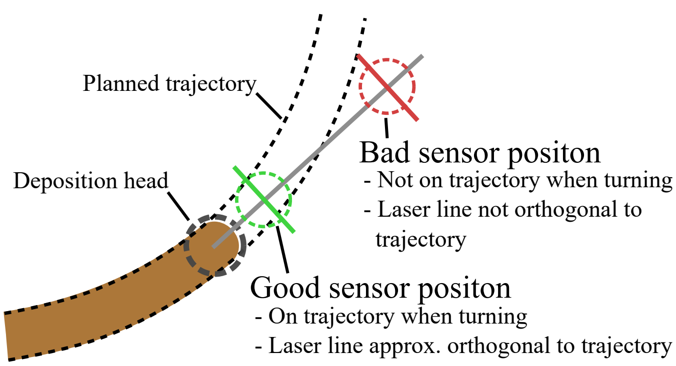

Fig. 2. Benefit of placing height measurement sensors close to the melt pool for curved trajectories.

However, a measurement this close to the melt pool was only possible due to the installment of a 520 nm band-pass filter in front of the camera to dampen the luminance noise from the melt pool. Furthermore, Takushima et al. propose a simple numerical controller to control the wire-feeding speed, and achieved a measurement of the gap between the weld bead and the feed wire at ± 0.1 mm accuracy. This had a large effect on the stability of deposition and layer height as demonstrated with walls printed up to 50 mm in height.

III. Discussion

A. Sensing Schemes

To enable online defect detection and correction of geometric shape in an FFF or DED AM process, a sensor scheme with high resolution relative to the smallest possible feature the AM system can create is needed. In addition, an efficient method and model for sensor measurement integration and CAD model comparison is needed. We will now consider the

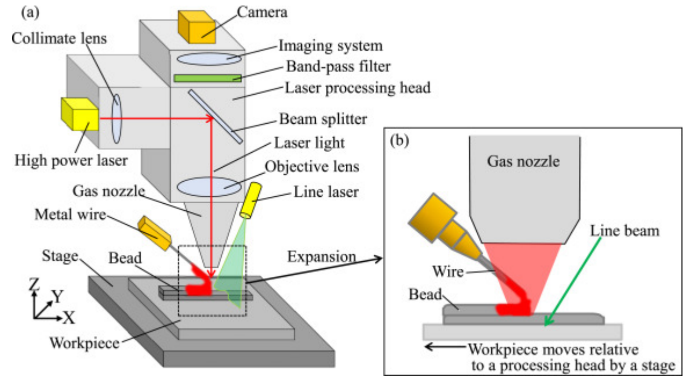

Fig. 3. Overview of LMwD deposition head with integrated laser triangulation for effective and precise height measuring, enabling closed-loop control of standoff distance. Figure by S. Takushima et al. [21], Creative Commons CC-BY-NC-ND.

challenges and opportunities of using different camera and laser scanning techniques for monitoring of AM processes.

To capture all the geometry of a printed object, the object will have to be measured from multiple angles. This can be done by installing multiple static cameras or laser scanners, around the build area and calculating the geometry from correspondences between the views. However, this would be costly in terms of equipment and given that the object geometry is complex, there is a high chance that there would be blind spots due to some parts of the object concealing other parts. Another approach is to install one or more cameras or similar geometrical measurement system on one or more dedicated robots. Move the cameras around the object during building and integrate the measurements with a virtual model. For this to work, the challenge of avoiding collisions between the robots will have to be solved. Another similar scheme that would remove the challenge of collisions is to use a rotational base for the build area and have one or more stationary cameras mounted around the base, but blind-spots is a possible issue with this setup as well.

A challenge with all the sensor placement schemes mentioned in the above paragraph is that of ignoring the print head when extracting depth measurements. An obvious solution would be to move the print-head away when scanning the object. This would work, but the building process would be slowed down. This approach could also be problematic with AM techniques that should deposit material continuously and where starting and stopping the deposition have their own set of challenges.

Yet another approach is to place the sensors, i.e. camera, laser scanner, e.g., on the deposition head, removing the challenges of filtering out the deposition head, as done by [7], [8], [10], [12]–[16], [19]–[21]. This approach also appears ideal as the biggest changes to the geometric shape of the built object comes from the deposition of material through the deposition head. Apart from the deposition area there is usually not much change in the outer geometric properties in the rest of the built object. Therefore, continuously measuring

TABLE I
OVERVIEW OF REVIEWED ARTICLES ADDRESSING CLOSED-LOOP CONTROL IN ADDITIVE MANUFACTURING.

Article	Year	Method	Sensing technology	Closed-loop approach	Manipulator type
[7]	2019	FFF	Laser triangulation	Layer height control	6DOF articulated
[8]	2019	FFF	Two cameras	over- and under-fill correction	3DOF Cartesian
[9]	2019	FFF	Thermal camera	Temperature and Layer time control	3DOF Cartesian
[10]	2019	FFF	laser triangulation	Alert user on print failure	3DOF Cartesian
[11]	2016	FFF	Single camera	Alert user on print failure	3DOF Cartesian
[12]	2018	FFF	Single camera	n/a	6DOF articulated
[13]	2019	DED	Single camera	standoff distance control	6DOF articulated
[14]	2019	DED	laser triangulation	standoff distance control	6DOF articulated + 2DOF turn-tilt table
[15]	2019	DED	Single camera	Standoff distance and layer height control	6DOF articulated
[16]	2017	DED	Single camera	n/a	3DOF Cartesian.
[17]	2018	DED	Structured light stereoscopy	layer height control	6DOF articulated
[19]	2018	DED	Single camera	knowledge-based control of process parameters	3DOF Cartesian
[20]	2010	DED	Camera and laser triangulation	Bead height and width	6DOF articulated
[21]	2020	DED	Laser triangulation	Standoff distance & layer height control	3DOF Cartesian + 2DOF

the whole geometric model is for the most part unnecessary. Some materials, e.g. ABS, may warp during cooling, this changes the outer shape of the object and are not necessarily observable when the sensor is placed on the deposition head.

