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A virtual prototyping system with reconfigurable actuators for multi-material layered manufacturing

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ABSTRACT

Proliferation of layered manufacturing (LM) in various sectors has been calling for fabrication of large, complex products with more materials and efficiency. We address this issue by integrating reconfigurable manufacturing (RM) with LM. This paper first analyses the benefits of such integration, and then presents a virtual prototyping system with reconfigurable actuators (VPRA) that can increase the number of materials, speed, and build volume to improve the efficiency and flexibility of multi-material layered manufacturing (MMLM). The VPRA system offers a test bed for design, visualization, and validation of MMLM facilities and processes. It takes advantage of the convenient graphics platform of SolidWorks™ for constructing a virtual MMLM facility by selecting reconfigurable actuators from predefined templates. The characteristics, including the dimensions and relative spatial constraints, of the actuators can be conveniently configured to suit design requirements. The mechanism and the operation process of the resulting MMLM facility can then be simulated and validated through digital fabrication of complex objects. Case studies are presented to demonstrate some possible applications of the VPRA system. Overall, the VPRA system gives insights into the characteristics of a reconfigurable MMLM system, which can be subsequently materialized for physical fabrication of multi-material objects. This approach highlights a possible direction for development of MMLM technology.

1. Introduction

In recent years, there has been pressing demand for multi-material objects to facilitate advanced product development and biomedical applications. Some experimental multi-material layered manufacturing (MMLM) systems [1–4] have been adapted from vector-based LM processes for fabrication of multi-material objects. Vector-based LM processes drive tools or nozzles in linear motions to deposit fabrication materials. They offer versatile choice of materials, better control of material composition, high material utilization, and convenient maintenance. However, there are several shortcomings, particularly with respect to fabrication materials, speed, and build volume.

Most current MMLM systems cannot handle more than four materials, although new fabrication materials are being explored. Attaching additional deposition mechanisms to handle more materials would not only make the system cumbersome and hamper its structural stiffness, but also incur extra costs which may not be justifiable without sufficient utilization. This limitation hinders fabrication of complex parts with more materials.

Another major problem is the relatively low fabrication speed [5–7]. Indeed, most systems have only one actuator to deposit solid contour areas with single lines of material, which is particularly slow for large, complex parts involving more materials.

The build volume is also a limitation. Prototypes for various applications have been growing in both size and complexity, taking larger envelopes to build. However, with a single actuator, the end-effector often needs to travel long distances to deposit materials, delaying fabrication of each layer [8]. Moreover, a system with a large build volume may become wasteful if it is not sufficiently utilized. In fact, it is difficult to determine an appropriate build volume for an MMLM system to meet changing product demands.

To mitigate the above problems, we adopt the concept of reconfigurable manufacturing (RM) to improve vector-based MMLM systems. Since its emergence in the late 1990s, RM has been successfully applied in manufacturing to improve process efficiency, capability and cost-effectiveness [9–11]. It has indeed been identified as among the six major challenges for competitive manufacturing in the coming years [12].

An RM system is primarily designed for rapid changes of capacity and functionality to suit production demands [13]. It is characterized by open architecture, which is modular, integral, diagnosable, customizable, and convertible. While modularity, integrability, and diagnosability reduce the time and effort spent on reconfiguration, customization and convertibility cut the cost [13]. As such, an RM system can be rapidly synthesized with basic hardware and software process modules that can be integrated

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readily and reliably [14], and upgraded accordingly to meet future needs.

To facilitate the proposed integration of RM with MMLM, we incorporate virtual prototyping (VP) to develop a virtual prototyping system with reconfigurable actuators (VPRA), which provides a simulation platform for design, synthesis, visualization, and validation of the resulting reconfigurable MMLM mechanisms. As such, the costs and risks in development of physical MMLM facilities can be greatly alleviated.

2. RM for reconfigurable MMLM

2.1. Advantages of integrating RM with MMLM

Integrated with RM features, the actuators together with the nozzles of an MMLM system can be flexibly reconfigured for concurrent deposition of multiple materials. This would not only avoid clumsiness of attaching many nozzles to a single actuator, but also facilitate effective fabrication of objects larger than the work envelope of a single actuator. As such, the overall efficiency, build volume, and number of fabrication materials of MMLM can be significantly improved.

2.2. Critical issues

Practical integration of RM with MMLM warrants consideration of two main issues regarding deposition mechanism and process planning.

