Establishing in-process inspection requirements for material extrusion additive manufacturing [conference paper]

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Establishing In-Process Inspection Requirements for Material Extrusion Additive Manufacturing

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Abstract

This paper proposes a concept for the development of an in-process monitoring system to assess the quality of components manufactured via the Material Extrusion (ME) Additive Manufacturing (AM) process. The development of such a system has the potential to allow component manufacturers to identify weaknesses within the structure of a built component prior to distribution to customers and subsequent premature in-service failure. Following proposal of the concept, this paper proceeds to highlight a number of key hardware and software components which are fundamental to the further development and implementation of the in-process monitoring system.

1 Introduction

Additive Manufactured processes are increasingly being utilised for the production of high quality end-use components in a range of high performance applications from Personal Protective Equipment and complex aerospace parts, to lifesaving medical implants [1], [2]. The development of such AM systems can be seen as a result of a number of significant improvements in materials properties and processes accuracy [3]. A number of inherent benefits exist when utilising AM processes in comparison to conventional manufacturing methods - for example, the ability to produce low-volume, highly customised, geometrically complex parts [4]. Consequently, it is becoming essential for manufacturers of AM components to ensure their products meet high levels of quality assurance - thus the inspection of such parts is becoming a high priority.

Product and assembly inspection systems are well established - monitoring surface quality, dimensional accuracy, inter- and outer-structural defects. Such assurance can be achieved via either destructive or non-destructive means - with parts typically inspected post-manufacturing phase [5], [6]. With a growing uptake in utilising AM processes for end-use components, there is a requirement for the development of non-destructive in-process monitoring systems capable of identifying part failures during the primary manufacturing phase - for example mid-build when using an AM process.

Ponomarev, M.G., et al. has established an inline inspection system for use within a Powder Metallurgy (PM) production line. PM process is inherently suitable for high volume production - with a range of desirable part properties including good dimensional stability, and able to achieve high density components with high strength. The developed inline inspection system uses X-ray radiation to 3D-scan multiple manufactured parts. Within a dedicated inspection software environment for image processing, the captured data is compared with a reference data. The output inspection data provides information on the density and any defects identified within the manufactured components. The in-service failure of PM manufactured components typically occurs due to internal cracks or voids - of which are not easily detectable via standard visual inspection systems. By establishing a radiographic inspection process, researchers were able to identify faulty components within the early stages of the PM process [7], [8].

Penchev, P., et al. has also established an in-process inspection system embedded within a hybrid manufacturing platform to produce highly customised miniaturised components. Parts are initially manufactured by a 3D printing technique with dimensions near to net shape - with a positive dimensional tolerance greater than their CAD model. Parts are then scanned with a 3D optical measurement system to obtain a digital representation. Following this, the original CAD file and acquired digital representations are compared, resulting in the identification of a ‘rest volume mode’. Laser micro processing is performed to achieve the desired dimensional accuracy and surface quality by subtracting the material according to ‘rest volume model’. The optical measurement and laser processing steps are repeated until the manufactured components achieve the anticipated technical specifications [9].

Gatto, M. and Harris, R. A. have previously identified a method of performing real-time non-destructive inspection system within the three-dimensional printing process (3DP). The 3DP technique is an AM method in which liquid binder is printed over a powder bed.
Visual inspection information was captured every layer, and a 3D representation model was created by combining the captured information together - thus enabling the generated model to be compared against the nominal model [10].

With an increasing range of Material Extrusion (ME) based Additive Manufacturing systems being made available for purchase, as well as significant improvements in the quality of the components they are able to manufacture, the purchasing of such systems by small-medium sized companies is looking more desirable. With the widening availability of such systems, there is a growing need to ensure the manufacturing quality of the components manufactured via these systems can be monitored - with parts which are likely to fail prematurely prevented from being used. This paper therefore outlines a concept for the development of a non-destructive in-process monitoring for the Material Extrusion (ME) Additive Manufacturing technique - factoring in for its scaling up and down to fit a range of applications and specifications.

2 In-Process Monitoring Concept

An in-process monitoring concept has been proposed for use with ME-based AM systems, as shown in Figure 1.

Following inspection of a given layer, the printing process recommences until a further inspection is triggered. The rate at which inspection occurs is specified by the operator and can be dependent on a range of factors such as the critical nature of the part, quality reporting standards, available time for completion of the build, the inherent size of the component. Example inspection rates may include:

- Low level inspection triggered every 25 layers.
- Medium level inspection triggered every 10 layers.
- High level inspection triggered after each layer.

The following sub-sections outline the hardware and software requirements for the development of the in-process monitoring system.

