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An adaptive process planning approach of rapid prototyping and manufacturing

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ABSTRACT

This paper presents an adaptive approach to improve the process planning of Rapid Prototyping/Manufacturing (RP/M) for complex product models such as biomedical models. Non-Uniform Rational B-Spline (NURBS)-based curves were introduced to represent the boundary contours of the sliced layers in RP/M to maintain the geometrical accuracy of the original models. A mixed tool-path generation algorithm was then developed to generate contour tool-paths along the boundary and offset curves of each sliced layer to preserve geometrical accuracy, and zigzag tool-paths for the internal area of the layer to simplify computing processes and speed up fabrication. In addition, based on the developed build time and geometrical accuracy analysis models, adaptive algorithms were designed to generate an adaptive speed of the RP/M nozzle/print head for the contour tool-paths to address the geometrical characteristics of each layer, and to identify the best slope degree of the zigzag tool-paths towards achieving the minimum build time. Five case studies of complex biomedical models were used to verify and demonstrate the improved performance of the approach in terms of processing effectiveness and geometrical accuracy.

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1. Introduction

Before undergoing complex operations, surgeons usually experience difficulties in figuring out the exact location/profile of a defect or developing a precise implant for a patient. As an innovative manufacturing technology [1], Rapid Prototyping/Manufacturing (RP/M) can enable a surgeon to practice on a tangible prototyping model in order to understand details before actual operations and is efficiently used to fabricate a customized implant suitable for a patient. Different from conventional forming and machining processes, RP/M is an additive manufacturing process by adding materials layer-by-layer to build up complex models such as biomedical models digitally represented in Computer-Aided Design (CAD) systems. The distinguished advantage of RP/M is that it is a mold-less process, suitable for free-form and complex geometrical model realization [2]. Biomedical models are usually characterized with highly customized and complex geometry, and the research to exploit the RP/M technology to support biomedical applications is becoming increasingly active in recent years [3]. Otherwise, for complex biomedical models, the current process planning strategies in RP/M software packages need to be improved significantly in the aspects of build time and geometrical quality. Meanwhile, geometrical errors inherent from the layer-by-layer and additive forming mechanism of RP/M have brought challenges on achieving high geometrical quality of biomedical products. Owing to quickly developed healthcare markets with stronger requirements for more complex applications, it is becoming a strong desire to develop better algorithms and strategies in RP/M to reduce build time and improve geometrical accuracy so as to meet the high-quality design and functional requirements of complex biomedical models [4].

Process planning is a critical task in RP/M. A good process plan can lead to a high-quality product model. Orientation determination, support structure determination, slicing and tool-path generation are four essential steps in process planning (shown in Fig. 1). For some RP/M techniques such as Wire and Arc Additive Manufacturing (WAAM) [5], support structure is not an issue, while for other RP/M techniques such as powder deposition, orientation determination, which is used to define the slicing direction of a RP/M model, will affect the support structure design of the model, the profile complexity and the total number of sliced layers, and further the build time and geometrical quality of the model. Support structures are used to uphold overhanging build materials during RP/M forming to avoid structural collapse or deformation of the model. An optimal structure can ensure short build time, high geometrical quality and good mechanical properties of the model [6]. Slicing is to transfer a product model

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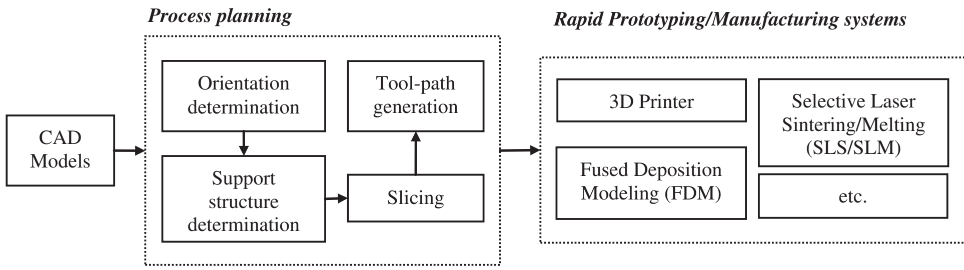

Fig. 1. Process planning for RP/M systems.

Table 1
A summary of RP/M model representation.