2.2.1. Deposition mechanism

Traditional vector-based MMLM systems often make use of the XY-stage mechanism based on precise lead screws, taking advantage of their relatively low cost, high precision, and simple control. While similar mechanisms may still be used in reconfigurable MMLM systems, some researchers have attempted to use robotic arms for LM processes [15–18]. Although robotic mechanisms may be more expensive and complicated in control, they exhibit more flexibility in material deposition and work envelope during fabrication, as well as easy concurrent fabrication by multiple units. Therefore, we incorporate both the XY-stage mechanism and robotic arms for integrating RMS with MMLM in the proposed VPRA system.

2.2.2. Process planning

Process planning plays an important role in exploiting the hardware to improve fabrication speed and quality. In MMLM, the main steps generally include determination of build orientation, design of support structure if necessary, model slicing and toolpath planning [19].

Toolpath planning is particularly important because it impacts hugely on the overall fabrication efficiency and quality. It includes contour filling and tool sequencing strategy. Contour filling determines the internal pattern for filling a contour area, and has been well studied in LM. Tool sequencing, on the other hand, coordinates the motions of multiple tools (nozzles) to build an object safely and efficiently, and has yet to be fully addressed in MMLM [20]. Intuitively, fabrication speed can be increased by concurrent deposition of actuators. Indeed, toolpath planning approaches with multi-actuators have been developed for single-material objects [8,21] or simple multi-material objects [22]. One main weakness of these approaches is that they consider very few operational constraints, which are essential for practicality and process safety [23–25].

To address this weakness, we have previously developed a deposition group-based toolpath planning approach with multi-actuators [26]. This approach classifies and models operational spatial constraints leading to possible actuator collisions, as well as indexing material deposition priorities. The contours within each layer of a multi-material object are sorted according to material deposition priorities, material distribution on the actuators, and the criteria of actuator collision avoidance. The sorted contours are then arranged into a series of deposition groups for concurrent deposition. This approach would be incorporated into the proposed VPRA for generation of feasible and efficient toolpaths in digital fabrication. The details of this approach can be found in the above paper and will not be elaborated here.

2.3. Virtual prototyping for reconfigurable MMLM

The benefits of VP for optimization of LM processes and subsequent digital fabrication of complex objects have been discussed in the literature [27–30]. Using VP, a virtual MMLM system can be built for visualization and simulation of the mechanism to validate and improve performance. As such, designs of new MMLM systems can also be modelled and evaluated to facilitate physical development.

We therefore take advantage of VP to integrate reconfigurable manufacturing with layered manufacturing. The proposed VPRA system provides a test bed for design, visualization, validation, and subsequent improvements of vector-based MMLM facilities and processes. It is built on SolidWorks^{TM}, a commercial CAD software, to provide a convenient graphics platform for synthesizing a virtual MMLM facility with actuator templates predefined in a library. After planning toolpaths for an object by considering operational constraints of actuators, material attributes, process safety and efficiency, digital fabrication can be conducted to study, validate, and hence improve the performance of the virtual MMLM facility. The following sections present the proposed VPRA system in detail.

3. The VPRA system

The VPRA system is developed as an add-in of Solidworks in its Application Programming Interface (API), the VB.net and C/C++ languages, and the OpenGL graphics library. Fig. 1 highlights the system flow of its main modules for virtual MMLM facility synthesis, object and actuator data management, and toolpath planning and digital fabrication.

3.1. System structure of VPRA

SolidWorks provides a convenient graphical user interface (GUI) for interaction with virtual objects, in that the dimensions of an object can be changed and the relation between two objects determined easily. An object for fabrication can be created directly in SolidWorks or imported from another CAD system or from an

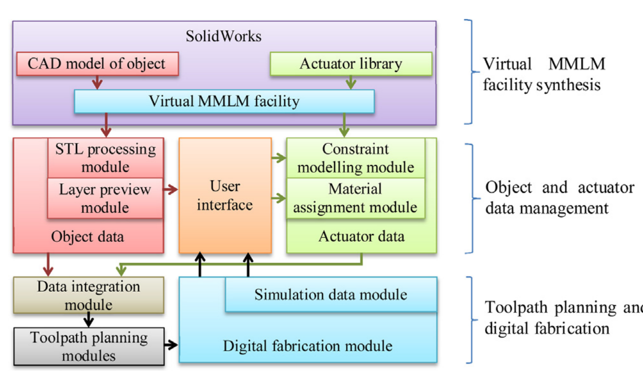

Fig. 1. System structure of VPRA.