3 Hardware

The dedicated in-process inspection concept consists of the following hardware components:

- A high specification camera and lens
- Inspection lighting and power supply units
- An appropriate I/O box
- An industrial personal computer (IPC)

The methods in which the outlined components communicate with the ME printer motherboards and the IPC is shown in Figure 3.
The in-process inspection camera and lens are connected to the IPC via a USB 3.0 connection. Captured images are fed back to the IPC for processing within a dedicated in-process inspection software programme. The appropriate selection of a camera and associated lens is essential to ensure high quality images are acquired during the inspection process. For example, if a dedicated print area of 200 x 200 mm was established along with the selection of a camera with a resolution of 2048 x 2048 pixels, an appropriately specified lens with the following characteristics would be required to ensure an image of the very top printed layer could be captured:

- Sensor size: 25.4 mm
- Focal length: 12.5 mm
- Working distance: 235-260 mm

Figure 4 pictorially demonstrates the working height distance of the inspection camera and lens in relation to a top printed layer with maximum dimensions of 200 x 200 mm.

Appropriate lighting is required to maximise the quality of captured reference image. Within this concept and application of the ME AM process, it is proposed that a dark field lighting arrangement is utilised. An example of its placement in relation to its orientation with the printed components is shown in Figure 5.

By using this method it is understood that the cast light will catch the very top printed layer thus illuminating it against the darker backdrop of printed layers beneath. An example to demonstrate the benefits of illuminating the edges of components prior to inspection is shown within Figure 6.

Illuminating the top printed layer in this manner, coupled with selection of high quality image acquisition hardware will assist the dedicated in-process inspection software to appropriately analyse the images.

An I/O box is used to turn on and off the inspection lighting devices. The negative wire from each line light
is directly connected to the PSU, while positive lines are connected to the I/O box. By establishing this connection it is possible to use an external trigger to switch the lighting on/off - for example, the use of an available pin on the ME printer motherboard. The proposed concept utilises such a method resulting in the following states:

- When the motherboard pin is inactive/low - no output voltage is registered and the logic state of the I/O box remains low.
- When the motherboard pin is active/high - an output voltage of 5V is registered and the logic state of the I/O box is switched to high.

4 Software

To facilitate the realisation of the proposed in-process inspection concept, a number of software requirements need to be satisfied, including:

- Generating reference image data
- Appropriately preparing/coding the I/O box
- Establishing the custom G-code to trigger the inspection system
- Designing and implementing an appropriate in-process software inspection system

4.1 Reference Image Generation

To minimise the replication of build information, the STL data used for the subsequent generation of G-code information, is also utilised for the creation of inspection image data in the form of Portable Network Graphics (PNG) files. An example of an extracted image slice is shown within Figure 7.

When preparing to create sliced reference images, it is important to ensure their resolution is in-line with that of the captured image data generated from the selected camera hardware. For example, if using a 200 x 200 mm print area with a camera resolution of 2048 x 2048 pixels, there will be approximately 10.24 pixels per mm. By establishing the number of pixels per mm, the size of the intended build part in both real world dimensions and resolution (pixels per inch), can be used to identify the resolution required to appropriately export the sliced PNG reference images – this is shown within Table 1.

<table>
<thead>
<tr>
<th>Demo Part</th>
<th>Length</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real Dimension (mm)</td>
<td>62.50</td>
<td>54.42</td>
</tr>
<tr>
<td>Real Dimension (inches)</td>
<td>2.46</td>
<td>2.14</td>
</tr>
<tr>
<td>Resolution (Pixels)</td>
<td>640</td>
<td>558</td>
</tr>
<tr>
<td>Reference Slice Export Resolution (PPI)</td>
<td>260.10</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Inspection G-Code & Inspection Processes

Communication between the inspection and printing processes can be established through the insertion of a number of custom g-code lines within the build part g-code file. An example of such a code specific for use on RepRap based ME systems is outlined within Table 2.

<table>
<thead>
<tr>
<th>; LAYER 'N'</th>
<th>This code triggers in the inspection lighting and process</th>
</tr>
</thead>
<tbody>
<tr>
<td>G0 X50.00 Y50.00;</td>
<td>Rapid linear move of print carriage to X50, Y50 to capture image</td>
</tr>
<tr>
<td>M400;</td>
<td>Wait until buffers are empty</td>
</tr>
<tr>
<td>M42 PXX S255;</td>
<td>Turns the inspection lighting on</td>
</tr>
<tr>
<td>G4 P1000;</td>
<td>System dwells 1000 milliseconds</td>
</tr>
<tr>
<td>M400;</td>
<td>Wait until the buffers are empty</td>
</tr>
<tr>
<td>M42 PXX S0;</td>
<td>Turn the inspection lighting off</td>
</tr>
<tr>
<td>M400;</td>
<td>Wait until the buffers are empty</td>
</tr>
</tbody>
</table>

Within the presented custom code, the print carriage is moved as to not obscure the view of the inspection camera. Following such, the inspection lighting is
turned on via the M42 command - in which PXX relates
to the specific printer motherboard pin number being
used. Inspection lighting is held in the 'on' state for a
given time period, and it is during this period the
dedicated inspection software and camera system
acquire an image of the top printed layer. Following
image acquisition a further M42 command is used to
turn the lighting off - with printing recommencing
shortly after. In addition, immediately following the
acquisition the image is appropriately analysed and
processed via dedicated image processing algorithms.

