Title:
**Reconfigurable Multi-material Layered Manufacturing**

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Introduction:
Despite recent advances in layered manufacturing (LM) technology, which is now often called 3D printing, most practicable systems can fabricate only objects of a single material or relatively simple objects of a limited number of materials. There has indeed been pressing demand for complex multi-material objects to facilitate advanced product development and biomedical applications.

Some experimental multi-material layered manufacturing (MMLM) systems [1-5] 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 utilisation, and convenient maintenance. However, there are several shortcomings, particularly with respect to fabrication materials, speed, and build volume.

To mitigate the above shortcomings in MMLM systems, this paper proposes integration of reconfigurable manufacturing (RM) with layered manufacturing (LM) to develop reconfigurable systems for multi-material layered manufacturing. Reconfigurable MMLM 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. Integrated with RM features, the actuators together with the nozzles of an MMLM system can be flexibly reconfigured conveniently to build complex multiple material objects efficiently. As such, the overall efficiency, build volume, and number of fabrication materials of MMLM can be improved significantly.

Main idea:
We first propose in this paper the concept of reconfigurable MMLM, with which an MMLM system can be rapidly synthesized and integrated with basic hardware and software process modules to satisfy current fabrication requirements, and upgraded accordingly to meet future needs. To implement reconfigurable MMLM, we then present 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 MMLM. The VPRA system offers a test bed for design, visualisation, and validation of reconfigurable MMLM facilities and processes.

Fig. 1 highlights the system flow of VPRA's main modules for virtual MMLM facility synthesis, object and actuator data management, and toolpath planning and digital fabrication. 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.

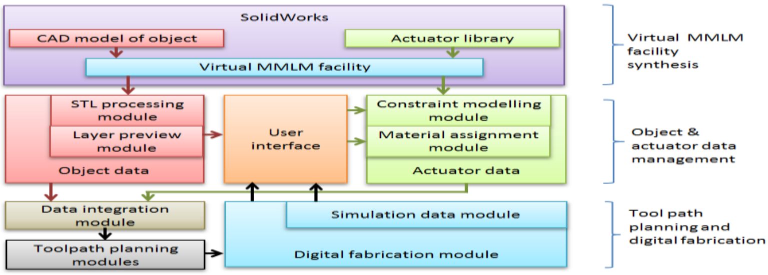
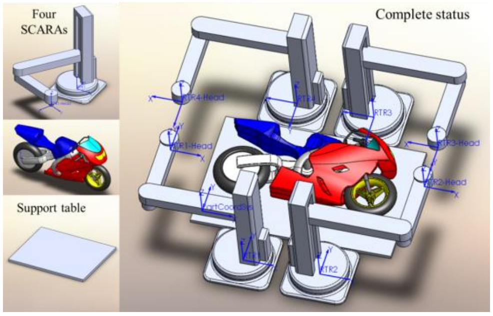


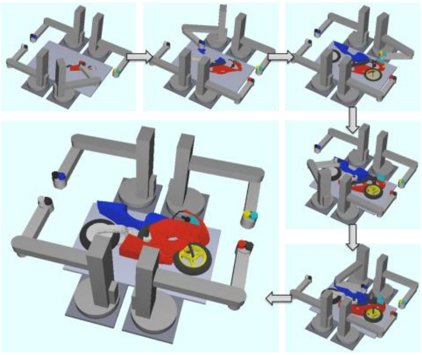

Fig. 1: System structure of VPRA.

Firstly, the VPRA system is integrated with SolidWorks™, a commercial CAD tool, to provide a flexible and convenient environment for synthesising virtual vector-based MMLM facilities based on several predefined types of manipulators. To facilitate the incorporation of RMS into MMLM, these manipulators are designed to offer three levels of reconfigurability in the nozzle holders, the geometrical dimensions, and the spatial layout. A static virtual facility synthesized in SolidWorks can subsequently be commanded to simulate deposition operations and perform digital fabrication of various objects.

Secondly, VPRA can model the operational constraints among the manipulators in a synthesized facility to avoid potential collisions during concurrent deposition, as well as various requirements of deposition speed and priority for different materials. Based on such modelling, two toolpath planning approaches are proposed and integrated with the VPSRM for toolpath generation. One is aimed to improve the fabrication efficiency of multi-material objects, while the other to increase the utilization of the multiple manipulators in a facility and speeding up fabrication of relatively large single-material objects.

Finally, VPRA provides graphic digital fabrication for intuitive validation of the performance of the virtual MMLM facility synthesized and the toolpaths generated. An independent object-oriented intermediate file will serve as a set of script commands for digital fabrication. Moreover, a dynamic simplification algorithm can balance the display burdens and object resolution during the simulation. Fig. 2 shows an example of virtual MMLM system synthesized with four SCARA robotic actuators for fabrication of a multi-material toy motorcycle.



(a) Virtual MMLM system for fabrication of a motorbike
(b) Digital fabrication of the motorbike

Fig. 2: Synthesis of virtual MMLM facility and digital fabrication in VPRA.

Conclusions:

This paper proposes integration of reconfigurable manufacturing with layered manufacturing to improve the overall fabrication efficiency, build volume, and number of materials of complex multi-material objects. It also presents a virtual prototyping system with reconfigurable actuators (VPRA) as a test bed for design, visualization, and validation of reconfigurable MMLM facilities and processes. The VPRA system provides insights into the characteristics of reconfigurable MMLM, which can be subsequently materialized for physical fabrication of multi-material objects. This approach highlights a possible direction for development of MMLM technology. Case studies show that VPRA is useful for exploring solutions to mitigating the current limitations of MMLM through flexible facility synthesis, effective process planning and intuitive fabrication simulation. With VPRA, designers of new MMLM systems can conveniently validate and improve their designs, while users of current MMLM systems can try out process planning to enhance their systems.

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