A MULTI-MATERIAL VIRTUAL PROTOTYPING SYSTEM

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Abstract

This paper proposes a virtual prototyping system for digital fabrication of multi-material prototypes. It consists mainly of a topological hierarchy-sorting algorithm for processing slice contours, and a virtual simulation system for visualisation and optimisation of multi-material layered manufacturing (MMLM) processes. The topological hierarchy-sorting algorithm processes the hierarchy relationship of complex slice contours. It builds a parent-and-son list that defines the containment relationship of the slice contours, and subsequently arranges the contours in an appropriate sequence which facilitates optimisation of toolpath for MMLM by avoiding redundant movements. The virtual simulation system simulates MMLM processes and provides vivid visualisation of the resulting multi-material prototypes for quality analysis and optimisation of the processes.

1. Introduction

Layered Manufacturing (LM) is an additive manufacturing process that produces a physical prototype from a CAD model layer-by-layer. The CAD model can be generated from many sources, including CAD designs and conversion data from a 3D scanner. LM systems are widely adopted in manufacturing and medical applications to save cost and time. Manufacturers use LM technology to produce prototypes of products for design evaluation, and as master patterns for production tools. Surgeons use it to plan and explain complex surgical operations, especially craniofacial and maxillofacial surgeries. LM technology has also been explored for direct manufacture of biologically active implants. Currently, commercial LM machines can only produce single-material prototypes (Qiu et al., 2001; Zhu and Yu, 2002). However, there is an increasing demand for multi-material prototypes. This is because high value-added products tend to involve advanced and complex design, while medical operations are becoming more complicated and delicate. Indeed, a multi-material prototype that can clearly differentiate one part from another of a product, or tissues from blood vessels or bone structure of a human organ, will be particularly useful for designers or surgeons, respectively. Therefore, it would be very desirable and useful to develop multi-material layered manufacturing (MMLM) technology.

In general, a multi-material object may compose of either several materials with varying composition or a collection of discrete materials (Kumar etc al., 1998; Qiu and Langrana, 2002). Effective representation of multi-material objects is a vital step in the development of MMLM technology. However, a critical problem is that current CAD models do not contain any material information. Consequently, most LM systems treat a model as homogeneous models during down-line process planning (Cheng and Langrana, 2001; Patil et al., 2002).

Although MMLM technology has attracted much research interest and some pioneering work has started, practical and viable MMLM machines have yet to be developed.

A MMLM machine may include mainly two sub-systems, namely a hardware material-depositing mechanism and a computer control software system that is able to process multi-material slice contours to control the material-depositing mechanism, as shown in Fig. 1.
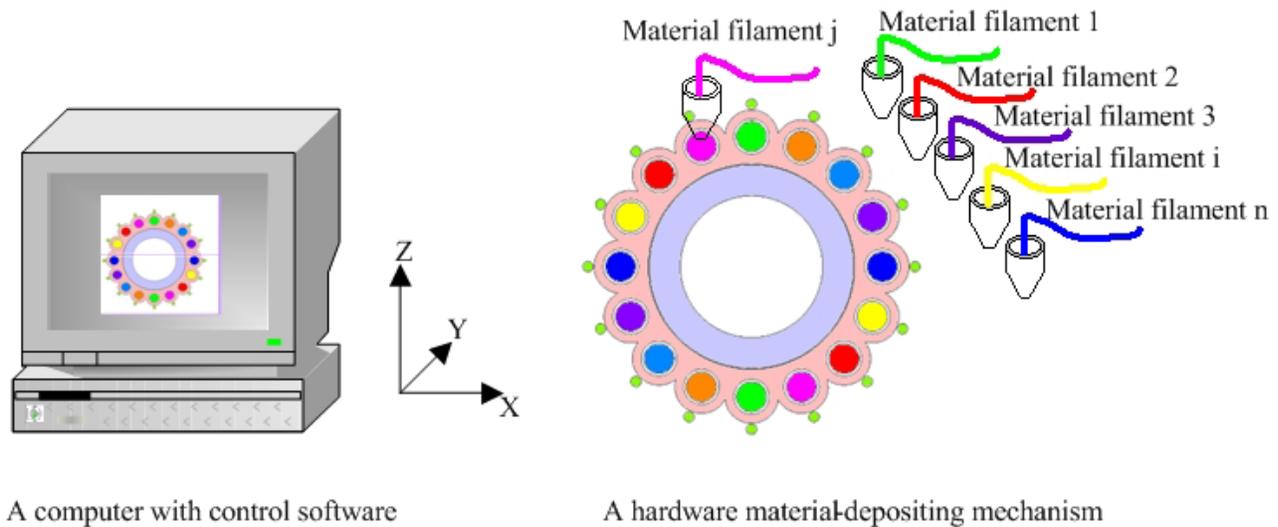
Fig. 1. A layer of a multi-material part being fabricated

The development of MMLM technology is largely a software issue. The material-depositing mechanism may consist of an array of nozzles or tools, each of which deposits a type of material on specific areas of a layer. The tools may be bundled together or may be controlled to move independently. They may be adapted from those used in the existing single-material LM machines. However, a viable computer software system for MMLM processes has yet to be developed. The system should be able to generate multi-material slice contours, which are subsequently sorted and intra-connected to relate specific slice contours to a particular tool, such that the area is appropriately deposited with the desired material. Hence, the processing of complex multi-material slice contours and the planning of multi-toolpath are particularly important. They facilitate the system to control tools depositing selected material at the appropriate contours and simultaneously avoid redundant movements and possible collisions of the tools which move otherwise independently to increase efficiency.

