Computer-Aided Design 42 (2010) 1095–1107

Contents lists available at ScienceDirect

Computer-Aided Design

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

A dynamic priority-based approach to concurrent toolpath planning for multi-material layered manufacturing

S.H. Choi *, W.K. Zhu

Department of Industrial and Manufacturing Systems Engineering, Faculty of Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong

ARTICLE INFO

Article history:
Received 9 October 2009
Accepted 19 July 2010

Keywords:
Layered manufacturing
Multi-materials
Toolpath planning
Multi-object motion planning
Dynamic priority

ABSTRACT

This paper presents an approach to concurrent toolpath planning for multi-material layered manufacturing (MMLM) to improve the fabrication efficiency of relatively complex prototypes. The approach is based on decoupled motion planning for multiple moving objects, in which the toolpaths of a set of tools are independently planned and then coordinated to deposit materials concurrently. Relative tool positions are monitored and potential tool collisions detected at a predefined rate. When a potential collision between a pair of tools is detected, a dynamic priority scheme is applied to assign motion priorities of tools. The traverse speeds of tools along the *x*-axis are compared, and a higher priority is assigned to the tool at a higher traverse speed. A tool with a higher priority continues to deposit material along its original path, while the one with a lower priority gives way by pausing at a suitable point until the potential collision is eliminated. Moreover, the deposition speeds of tools can be adjusted to suit different material properties and fabrication requirements. The proposed approach has been incorporated in a multi-material virtual prototyping (MMVP) system. Digital fabrication of prototypes shows that it can substantially shorten the fabrication time of relatively complex multi-material objects. The approach can be adapted for process control of MMLM when appropriate hardware becomes available. It is expected to benefit various applications, such as advanced product manufacturing and biomedical fabrication.

1. Introduction

1.1. Layered manufacturing

Layered manufacturing (LM), or rapid prototyping (RP), is an additive process that fabricates a physical prototype from a CAD model layer by layer, more rapidly than conventional manufacturing processes [1]. LM technology is now seen in a wide range of applications, such as product development, biomedical engineering, and architecture, etc. It offers huge potential to reduce or eliminate some stages of the traditional supply chain. The global market for LM products and services grew to an estimated USD1.183 billion in 2008, and the LM industry is expected to more than double in size by 2015, according to Wohlers Report 2009 [2].

LM processes can be roughly categorised as vector-based or raster-based. While a vector-based LM process drives a tool along a predefined path to deposit fabrication material, a raster-based process selectively generates specific contours out of an entire layer of material. Each of these LM processes offers distinctive traits for some specific types of prototypes [3].

Although LM can shorten prototyping cycles, the process is not as rapid as desired. Wohlers [2] pointed out that applications of LM are increasing, yet current LM systems are becoming unacceptably slow in respect of the increasing size and complexity of prototypes being made. Kochan [4] claimed that one of the main limitations of rapid prototyping was the low speed at which a part was fabricated. Bellini [5] presented that Fused Deposition Modelling (FDM) was fast enough for small parts of a few cubic inches, or those of tall, thin features, but it could be very time-consuming for parts with wide cross-sections. Hauser et al. [6] also pointed out that the methodology of LM was essentially a start–stop process because each layer was processed and deposited sequentially. The breaks in the build cycles, for example the positioning of hardware, often slowed down the build rate.

Some efforts have been devoted to enhancing the fabrication efficiency of LM. Sintermask Technologies [7] developed a machine with a Selective Mask Sintering (SMS) process capable of projecting infrared radiation through masks to sinter a whole layer of polyamide powder in ten seconds. Voxeljet [8] introduced a plastic powder binding system capable of building 400 cubic inches per hour. Hauser et al. [6] developed a software system to control a process called spiral growth manufacturing (SGM), capable of building ten layers per minute. Despite these developments, most commercial LM machines are still slow for relatively large and complex prototypes.

* Corresponding author. Tel.: +852 2859 7054; fax: +852 28586535.
E-mail addresses: shchoi@hku.hk (S.H. Choi), h0795413@hkusua.hku.hk (W.K. Zhu).

0010-4485/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cad.2010.07.004

1.2. Multi-material layered manufacturing

Another major problem is that most LM machines to date can only fabricate homogeneous prototypes of a single material. However, recent trends in various industries, particularly advanced product development [9] and biomedical engineering [10], have warranted heterogeneous objects which offer superior properties unparalleled by homogeneous ones [1]. Heterogeneous objects may be classified into two major types, namely discrete multi-material (DMM) objects with a collection of distinct materials divided by clear boundaries, and functionally graded multi-material (FGM) objects with materials that change gradually from one type to another [11]. There is indeed an imminent need to develop multi-material layered manufacturing (MMLM) for fabrication of heterogeneous objects, and some pioneering works have been reported in recent years.