Research	Original models	RP/M models	Major characteristics
Chen and Shi [19,20]	PowerSHAPE models	Lines, arcs and Bezier curves for sliced contours	A macro-AutoSection software package was developed to collect sliced contour data and produce PIC files; Another software package PDSlice was devised to support the RP/M process.
Cao and Miyamoto [21]	AutoCAD models	Lines, arcs, circles for sliced contours	An ASCII DXF file was used to store sliced layer data. Material information can also be stored in this file.
Ma et al. [22]	3D CAD models	NURBS representation for sliced contours	A NURBS surface model was used to obtain more accurate and smoother surface for RP/M, and a selective hatching strategy was developed to further reduce build time and improve geometrical quality.
Starly et al. [23]	3D CAD models	STEP based NURBS-represented contours	A slicing algorithm was designed to determine the optimal direction, and an adaptive subdivision strategy was also applied for geometrical refinement.
Yin [24]	Point cloud data	NURBS or Bezier-based sliced contours	An approach was developed to build a bridge between scattered points and a slicing algorithm was designed to integrate RE-based data and RP/M to reduce modeling time.
Liu et al. [25]	Contour data from digital camera	STL files	A NC milling machine and a digital camera were used to capture the cross-sectional images of a model used to generate the contour data for directly adaptive slicing to reduce modeling time.

into a series of 2D sliced layers perpendicular to the orientation direction with a pre-defined or adaptively adjusted layer thickness. If each layer is too thick, the build time is reduced but the geometrical accuracy of the product could be relatively poor. Otherwise, the geometrical accuracy is improved but the build time is also extended [7,8]. A tool-path is the trajectory of the nozzle (e.g., in a Fused Deposition Modeling (FDM) system)/print head (e.g., in a 3D Printer) in a RP/M process to fill the boundary and interior areas of each sliced layer. A tool-path strategy includes the determination of the topological, geometrical and process parameters. Various types of tool-path strategies and algorithms such as zigzag, contour, spiral and partition patterns were developed with different considerations on the build time, cost, geometrical quality, warpage, shrinkage, strength and stiffness of a RP/M model [9–15].

The research presented in this paper focuses on addressing the major issue of RP/M process planning, and a systematic approach was developed to improve the RP/M model representation, tool-path generation and nozzle/print head speed to adapt to the various geometrical properties of complex product models such as biomedical models. The approach includes the following algorithms:

(1) A Non-Uniform Rational B-Spline (NURBS)-based slicing algorithm—used to convert a product model to a series of 2D parametric contours of sliced layers. The algorithm enhances the representation accuracy of the model during RP/M and replaces Stereolithography (STL)-based representation strategy, which is a de facto but less accurate standard to support RP/M in industries.
(2) A mixed tool-path generation algorithm—used to generate a series of contour and offset tool-paths along the NURBS-based represented boundary of the model to improve the geometrical quality during RP/M, and zigzag tool-paths for the internal area of the model to simplify computing and fabrication processes.
(3) An adaptive speed algorithm for RP/M—used to control the speed of the RP/M nozzle/print head adaptively for the various geometries of the model so as to improve the efficiency of contour tool-paths, and to determine the slope degree of zigzag tool-paths leading to the shortest build time.

In the end, five case studies of complex biomedical models were used to verify and demonstrate the performance of this research in terms of processing efficiency and geometrical accuracy.

2. Related works

2.1. RP/M model representation

STL, which has been a widely adopted data standard in the RP/M industry, is an approximation representation scheme of product models based on triangles or quadrilaterals. However, there are some intrinsic problems in STL files such as gaps, holes, missing/degenerated/overlapping facets, etc. during the conversion process from native CAD files. Therefore, repairing algorithms of errors in STL files and simplification algorithms of STL files were developed [16–18]. On the other hand, STL is less inaccurate in geometrical representation and needs much more storage spaces for a complex model than parametric mathematical representation themes such as NURBS, Bezier, B-Spline, etc. Recently, there are active research and development to introduce parametric mathematical representation to better support RP/M. A short summary of the previous work is given in Table 1, and the detailed discussions are expanded below. The tables in Section 2 are not comprehensive and for indication.

In Chen and Shi's approaches, arcs, lines and Bezier curves were used to describe the cross-sectional contour geometries of sliced layers [19,20]. A macro-AutoSection software package was developed to collect the sliced contour data, and a software package, i.e.,

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