This is, however, a daunting task because slice contours are generally random in nature with no explicit topological hierarchy relationship. As a result, it is very difficult to identify one contour from another within a slice as required for generating toolpath for MMLM fabrication. Therefore, it can be seen that the difficulty of processing slice contours, and the required software system, largely hinders the development of MMLM technology.

In this paper, a multi-material virtual prototyping system for digital fabrication of multi-material prototypes is proposed. The software system may be subsequently adapted and integrated with a material deposition mechanism to form a practical MMLM machine. It consists mainly of (1) a topological hierarchy-sorting algorithm for processing slice contours and arranging the contours in an appropriate sequence which will facilitate optimisation of toolpath for MMLM by avoiding redundant movements; and (2) a dexel-based virtual simulator for visualisation and optimisation of MMLM processes.

2. Review of the related works

MMLM technology provides a powerful way to fabricate multi-material parts, such as micro electronic parts, bone replacement products, innovative cellular and cell-containing tissue scaffolds. Its benefits and needs have been widely recognised. Some researchers have recently started working on MMLM and they have made important contributions. Their work has been categorically focused on a few areas, such as CAD representation of heterogeneous objects for MMLM, optimisation of multi-toolpath for MMLM, development of experimental systems for simple objects, and virtual simulation of MMLM processes.

2.1. CAD representation of heterogeneous objects for MMLM

In order to fabricate multi-material prototypes with MMLM technology, both material and geometrical information of the objects must be made available. Although STL is now a de facto standard file format for LM industry, it only contains geometrical information. Therefore, some researchers have recently proposed CAD formats for heterogeneous objects to facilitate general CADCAM applications, including MRPII (Kumar et al., 1998 and Morvan and Fadel, 1999). Chiu and Tan (2000) proposed a modified STL file format in which a material structure is used to represent materials. Patil et al. (2002) proposed an R-function and a standard file format to model and represent heterogeneous solids using the concepts of ISO 10303.

Such proposed formats, when fully developed and widely adopted, will be useful for MMLM. However, there are still some major problems to solve. Indeed, a significant proportion of complex objects, particularly human organs and bone structures are not designed using CAD systems. Instead, they are captured by laser digitisers, or Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) scanners. The digitised images are normally processed to form a model in STL format or to extract the slice contours, which are random in nature without any explicit topological hierarchy relationship. Hence, processing such slice contours for mutli-toolpath generation remains a challenging obstacle that has yet to be surmounted for the development of MMLM.

2.2. Optimisation of multi-toolpath for MMLM

Toolpath generation plays an important role in automated fabrication of multi-material prototypes. The main purpose of toolpath planning is to find a solution that requires the shortest processing time possible. Park (2003) suggested a toolpath generation procedure for the Z-constant contour machining. It involved the generation of slice contours and the subsequent toolpath by linking the contours. In MMLM, the slice contours are random in nature without any explicit topological hierarchy relationship. There may be redundant movements and collisions when the nozzles move to extrude the specific material at the related contours in a slice. Zhu and Yu (2002) described that two holders would collide with each other if their distance was shorter than the diameter of the tool holders when they attempted to fill two very close contours. They proposed a dexel-based spatio-temporal modelling approach for detecting collisions. Such pioneering works are useful for optimisation of mutli-toolpath for MMLM, although they could only be used to process simple objects.

2.3. Development of experimental multi-material LM machines for simple objects

A few researchers have recently attempted to develop experimental MMLM machines for simple objects. Weiss et al. (1997) described building multi-material structures with pre-fabricated parts, such as advanced tooling and embedded electronic devices. Qiu and Langrana (2002) reported the development of a MMLM machine for fabrication of multi-

phase electromechanical components for naval and other military applications. These systems are among the pioneering work, despite that they could only handle very simple parts.

2.4. Virtual simulation of MMLM process

Cheng and Langrana (2001) and Qiu et al. (2001) described a virtual simulator used to simulate the fabrication of multi-material prototypes. Using computer graphics technology, the simulator was able to detect and remove errors of MMLM process easily and quickly. Generating a virtual multi-material part by the simulator is much faster than the time to generate a physical part. Virtual reality technology has been used for medical applications (Zajtchuk and Satava, 1997). Although their systems have focused more on relatively simple objects, they have highlighted the uselessness of virtual simulation for MMLM.

