The Principle and Process of Digital Fabrication of Biomedical Objects

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INTRODUCTION

Mounting pressure of market globalization and intensifying competition has ferociously been driving the manufacturing industry to survive on incessant reductions in cost and lead-time. However, conventional manufacturing methods can no longer satisfy increasingly diverse customer demands, tight cost control, and complex new products.

Against this background, much research efforts have been devoted to developing various technologies to help the manufacturing industry, and layered manufacturing (LM, or now often called 3D printing) and virtual reality (VR) simulation have been among the most significant technologies developed over the past couple of decades.

Despite recent proliferation of LM (3D printing) for free-form fabrication, most of the current systems can only fabricate objects of a single material (Wohlers Report, 2013). There are imminent demands for multi-material layered manufacturing (MMLM) processes to fabricate advanced products and biomedical objects comprising of multiple materials. A few experimental MMLM machines have been developed based on the conventional single material LM systems for relatively simple objects (Bellini, 2002; Wang & Shaw, 2006; Wachsmuth, 2008; Li et al, 2009; Åklint et al, 2013). However, their fabrication speed is unsatisfactory for most complex, large products or medical objects for emergency cases.

More recently, many researchers have worked on virtual prototyping and virtual manufacturing (VPM) (Bracht and Masurat, 2006; Wang and Li, 2006), which is regarded as one of the most important technological advancements for product design and development. VPM has been successfully used in ship-building and car industries (Kim et al, 2002; Wöhlke and Schiller, 2005). It uses simulation techniques to analyze and improve a product design and validate the fabrication processes and production schedules.

Through simulations in a VR environment, key factors such as the product shape, manufacturability, and durability that may affect the profitability of manufactured products are optimized. VPM enhances profitability by reducing production cost and material usage, etc. Moreover, it reduces time and tooling cost by eliminating the need for multiple physical prototypes. This allows the users to review and validate a product design to "get it right the first time" for delivery of quality products to market on time and within budget.

This chapter describes the principle of virtual prototyping and virtual manufacturing, with a focus on the processes of modeling and subsequent digital fabrication of multi-material biomedical objects. Case studies of modeling and digital fabrication of biomedical objects using a multi-

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material virtual prototyping and manufacturing (MMVPM) system will be presented to demonstrate its principle and possible applications in biomedical engineering.

BACKGROUND

There has been a huge surge in demand for biomedical objects in recent years for various medical and dental purposes (Khan & Dickens, 2014; Lee et al., 2001; Maji et al., 2014; Pinnock et al., 2016; Ripley et al., 2016; Sanghera et al., 2001; Winder et al., 1999).

Biomedical objects have been traditionally used as prostheses to repair damaged bone structures or to replace missing body parts (D'Urso et al., 2000; Eufinger et al., 1995; Sannomiya et al., 2008). They are now commonly used by medical students, surgeons, and dentists to help study the intricate anatomical details of human organs and bone structures, as well as to facilitate planning of implantations and surgical procedures (Singare et al., 2009). For example, artificial hip joints, and bone and jaw structures are often used in hospitals to assist complex medical operations. In addition, they are used as specimens for experiments in pharmaceutical manufacturing enterprises.

Depending on the required properties and applications, biomedical objects can be made of either homogeneous (single) material, or heterogeneous (discrete multiple) materials, or functionally graded materials (FGM) (Pompe et al., 2003; Sun et al., 2005). Watari et al. (2004) described the fabrication of an FGM dental implant by powder metallurgy. Experimental results showed that the implant could achieve better mechanical properties and biocompatibility, and that it could control the tissue response through the gradient function of FGM.

But over the years, biomedical objects have been getting more complex, both geometrically and structurally, with more intricate internal details and delicate material variations. As such, most biomedical objects are not economical, and very often not possible, to make by the traditional manufacturing processes.

To fabricate biomedical objects of multiple materials, some researchers have explored the MMLM technology, which is a layer-by-layer additive process that fabricates a heterogeneous object of a number of different materials, which can be discrete with distinctive boundary interfaces, or functionally graded with composition gradients changing gradually from one to another. This process requires a computer-aided design (CAD) model with sufficient material information (Gu and Li, 2002; Gupta et al., 2015; Jafari et al. 2000; Sun et al., 2005).

MMLM, however, remains experimental, and its practical application for fabricating biomedical objects is limited. Indeed, most current MMLM systems can only handle relatively small, simple objects of few materials. More importantly, they are slow and expensive to operate. To address the limitations of MMLM, research efforts have recently focused on developing multi-material virtual prototyping and manufacturing (MMVPM) technology for digital fabrication of complex biomedical objects in a convenient and cost-effective manner.

MMVPM provides a digital platform that integrates virtual reality (VR) simulation technique with MMLM processes. It is an effective tool that can digitally fabricate complex biomedical objects for use in lieu of physical ones. The user can model a complex biomedical object and digitally fabricate its prototypes. Subsequently, the resulting digital biomedical prototypes can be visualized and analyzed in a VR environment, as if the user is manipulating physical objects, for some medical and dental purposes.

The following sections describe the workflow of the MMVPM system in detail. Case studies of modeling and subsequent digital fabrication of biomedical objects using MMVPM would be presented to demonstrate the principle and process of digital fabrication of complex objects for possible applications in biomedical engineering.