Journal of Manufacturing Systems 45 (2017) 17–27

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Technical Paper

Material handling and registration for an additive manufacturing-based hybrid system

Steven Ambriz[a], Jose Coronel[a], Bob Zinniel[b], Ron Schloesser[b], Chiyen Kim[a],
Mireya Perez[a,*], David Espalin[a], Ryan B. Wicker[a]

[a] W.M. Keck Center for 3D Innovation, The University of Texas at El Paso, El Paso, TX 79968, United States
[b] Stratasys, Inc., Eden Prairie, MN 55344, United States

ARTICLE INFO

Article history:
Received 27 January 2017
Received in revised form 1 July 2017
Accepted 10 July 2017

Keywords:
Additive manufacturing
Hybrid manufacturing
Fused deposition modeling
Portable build platform
Material handling
Registration

ABSTRACT

The final functionality of parts produced by Additive Manufacturing (AM) can, in part, be improved by the inclusion of multi-material capabilities. The Multi^{3D} Manufacturing System uses material extrusion printing (fused deposition modeling technology from Stratasys), solid conductor wire embedding, direct-write, component placement, and micromachining to enable the fabrication of multi-functional products. The material handling methodology, implemented by the Multi^{3D} System, transports a workpiece between manufacturing stations via a six-axis robot, portable build platform, and a controlled temperature environment or chamber that travels to each manufacturing station. Also discussed in this work, is the investigation and improvement of registration parameters between the two material extrusion printers within this system. The registration was ultimately quantified to have minimal errors: 69 μm along the x-axis, 183 μm along the y-axis, and 215 μm along the z-axis. The fabrication of a multi-colored part demonstrated the automated transfer of the workpiece, which offers early promise for an automated solution for multi-material fabrication using commercially-available fused deposition modeling machines.

1. Introduction

Additive Manufacturing (AM), otherwise known as 3D printing, is a process that implements a layer-by-layer approach to fabricate complex 3D objects from computer-aided design (CAD) models. Additive manufacturing is being explored for a wide array of applications, including biomedical, automotive, and aerospace. Recently, the fabrication of functional “end-use” products has been a popular trend in the AM field [1]. For example, Murr et al. studied complex cellular mesh structures manufactured via electron beam melting (EBM), a powder bed fusion AM technology, for their potential use as bone tissue replacements [2]. Savastano et al. looked at additive manufacturing and its potential impacts in supply chain configurations of the automotive industry [3]. Espalin et al. printed CubeSat satellite components using stereolithography (vat photopolymerization) and fused deposition modeling (FDM) substrates with conductive silver ink traces acting as interconnects between electronic components. The former became the first 3D printed electronics in low earth orbit [4]. These are all complementary areas of research in 3D printing multi-functional parts.

To fabricate multi-functional parts using 3D printing, varying technologies are required to deposit or dispense multiple materials, remove material to produce high-resolution features, and introduce components that cannot be easily 3D printed. The inclusion of differing technologies into one manufacturing station has been demonstrated by Keating and Oxman [5] in a fabrication system that includes material extrusion 3D printing and milling. Their work utilized a KUKA robot for tool handling, in addition to the system’s capabilities for material extrusion 3D printing, sculpting tools, and milling. Advantages of using a six-axis robot over a conventional gantry CNC machine were noted as, a minimal physical footprint of the system, easy adaptability to a wide variety of tools, and access to internal spaces within parts that are not reachable with a gantry arrangement. However, there was no discussion of registration between the various disparate processes. The work presented in this manuscript, on the other hand, offers detailed methods and quantified results related to registration between disparate manufacturing stations, two of which are professional-grade (i.e., not open air, hobbyist, desktop 3D printer) material extrusion AM machines. The KUKA robot in Keating and Oxman was also

---

* Corresponding author.
E-mail address: maperez4@utep.edu (M. Perez).

http://dx.doi.org/10.1016/j.jmsy.2017.07.003
0278-6125/

used to handle a milling tool, whose feed rate was limited because of the robot's vibrations during machining. The limited machining speed is not experienced in the conventional gantry configuration because that structure is more rigid than a six-axis robot. Also, in Keating and Oxman, printing demonstrations were carried out in open air, which caused warping due to rapid cooling of the extruded plastic. Warping is often mitigated by using material extrusion AM machines with heated build chambers, which is the approach followed in this manuscript. Another approach is processing of a work piece with disparate manufacturing stations. This approach is found in well-established industrial processes including semiconductor fabrication [6,7] and pharmaceutical manufacturing [8,9]. The semiconductor fabrication process includes six serial processes: material fabrication, wafer fabrication, wafer probe, assembly, raw testing, and final testing. Pharmaceutical manufacturing can include multiple stages specific to the pharmaceutical being produced, but often entails granulation, milling, tablet compression, and tablet coating. The manufacturing process described in this paper is similar to semiconductor and pharmaceutical manufacturing in that multiple discrete manufacturing stations are employed. In semiconductor and pharmaceutical batch manufacturing, the different fabrication jobs are performed simultaneously in disparate manufacturing stations on a batch of identical workpieces. While the manufacturing system described in this manuscript can also fabricate batches, the manufacturing system, due to the inclusion of material extrusion AM, has the added capability of making each workpiece within the batch different in shape due to the CAD-driven AM process. It would also be possible to print multiple materials within a single batch with the Multi^{3D} System.