Thinking in terms of mass or volume balance, if the only areas where changes can happen is measured continuously, then it should be possible to observe all changes to the object and use this information to build a correct virtual model over time for comparison purposes. However, the challenge is to know the deposition head or sensor position with a high enough accuracy to be able to register measurements correctly with a virtual model. Also, the material density usually change with temperature. The challenge with low accuracy is expected to be greater for articulated manipulators than for Cartesian ones because of the inherent structure of the manipulators. Possible solutions for increasing position accuracy of deposition head and sensor readings could be laser tracking of the deposition head [22].

Another challenge with the metal deposition processes is that of strong radiation from the melt-pool. This radiation makes online sensing with cameras close to the deposition area a big challenge. For instance, measuring the geometry around the melt pool with a structured light dense stereo camera poses problems when thinking of the noise-to-signal ratio of the projected pattern. However, by filtering away most of the light coming from the melt pool, with special lenses like the band-pass filter used in [21], the noise-to-signal ratio can be reduced, enabling measurements during deposition.

Standoff distance feedback control during deposition has proven to be vital for several DED techniques in order to ensure stable deposition over multiple layers. Having a reliable and robust way of measuring the standoff distance has been a challenge. If the standoff distance is measured too far in front of where the deposition happens, the height sensor runs the risk measuring outside of the deposition path. Especially when the deposition path is curved or contains sharp turns. In [21] the height measurement was captured 4 mm in front of the melt pool center, giving the system a reliable way to measure standoff distance, even when depositing along sharp curves. In [23], height measurement in the center of the melt pool area was demonstrated.

B. Online 3D Reconstruction

To date, most additive manufacturing systems build in planar and parallel layers with fixed layer height, also called 2.5-axis volume printing [24], because of the relative simplicity of path planning (e.g. simple general slicing algorithm and simple solution to collision avoidance) and the robustness of Cartesian manipulators. However, this method has several undesired effects. Such as the need for support structure when building parts with significant overhang, undesirable anisotropic material properties that may reduce part strength, and poor surface finish of non-planar faces due to the staircase effect [25]. In an attempt at improving on these undesired effects, deposition of both curved and planar layers with adjustable build direction, called multi-axis additive manufacturing, are being considered. However, moving from 2.5-axis volume printing to multi-axis deposition of curved layers makes path planning and collision avoidance a real challenge, increasing the complexity considerably.

The current state of the art in online geometry monitoring of AM processes with cameras and lasers are focusing on methods for capturing 2D geometry of planar and parallel layers. If AM technology transitions in the direction of multi-axis deposition, it is expected that the current methods will be of limited value, and that the need for new monitoring systems will surface.

The authors believe that recent advancements in real-time 3D reconstruction [26] with volumetric fusion techniques have the potential to enable online real-time geometry monitoring in AM. Especially in multi-axis deposition where an object can grow in nearly all directions. Of special interest are therefore the voxel-based volumetric representations building on truncated signed distance functions (TSDF) because the geometry can be arbitrarily and quickly changed in small areas at a time, supporting freeform objects. However, a downside of voxel-based TSDF models is that they usually require lots and lots of memory, seeing that the memory requirements are growing exponentially with both increased volume size and reduced voxel size. But this may, however, match well with an AM system that can build objects with an upper size defined partially by the available build volume and partially by the total build time, and with a set lower resolution determined by the height of the deposited beads. This shared property of both an upper bound on total volume and a lower bound on the resolution, in addition to the support for arbitrarily growing volumes, is interesting. Further research on the use of volumetric TSDF models for monitoring of multi-axis AM should, therefore, be carried out.

Looking to the future, we can expect to see robust additive manufacturing systems that can correct print errors on the fly and adjust itself based on observed discrepancies. For such a system to support multi-axis deposition and non-horizontal build layers, new methods for capturing and filtering geometry data, evaluating geometry discrepancies and a new control framework will need to be developed.

IV. Conclusion

In this paper, we have reviewed the recent literature on closed-loop control for the FFF and DED additive manufacturing processes with cameras and laser. The area can be roughly divided into three areas: geometric error detection and correction, deposition process control, and thermal monitoring for layer scheduling and cooling control. A discussion on the placement of camera and laser sensors have been given and inspired by the recent advances in 3D reconstruction, it is suggested that volumetric TSDF models and volumetric fusion techniques may be a good approach for online monitoring of a parts outer geometry in the case of multi-axis deposition. Furthermore, research on in-process monitoring and control for AM is expected to be a crucial research area if AM is to achieve its full potential as a robust, customizable manufacturing technique for the future.

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