Qiu et al. [12] developed a virtual simulation system for fabrication of parts consisting of discrete materials; a toolpath planning method for two materials was reported to reduce defects and voids of a virtual part. Jepson [13] developed an experimental MMLM machine, which could blend two types of metallic powders to form a layer of some material gradients and subsequently sinter it to build an FGM part. Cho et al. [14] extended their patent "3D printing" to fabricate FGM parts; two materials were dispersed through their respective inkjet tools and printed into the powder bed. Khalil et al. [10] developed a multi-nozzle biopolymer deposition system, which was capable of extruding biopolymer solutions and living cells for freeform construction of tissue scaffolds. Cesarano III [15] developed a so-called Robocasting technology which was able to fabricate either single material or multi-material ceramic parts. By turning the blender on or off, fabrication of graded alumina/metal composites, and discrete placement of fugitive materials could be achieved. Inamdar et al. [16] developed a multiple material stereolithography machine. The mechanism consisted of three vats, each of which contained a specific material, and a customised LabVIEW system was used to control the rotating multiple vat system to fabricate a multi-material model. Wang and Shaw [17] introduced a method for fabricating functionally graded materials via inkjet colour printing. The print heads dispatched Al_2O_3 and ZrO_2 aqueous suspensions in different quantities to form a particular composition. Malone et al. [18] developed the Fab@Home multi-material 3D printer for fabrication of electro-mechanical systems. Typical materials included polypropylene and ABS thermoplastics, and low melting-point metal alloys such as lead and tin. A Zn–air cell battery of about the size of a coin, composed of five layers of different materials in a plastic case, was fabricated. Objet Geometries Ltd. [19] claimed that its Connex350 offered the ability to fabricate assemblies made of two types of photopolymer materials, with different mechanical properties. The photopolymer materials were cured by ultra-violet light immediately after jetting.

These systems have made significant contributions to the development of MMLM, although they were mostly experimental and could only make simple prototypes of a few types of materials. However, practical and viable MMLM systems for relatively large, complex objects have yet to be developed.

It can be said that development of MMLM is mainly concerned with three major research issues, namely (1) fabrication materials, (2) hardware mechanism for deposition of materials, and (3) computer software for planning the toolpaths and subsequent process control of multiple tools for prototype fabrication. These three issues are generally studied by researchers of specialised expertise. Nevertheless, the software issue of toolpath planning is particularly important as it has a significant impact on the overall efficiency and quality of fabrication, especially of large and complex prototypes.

1.3. Issues of toolpath planning

Toolpath planning for LM is mainly concerned with (i) contour filling strategy, and (ii) tool sequencing strategy [20]. Contour filling strategy concerns mainly with how to fill up the internal area of a contour. This issue has been well-studied and standard contour filling patterns have been developed for LM [21]. On the other hand, tool sequencing strategy is more about coordinating the motions of a set of tools, each of which deposits a material on specific contours, to fabricate a multi-material prototype safely and effectively. Tool collisions and fabrication efficiency are main considerations, which may be exacerbated by the need to vary the tool deposition speeds to suit different material properties and fabrication requirements [22]. Tools can be planned to deposit materials either sequentially to avoid collisions at the expense of fabrication efficiency, or concurrently to enhance fabrication efficiency with risks of collisions. This is a difficult problem of MMLM.

Few research works on toolpath planning for MMLM have been reported. Qiu et al. [12] developed a simulation system for toolpath analysis of MMLM. In the system, a toolpath file per material was generated first and then integrated into one multi-material toolpath file. A toolpath planning method for two materials was reported to reduce the defects and voids of a virtual part. This method could process relatively simple objects, such as cylinder and cube. Zhu and Yu [23] proposed a collision detection and tool sequencing method for simple multi-material assemblies. Zhou [24] proposed a toolpath planning algorithm for fabrication of functionally graded multi-material (FGM) objects. First, the gradual material distribution in each layer was discretised into step-wise sub-regions, in each of which the material could be assumed homogeneous. Then, sequential toolpath for each sub-region was generated separately.

The experimental MMLM systems described in the previous section also involved some basic toolpath planning algorithms which were either sequential or could only handle relatively simple prototypes. Choi and Cheung [25] developed a multi-material virtual prototyping system integrated with a topological hierarchy-based approach to toolpath planning for MMLM. This approach was later improved with an entire envelope-based approach [20] and with a separate envelope-based approach [26]. These approaches were characterised by the construction of bounding envelopes around slice contours by offsetting outward a distance of the tool radius. Overlap test was executed for these envelopes. Tools in the non-overlapped envelopes could deposit their specific materials concurrently without any collisions. Nevertheless, they did not allow tools to move concurrently when the associated envelopes of the contours overlapped, incurring some idle time of tools.

1.4. Research objective

It can be concluded that toolpath planning for MMLM remains a vital but difficult research issue, which has yet to be fully tackled. This paper therefore proposes a new approach to concurrent toolpath planning for MMLM to further improve the fabrication efficiency of relatively large, complex prototypes. This approach eradicates the associated constraints of the previous approaches [20,25,26] to further improve the fabrication efficiency. It is characterised by the construction of envelopes around individual tools directly, rather than around the slice contours of each layer. Relative tool positions are monitored to detect potential collisions at a predefined rate. A dynamic priority assignment scheme is applied to assign motion priorities of the tools to avoid collisions and to coordinate the tool motions accordingly. Deposition speeds of tools can also be adjusted to suit different material properties and fabrication requirements. This concurrent toolpath planning approach can substantially shorten the build-time of MMLM, in comparison with the previous approaches.