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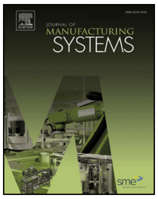

In-situ droplet inspection and closed-loop control system using machine learning for liquid metal jet printing

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ABSTRACT

Liquid Metal Jet Printing (LMJP) is a revolutionary three-dimensional (3D) printing technique in fast but low-cost additive manufacturing. The driving force is produced by magneto-hydrodynamic property of liquid metal in an alternating magnetic field. Due to its integrated melting and ink-jetting process, it can achieve 10x faster speed at 1/10th of the cost as compared to current metal 3D printing techniques. However, the jetting process is influenced by many uncertain factors, which impose a significant challenge to its process stability and product quality. To address this challenge, we present a closed-loop control framework by seamlessly integrating vision-based technique and neural network tool to inspect droplet behaviours and accordingly stabilize the printing process. This system automatically tunes the drive voltage applied to compensate the uncertain influence based on vision inspection result. To realize this, we first extract multiple features and properties from images to capture the droplet behaviour. Second, we use a neural network together with PID control process to determine how the drive voltage should be adjusted. We test this system on a piezoelectric-based ink-jetting emulator, which has a very similar jetting mechanism to the LMJP. Results show that significantly more stable jetting behavior can be obtained in real-time. This system can also be applied to other droplet related applications owing to its universally applicable characteristics.

1. Introduction

Additive manufacturing (AM) or 3D printing has been hailed as the third industrial revolution in the unique way that products are designed and manufactured [1]. Due to the elegant concept of the layer by layer fabrication, AM can build complex objects with a wide variety of materials and functions. This opens up tremendous opportunities for a wide range of applications including aerospace, automotive, defence, and biomedical industries [2]. With the advancement of material, machine, and process, metal 3D printing is now the fastest growing segment among 3D printing technologies [3]. However, most of the current metal 3D printing applications involve high cost and low-speed metal powder sintering or melting [4–7]. Recently, a revolutionary liquid metal jet printing (LMJP) alternative [8,9] has been explored and recognized as a promising emerging process that can drastically lower manufacturing part costs while doubling existing printing speed. This game-changing technology is opening unprecedented opportunities in advanced manufacturing.

Vader Systems, a startup company in Buffalo, NY, is developing and commercializing the world's first molten metal 3D printer using proprietary LMJP technology based on magneto-hydrodynamic inkjet printing process [8]. The LMJP technology patterns magneto-hydrodynamic liquid metal into complex 3D parts **10x faster at 1/10th of the part cost as compared to current methods** [8]. This includes the earth's most abundant metal – Aluminum, which has been widely used in mission-critical heavy industries, yet extremely challenging to handle by other metal printing technologies. The molten solid metal in LMJP rather than sintered powder leads to dense metal parts with much finer micro-structure that have 30% or greater increase in ultimate tensile strength [11]. The main structure of this system is shown in Fig. 1.

Though tremendous efforts and progress have been made in the LMJP process during the past few years, as a brand-new technology, there are still multiple challenges such as the limited choice of material, e.g., has to be conductive or pre-charged, low melting point (660 °C), and the difficulty in controlling the wetting property and coalescence behavior of the jetted metal droplet, which handicap its large-scale commercialization in practice. One of the major challenges is that LMJP process suffers from low process reliability and product quality issues. Physics-based modeling approaches have been proposed to predict the process drift and suggest corrective actions. However, the complex

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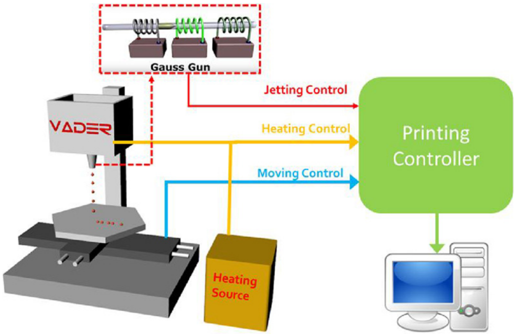

Fig. 1. Liquid metal jet printing system.