5 Conclusion
This paper outlines a proposal for the development of an
in-process monitoring system for use with Material
Extrusion Additive Manufacturing systems. The
primary aim of developing such a system is to provide
feedback to the machine operator as to the quality of the
manufactured component(s). The development of such
a system has inherent benefits, beyond savings in time
and money, such as enabling manufacturers of
components to identify defective regions within the
build which could potentially lead to premature in-
service failure.

A range of hardware and software components have
been highlighted within this paper. The specification of
any components outlined within this paper are for
demonstration purposes, instead the proposed concept
has the potential for scaling up/down depending on
manufacturing or quality control standards. For
example, additional cameras could be added to the
system to enhance the precision of quality control or to
increase the print area for inspection.

Due to the complex nature of the interaction between
the various hardware and software components, a
number of next steps have been established in an
attempt to physically demonstrate the performance of
such a system.

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Introduction
Additive Manufacturing (AM) techniques comparing to conventional manufacturing techniques offer production of low-volume, highly customised, geometrically complex parts[1]. In recent years, as a result of significant improvements in materials properties and processes accuracy, AM processes are increasingly being utilised for the production of highly complex and quality critical components within sectors such as the aerospace industry[2,3,4]. Therefore inspecting the surface quality, dimensional accuracy, inter- and outer-structural defects of components become critically important[5,6,7].

Typically manufacturers are leaning towards the in-process and non-destructive inspection of their components, therefore enabling them to identify defective parts during the primary manufacturing phase, and consequently leading to savings in costs and time. Various studies have been performed to investigate the in-process monitoring approach for a number of AM techniques[7,8,9,10].

With substantial growth and availability of Material Extrusion (ME) based AM systems, improvements in the quality and monitoring of the components which they are able to manufacture is important. Therefore the presented study outlines a concept for the development of a non-destructive system for the in-process monitoring of the ME-based AM process.

In-Process Monitoring Concept
The intention for the in-process inspection concept is to provide live feedback to the operator relating to the quality of the printed component(s). An overview of the in-process monitoring concept is shown within Figure 1.

![Figure 1: In-process inspection concept overview](image)

The proposed concept works on a basis of comparing a range of sliced inspection images against captured image printed via a ME system - reporting any deviation within the captured image within established tolerances. An example of the reporting mechanism is shown within Figure 2.

![Figure 2: An example comparison between reference and captured image](image)

The rate at which inspection occurs can be defined by the operator and can be dependent on a number of factors such as the inherent size of the component, the critical nature of the part, inspection requirements as defined by international standards, etc.

Hardware Implementation
The dedicated in-process inspection concept consists of the following hardware components:
1) A high specification camera and lens, 2) Inspection lighting and power supply units, 3) An appropriate I/O box, 4) An industrial personal computer

![Figure 3: Inspection hardware components and primary connections](image)

The appropriate selection of a high specification camera(s), associated lens, and their accurate set up are essential to ensure a high quality image of the top printed layer can be captured. An example of this setup is depicted within Figure 4.

![Figure 4: Inspection hardware placement within ME system - top (a) & side (b) views](image)

A dark field lighting set-up is utilised to illuminate the printed top layer – therefore maximising the quality of the captured image. Due to the nature of the system and hardware, the outline concept has the potential to scaled up/down depending on the required inspection footprint.

Software Implementation
To facilitate the realisation of the proposed in-process inspection concept, a number of software requirements need to be satisfied, including:
1) Generating reference image data from the original 3D drawing
2) Appropriately preparing/coding the I/O box
3) Establishing the custom G-code to trigger the inspection system
4) Designing and implementing the in-process software inspection system

The latter of the outlined requirements is currently under development within the CassaMobile project and may therefore be the subject of future dissemination activities.

Conclusion
This poster outlines a proposal for the development of an in-process monitoring system for use with ME-based AM systems to provide quality feedback with regards to manufactured components. The development of such a system has inherent benefits, beyond savings in time and money, manufacturers will be able to identify defective regions within the build – which may have potentially lead to the premature in-service failure of their products.

A range of hardware and software components have been highlighted within this concept. The specification of any components outlined are for demonstration purposes, instead the proposed concept has the potential for scaling up/down depending on manufacturing or quality control requirements.

Due to the complex nature of the interaction between the various hardware and software components, continued development of the proposed concept and demonstration system is being performed as part of the CassaMobile project.

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Acknowledgements
This research was conducted as part of the CassaMobile project and is co-funded by the European Union (Agreement No. 609148).