3. The Proposed multi-material virtual prototyping system

The above pioneering work has made much contributions to the development of MMLM technology. However, there is a lack of integrated effort to tackle the core software problem of processing and planning multi-toolpath for fabrication of complex objects. Therefore, a multi-material virtual prototyping system is proposed to fabricate digital multi-material prototypes. The system consists mainly of a topological hierarchy-sorting algorithm for processing slice contours, and a virtual simulation system for visualisation and optimisation MMLM processes. The topological hierarchy-sorting algorithm constructs the hierarchy relationship of complex slice contours for subsequent fabrication of multi-material prototypes (Choi and Kwok, 2002). In particular, slice contours with established hierarchy relationship facilitate collision detection, as well as the optimisation of toolpath by avoiding redundant back-and-forth movements. The virtual simulation system uses a dexel-based approach for digital fabrication of physical prototypes (Choi and Chan, 2002; Choi and Samavedam, 2001). The workflow of the proposed system includes multi-colour STL model design, slicing multi-material objects, sorting complex slice contours, generation of multi-toolpath, and digital fabrication of multi-material prototypes.

3.1. Representation of multi-material objects by multi-colour STL models

For building multi-material prototypes, both geometry and material information should be provided. In the proposed system, multi-colour STL models are used to represent multi-material objects. Each colour represents a particular type of material. Thus, a multi-colour STL model contains both geometry and material information. A software for processing multi-colour STL models has been developed as an integral part of the proposed system and is used to assign colours into STL models. Some commercial available software such Magics RP (Materialise, 2003) and FlashTL (TNO, 2003) are also able to assign colours into STL models. A tolerant slicing algorithm (Choi and Kwok, 2002) is used to generate multi-material slice contours that are outputted in a modified common layered interface (CLI) file format. Each colour that represents a particular type of material is assigned to each point of the related contours in a layer.

3.2. Optimisation of multi-toolpath with the topological hierarchy-sorting algorithm

In general, complex slice contours are random in nature without any explicit topological hierarchy relationship. This may result in redundant movements, and possibly collisions, when the nozzles move independently to extrude specific materials at the related contours. The topological hierarchy-sorting algorithm simplifies the relational complexity of slice contours, especially with respect to multiple-inclusion contours, by constructing the hierarchy relationship between the contours and the internal cavities. It first builds a parent-and-son list that defines the containment relationship of the slice contours, and subsequently

arranges the contours in an appropriate sequence. With the hierarchy relationship, a complex slice with multiple-inclusion contours can be treated as a family of contours, which can be conveniently processed for toolpath planning. Referring to Fig. 2, the slice contours are grouped into ten families to be made of five discrete materials. The materials are represented by five different colours, namely green, yellow, purple, red and blue. Therefore, five nozzles should be used to extrude five discrete materials in the slice. The contour families with the same material are grouped together, and are subsequently processed to generate hatching vectors that define the toolpath. Hence, the contour families are grouped into five sets of contour families, namely [family1, family 2, family3, family 4], [family5], [family 6, family 10], [family 7, family9] and [family 8]. Based on the grouping of contour families, sequential toolpath without any redundant back-and-forth movements is easily generated. Therefore, the topological hierarchy-sorting algorithm helps optimise the toolpath planning and hence the efficiency of MMLM.
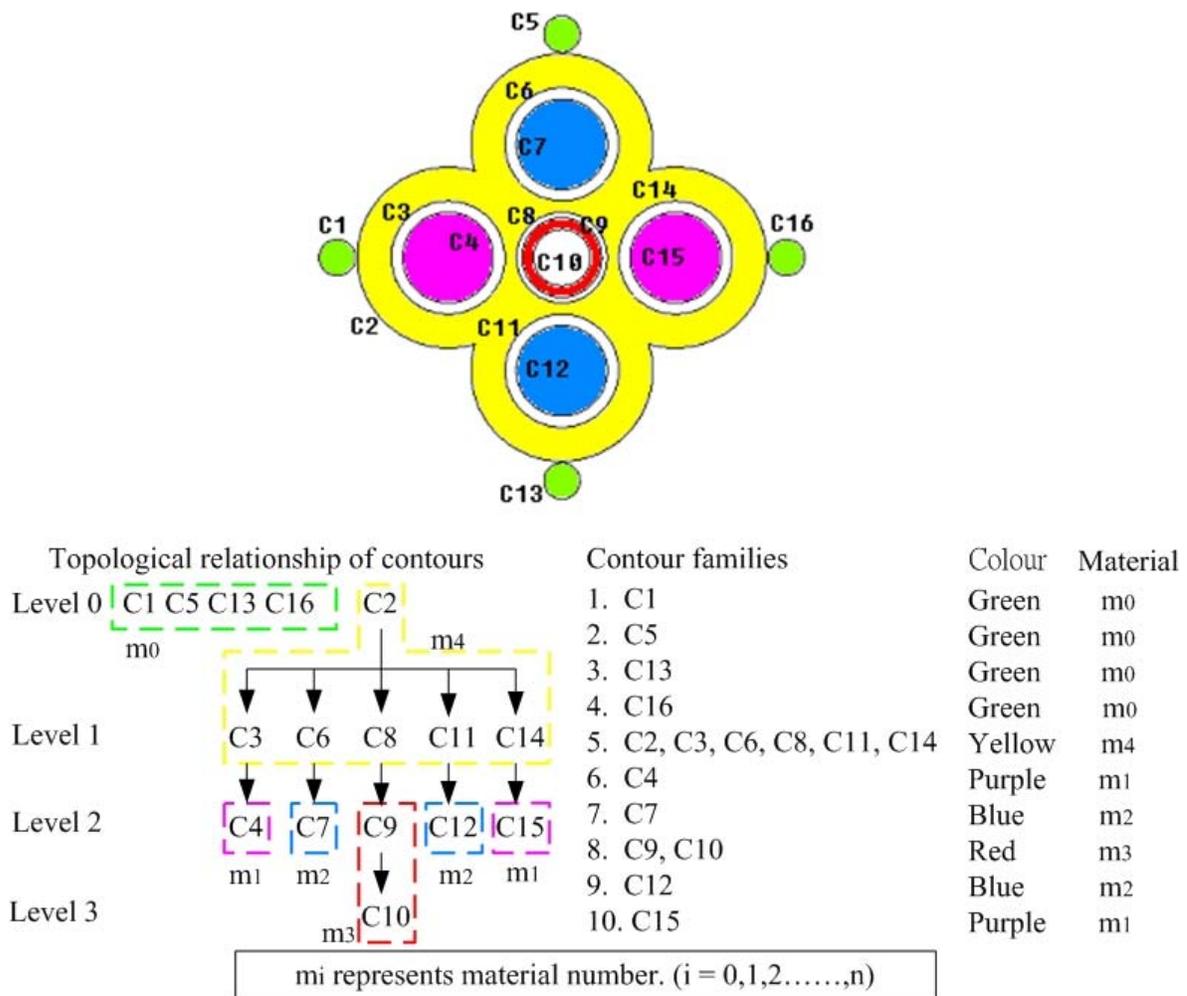
Fig. 2. Illustration of topological hierarchy relationship multi-material slice contours