The objective of this research was to mature multi-technology 3D printing fabrication by minimizing human interaction (or promoting full automation) in a system called the Multi^{3D} Manufacturing System (Fig. 1a). For the interested reader, the predecessor machine is described in a referenced paper [10]. The developed Multi^{3D} System contained two fused deposition modeling 3D printers (FDM1 & FDM2), one CNC machining station, robotic component placement capabilities, direct wire embedding tools, machine vision, and a six-axis robot for material handling. Multiple FDM machines enabled multi-material capabilities in the Multi^{3D} System, utilized in applications where disparate materials were required. Gaynor et al. [11] describe the difficulty of manufacturing and the need for multi-material compliant mechanisms which utilize materials with different phases, enabling deformation to transfer motion, force, and energy. In the current work, the Multi^{3D} manufacturing approach entails transporting a workpiece between the various discrete manufacturing stations. The capabilities of the Multi^{3D} System will enable the design and manufacture of novel aerospace components such as UAVs and small satellites.

The term hybrid manufacturing has been given numerous definitions in recently published works [12–14]. Zhu et al. [15] define it as the combination of two or more manufacturing processes and further divide the term into two categories: 1) hybrid manufacturing, and 2) sub-hybrid manufacturing. Hybrid manufacturing utilizes a combination of different technologies such as:

- additive and subtractive technologies,
- subtractive and joining technologies,
- additive and transformative technologies, and
- subtractive and transformative technologies.

On the other hand, sub-hybrid manufacturing uses different processes within the same manufacturing technology, including:

- additive technologies,
- subtractive technologies, and
- transformative technologies.

This work particularly focuses on additive and subtractive technologies. Additional information on joining and transformative technologies as part of hybrid systems can be found in Zhu et al.

Hybrid manufacturing systems, which employ both additive and subtractive technologies, are proliferating because manufacturers recognize that subtractive methods can be used to improve dimensional accuracy, surface finish, and resolution of AM parts. Ultrasonic Additive Manufacturing is a process by Fabrisonic [16], which uses ultrasonic welding (a sheet lamination process) in conjunction with CNC machining. The use of sheets rather than entire blocks of metal, as in conventional machining, reduces waste and allows for the layering of multiple material types within one part. Hybrid Manufacturing Technologies [17], has created a patented series of tool heads, which convert any CNC router or robotic platform into a hybrid system by combining machining with directed energy deposition AM. There also exist a number of systems which utilize sub-hybrid manufacturing focused solely on additive technologies. Voxel8 [18] is a commercially available desktop system for 3D printed electronics that uses a material extrusion process as well as direct write technology for conductive ink dispensing. Zhang et al. [19] designed a system, which they named E-FDM because it uses material extrusion AM in conjunction with electrohydrodynamic (EHD) jet printing. The purpose of the EHD component is to provide high voltage during the printing process, creating a much thinner line width (road width) for fabrication of high resolution polylactic acid (PLA) structures with potential use in tissue engineering applications. While significant to the AM industry as a whole, most of the hybrid approaches mentioned here are focused on metal printing processes. Furthermore, the polymeric sub-hybrid systems available, are most commonly based on desktop printers. While some of the methods described in this manuscript may not be considered novel to the manufacturing community, the innovation is in using these established methods with a manufacturing process that includes production-grade polymer AM systems.

Several factors were considered in the decision to use production-grade printers rather than desktop printers, as part of the Multi^{3D} System. The patented temperature controlled envelope [20] used in production-grade systems reduces the likelihood of thermoplastic warping. While some desktop printers have enclosed build envelopes, these are not temperature controlled as this would be a patent infringement. In addition, production-grade systems use sacrificial build sheets which protect the build plate from damage as well as provide faster setup time for continuous printing. Desktop systems do not use sacrificial build sheets and instead use plastic or glass beds coated with Kapton tape or polyetherimide (PEI) sheets for protection. Another difference is that production-grade systems provide a larger build volume, allowing for multiple parts to be printed simultaneously. The actuators which control motion of the extrusion tool are more robust on production-grade systems, leading to greater dimensional accuracy of printed parts. Production-grade systems also work with advanced slicing software which provides the ability to delete individual layers, customize the use of supports, designate starting points, and modify parameters at each individual layer (bead widths, air gaps, raster angles, etc.), among others. On the other hand, there are challenges with working with production-grade printers. Desktop printers provide a greater degree of flexibility due to the open-source architecture available on most systems. The closed-architecture of production-grade system means additional programing was required to interface with their controllers. Another challenge was that the cost of a production-grade printer is typically higher than that of a desktop printer, which may limit researchers with reduced resources. Production-grade print-