printing process (energy-matter interaction, phase changing, thermal-mechanical interaction) and the limitation of current computational tools hinders its practical applications in 3D printing processes [12,13]. This gap has been reported in recent additive manufacturing roadmap reports by both the government agencies and industrial stockholders [14–17]. Given the layer-by-layer nature of 3D printing, if the process drifts are not corrected in a timely manner, defects will propagate into subsequent layers, and thus deleteriously affect the function integrity (fatigue, strength, geometric integrity) of the part. Currently, the metal 3D printing systems are in an open-loop configuration, and the measurement of part quality is done offline, leading to material and energy waste and even devastatingly affect the structural health conditions and infrastructural integrity of many important engineering systems, especially for mission-critical applications such as aerospace, defence, and automobile areas. *In-situ* process-monitoring and process-control are promising to address this challenge. To fill in this research gap and advance the technology development, we develop and validate a novel closed-loop control system which has a vision-based droplet inspection and a neural network based proportional–integral–derivative (PID) technology. Specifically, droplet formation is one of the most important factors associated with the printing quality and reliability in the inkjet metal 3D printing process. It is vital to *on-line* monitor and *in-situ* control the jetting behavior including the droplet volume, speed, and location in jetting history, which would affect the geometrical and functional integrity of the printed part. The aim of this paper is to design and verify a sensing and detection module that can capture high-fidelity data of the droplet and extract critical information for the downstream decision making for *in-situ* correction, and ultimately improve the process reliability, reproducibility, and printing quality of LMJP process. The result from this paper will be a feedback control system that continuously monitors the pattern of the droplets in the LMJP process using the stroboscopic imaging technique and adjusts the applied voltage level to compensate the difference between the observed pattern and the desired pattern due to environmental changes and unexpected events. We acknowledge that these individual techniques (image processing, neural network, and closed-loop control) are well established and widely used in various applications. However, to the best of our knowledge, we for the first time seamlessly integrate these techniques by taking advantage of the unique merits of each technique to effectively solve the pressing problem encountered in 3D printing. We believe the research outcome opens up a new avenue for the research in the quality control area in additive manufacturing and other advanced manufacturing domain. More specifically, the integration and interaction between the key techniques provide valuable guidance to the researchers to explore new means to solve the process control and *in-situ* quality certification problems, which have been proven a grand challenge in the past years.

1.1. Related work

Image- and video-based approaches have been widely used for monitoring the 3D printing process to improve the printing quality. Mazumder [18] used cameras to monitor the height of metal deposition in a laser cladding 3D printing system, through which the layer height can be controlled and better printing quality can be obtained. However, this technology can only control the dimension in the vertical direction of the printed part, and the quality improvement is rather limited. Hu [19] built a closed-loop control system for the heat input based on infrared images of the molten pool in a laser-based additive manufacturing system. Toyserkani [20] developed a pattern recognition algorithm to obtain the clad's height and angle, and a PID controller is developed based on that. The results show an effective improvement of the geometrical integrity. Salehi [21] developed a PID closed-loop controller on LabVIEW to control the temperature of the melt pool, but the results show that controlling temperature alone cannot produce expected quality improvement due to the complexity of the laser cladding process. Faes [22] demonstrated a way to use laser scan to monitor the printed part shape on an extrusion based 3D printer prototype, but the application of this technique is limited to extrusion-based 3D printing, and the measurement error is related to the printing materials due to its interaction with the laser. Cheng [23] presented a closed-loop online system where the feedback is obtained from 3D images, and a fuzzy controller is developed to fulfill the process. Regarding vision and image processing for studying droplet behavior, there are different image processing technologies developed in different areas. Hijazi [24] used cameras to detect the small droplet from a spray nozzle to quantify the process in precision agriculture, and shape matching and contour tracking are used to detect the droplet. However, the high-speed camera is required for precision monitoring and detection, which limits its wide application in cost sensitive area. Pfeifer et al. [25] used camera coupled with pulse laser to characterize the fuel droplet from a spray system in high-pressure conditions. The droplet velocity, size, and spatial distribution are particularly studied. Kwon [26] used the camera to detect the droplet speed of ink printing. By image processing, Cabezas [27] shows that the surface tension of the liquid material can be measured. Blaisot [28] applied image processing to identify droplet size and morphology, which can be used to analyze the diesel spray behavior. Kwon [26] demonstrated that by using edge detection techniques, the speed of ink droplet can be measured, and this technology can be used for *in-situ* measurement. For the stereolithography-based 3D printing process, Xu et al. used a thermal camera to study the shape deformation [29] and also used a 3D scanner-based close loop framework for shape deformation control [30]. The research works reviewed above show that the image processing is promising for droplet characteristic analysis. However, the *in-situ* closed-loop control is still missing due to complex and dynamic droplet formation and propagation process. This paper proposes a holistic framework that seamlessly integrates online monitoring by image processing technique and *in-situ* closed-loop control module to effectively detect and subsequently correct the process drift and anomalies toward high-quality metal 3D printing.

2. Setup and framework

In LMJP process, the metal filament is melted by a resistive heater, and the liquefied metal is then propelled by alternative inductive force in a drop-on-demand manner. In this research, we first prototype a piezo inkjet printing emulator which applies the same drop-on-demand principle as LMJP, and develop a vision system to study the *in-situ* detection and correction problem.

2.1. Piezo inkjet printing emulator

The jetting force in LMJP system is produced by magnetic field constructed by a coil around the melted metal, and the current in the coil changes and creates a time-varying magnetic field. When the liquid metal is exposed in a time-varying magnetic field, eddy currents are