3.3 Digital fabrication of multi-material prototypes

After processing the slice contours and generation of multi-toolpath, the proposed system simulates a MMLM process to fabricate digital multi-material prototypes. Subsequently, it provides vivid visualisation of the resultant prototypes for quality analysis and optimisation of the MMLM process. The designer can manipulate the prototype using the utilities provided to visualise the quality of the product prototype that a MMLM machine will

subsequently deliver. The designer can also navigate around the internal and opaque structures of the prototype to investigate the product design. Furthermore, the digital multi-material prototype may be superimposed on its STL model to highlight dimensional deviations. The system also calculates the maximum and the average cusp heights that indicate the overall accuracy of the prototype. To study the dimensional errors, a tolerance limit may be set and any locations with deviations beyond the limit will be clearly highlighted. The designer may thus identify and focus on the parts that need modifications. To improve the accuracy and the surface quality of specific features of the prototype, the process parameters, such as orientation of the model, the layer thickness or the hatch space, may be changed accordingly.

4. A case study – a ring

Hong Kong is the leading exporter of imitation jewellery and the second largest exporter of precious jewellery in the world. It has also evolved into a trading and distribution centre for pearls in recent years. Jewellery products are getting more fashion-oriented. As a result, innovative designs are becoming more important. Some jewellery manufacturers realise that they should not only rely on individual skills. They have recently adopted LM technology to develop high value-added jewellery items. Hence, the proposed multi-material virtual prototyping system will be particularly useful for building digital multi-material prototypes to help improve designs and shorten development cycles of jewellery products at competitive costs. Designers can view and evaluate their designs with digital prototypes instead of physical ones, at minimal costs and time possible. Furthermore, digital prototypes may be conveniently transmitted over the Internet to facilitate global manufacturing.

A ring in Fig. 3 was therefore chosen as an example to illustrate how the proposed system fabricates digital multi-material prototypes of jewellery products. The ring is made of thirteen kinds of materials and its shape is complex. To produce such multi-material prototypes, an array of nozzles may be used to extrude materials on relevant slice contours in a layer. The topological hierarchy-sorting algorithm constructs the hierarchy relationship of complex slice contours which facilitates the optimisation of multi-toolpath in MMLM by avoiding redundant movements. The case study illustrates how the system generates efficient sequential toolpath of each nozzle, and subsequently how it facilitates quality analysis and optimisation of MMLM processes.

(a) Monochrome STL exported from CAD model

(b) Multi-colour STL model modified from monochrome STL model

Fig. 3. Monchrome and multi-colour STL models of the ring

Based on a monochrome STL model of the ring in Fig. 3a, a multi-colour STL model in Fig. 3b is created by assigning colours to represent appropriate materials of the ring. The multi-colour STL model is sliced to generate slice contours that contain both geometry and material information. A layer of the ring is shown in Fig. 4. In this layer, there are totally 52 contours that are sorted into three hierarchy levels and are grouped into 34 contour families. Each family has its own material property. The layer consists of 11 discrete materials. The contour families with the same material property are grouped into a set. The 34 contour families are grouped into 11 sets because the layer is made of 11 kinds of materials. For each set of contour families, hatching vectors are generated and then arranged in an appropriate sequence. Each set of hatching vectors is used to control a specific nozzle or tool that extrudes a material on the related set of contour families. Fig. 5 shows a layer of the digital fabrication process of the ring prototype. Each nozzle moves sequentially and deposits a material on the related set of contour families in the layer by avoiding redundant movements. More details of the digital fabrication process of the ring is shown in Fig. 6.
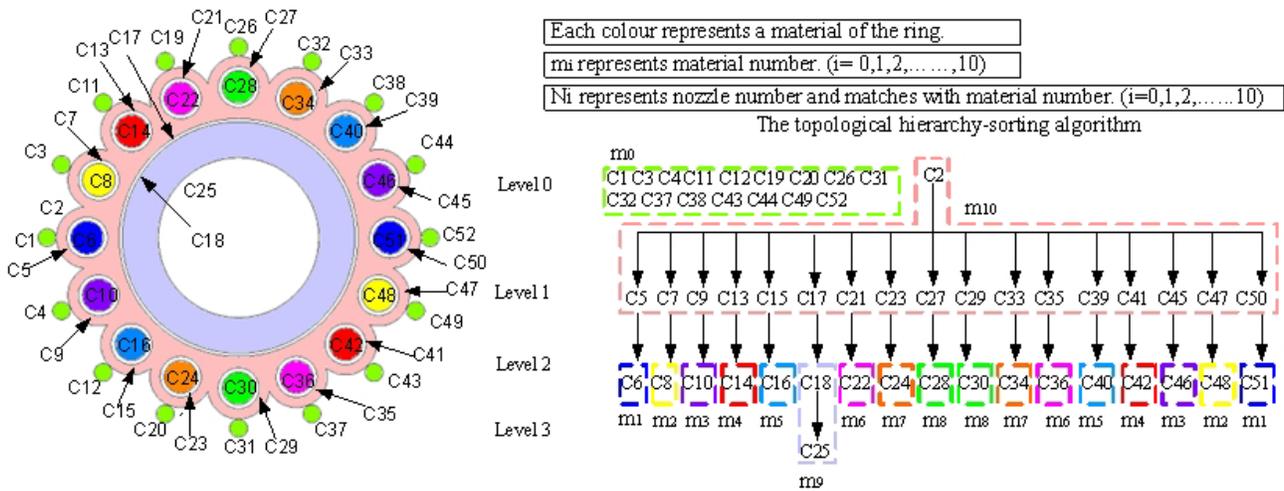
Fig. 4. A layer of complex slice contours with hierarchy relationship
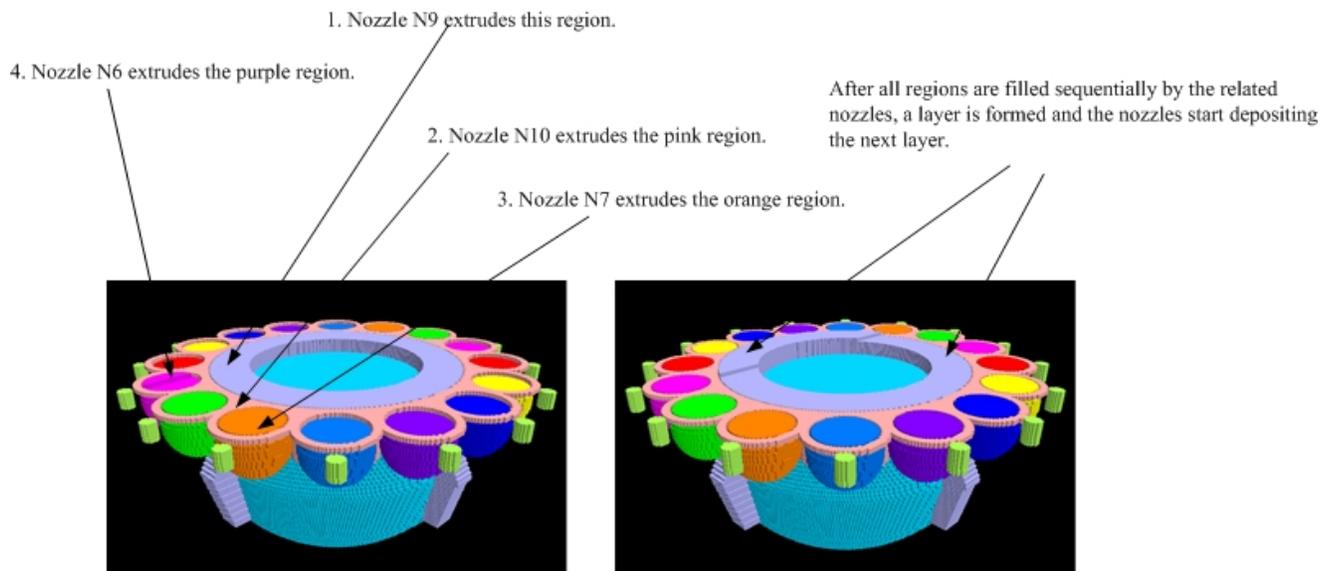
Fig. 5. Nozzles move sequentially to deposit materials on related contours
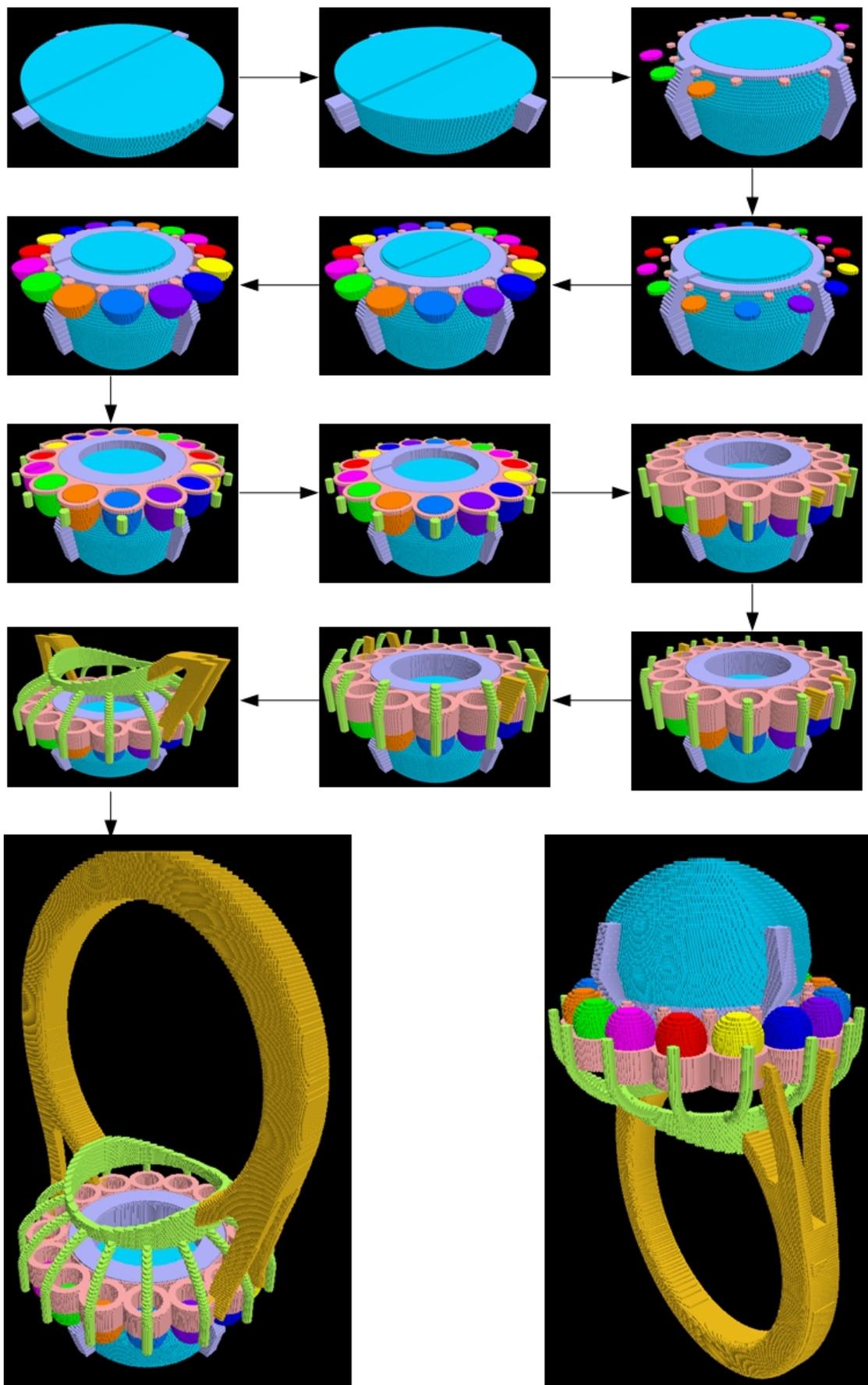
Top view   A complete multi-material virtual   Bottom view
prototype of the ring.

Fig. 6. Digital fabrication process of a multi-material prototype of the ring

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The system also provides vivid visualisation of the resultant prototypes for quality analysis and optimisation of the MMLM process. Fig.7 shows the ring prototype being superimposed on its STL model. The surface texture and the dimensional deviation are clearly illustrated. In addition, the system calculates the cusp heights to evaluate the overall dimensional deviations. In this case, the average and the maximum cusp heights are 0.097mm and 0.176mm, respectively. Suppose that any deviations more than 0.175mm are considered not acceptable, the designer may choose to highlight the areas which are out of the design limit for subsequent investigation of these important features. Fig. 8 shows the same ring with some pins on them. The pins indicate the facets of the STL model with cusp heights more than 0.175mm. The colour of the pins may be red or green. The red ones points to the maximum deviations whereas the green ones pointed to the unacceptable deviations. If unsatisfactory deviations are located at important parts of the model, the designer may choose either to change the model orientation to shift the deviations or to reduce the layer thickness and the hatch space to improve the accuracy.

excessive materials
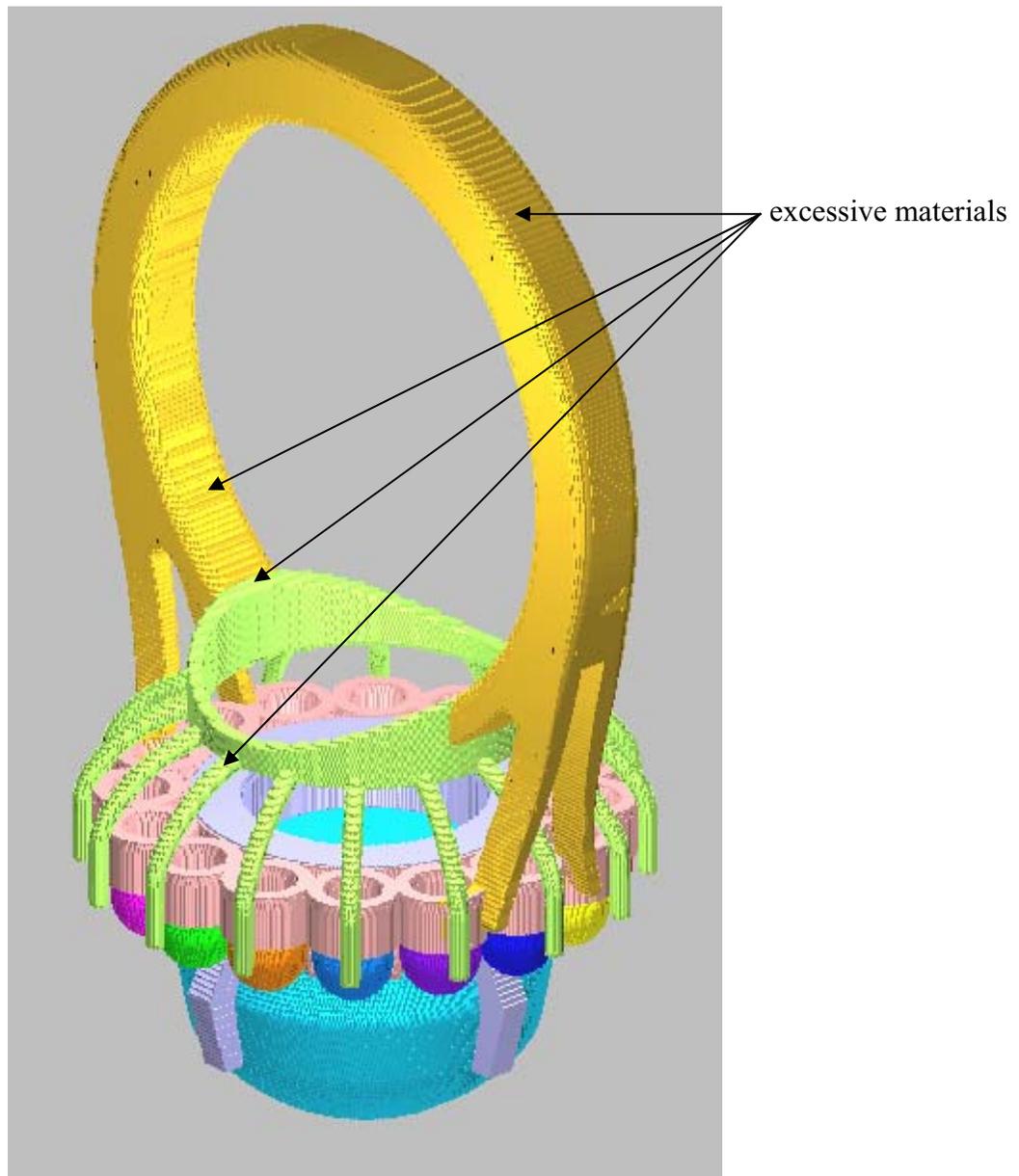
Fig.7. Superimposition of the ring prototype on its STL model

Red pins showing
maximum deviation

Green pins
showing
unacceptable
deviation
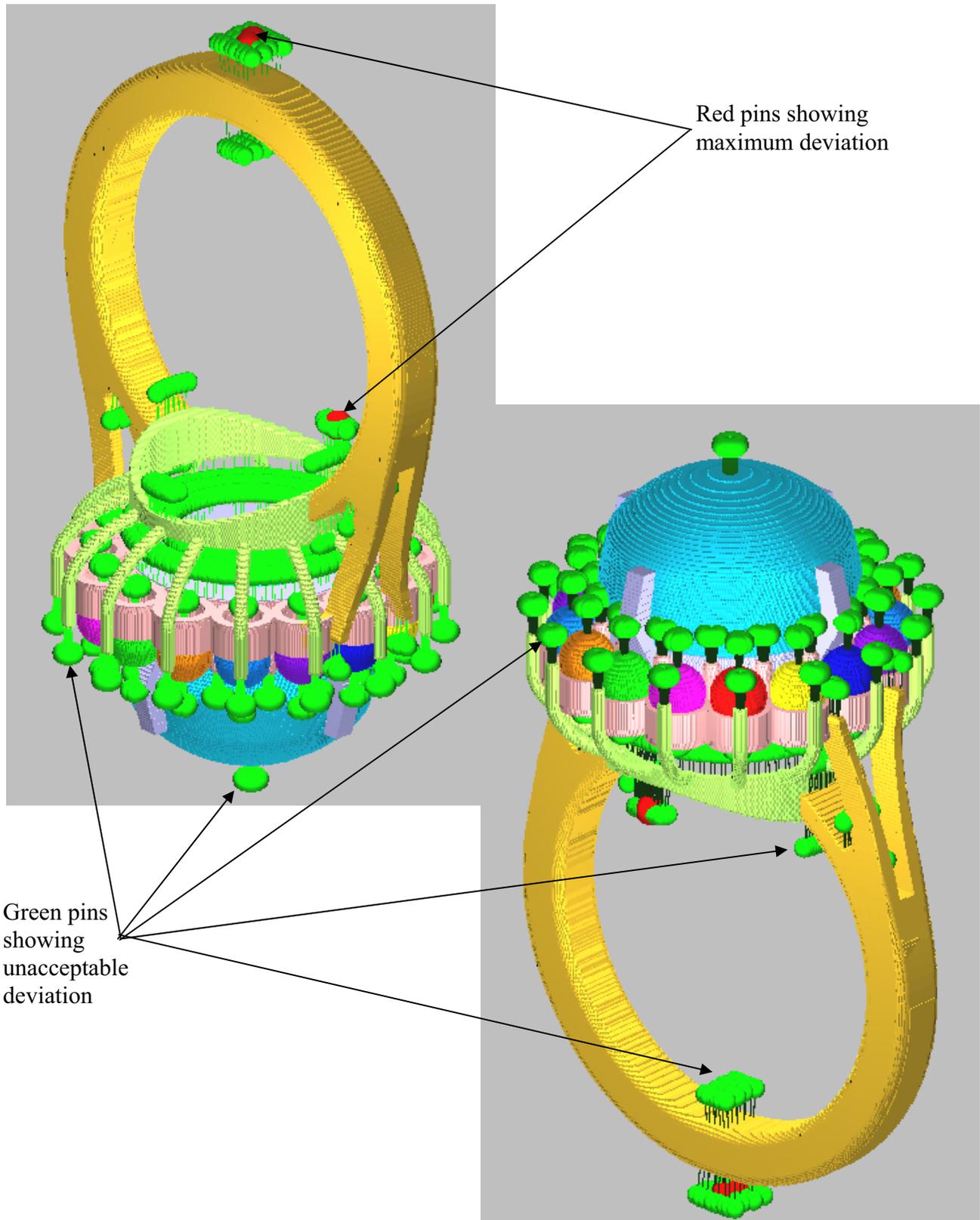
Fig. 8. Areas of the ring with dimensional deviations beyond design limits

5. Conclusion

This paper proposes a multi-material virtual prototyping system that processes complex multi-material slice contours for planning and validation of toolpath for subsequent control of nozzles or tools to fabricate multi-material prototypes. Indeed, multi-toolpath planning plays a significant role of in the development of practical MMLM machines. The proposed system uses a topological hierarchy-sorting algorithm to process the hierarchy relationship of complex slice contours. It builds a parent-and-son list, and subsequently arranges the contours in an appropriate sequence. With the hierarchy relationship of the contours, sequential toolpath are generated and used to control the nozzles or tools to sequentially move and deposit the selected materials at the appropriate contours by avoiding redundant back-and-forth movements. Besides, the proposed system simulates a MMLM process to fabriacte digital multi-material prototypes. Subsequently, it provides vivid visualisation of the resultant prototypes for quality analysis and optimisation of the MMLM process as a way of minimal costs and time possible. The system can be subsequently adapted and integrated with a material deposition mechanism to form a practical MMLM machine.

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