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Digital Fabrication of Multi-Material Objects for Biomedical Applications

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1. Introduction

Recent developments in medical and dental fields have warranted biomedical objects or implants with desirable properties for biomedical applications. For example, artificial hip joints, tissue scaffolds, and bone and jaw structures are now commonly used in hospitals to assist complex surgical operations, and as specimens for experiments in pharmaceutical manufacturing enterprises. But most biomedical objects are not economical to fabricate by the traditional manufacturing processes because of their complex shapes and internal structures with delicate material variations.

Layered manufacturing (LM) has been widely recognized as a potential technology for fabrication of such biomedical objects. Wang et al. (2004) developed a precision extruding deposition (PED) system to fabricate interconnected 3D scaffolds. Zeng et al. (2008) used fused deposition modelling (FDM) technology to build an artificial human bone based on computed tomography (CT) images. However, most commercial LM systems can only fabricate single-material objects, which cannot meet the needs for biomedical applications. A typical example of dental implantation requires a dental implant with functionally graded multi-material (FGM) structures to be composed of titanium (Ti) and hydroxyapatite (HAP) in order to satisfy both mechanical and biocompatible property requirements (Watari et al., 1997). Therefore, it is desirable to develop multi-material layered manufacturing (MMLM) technology for fabrication of biomedical objects.

Multi-material (or heterogeneous) objects may be classified into two major types, namely (i) discrete multi-material (DMM) objects with a collection of distinct materials, and (ii) functionally graded multi-material (FGM) objects with materials that change gradually from one type to another. In comparison with single-material objects, a DMM object can differentiate clearly one part from others, or tissues from blood vessels of a human organ, while an FGM object can perform better in rigorous environments. In particular, suitably graded composition transitions across multi-material interfaces can create an object of very different properties to suit various applications (Kumar, 1999; Shin & Dutta, 2001).

Multi-material layered manufacturing (MMLM) refers to a process of fabricating an object or an assembly of objects consisting of more than one material layer by layer from a CAD model with sufficient material information. Some researchers have explored different techniques to fabricate multi-material objects. A few experimental MMLM machines, such as a discrete multiple material selective laser sintering (M^2SLS) machine (Jepson et al., 1997;

Lappo et al., 2003), a shape deposition manufacturing machine (Merz et al., 1994; Fessler et al., 1997), a fused deposition of multiple ceramics (FDMC) machine (Jafari & Han, 2000), and a 3D inkjet-printing machine (Jackson et al., 1999; Cho et al., 2003; Wang & Shaw, 2006) have been developed. Although these systems seemed suitable for relatively simple objects of a limited variety of materials, they provided a good foundation for further hardware development. It can be said that development of MMLM is mainly concerned with three major research issues, namely (1) fabrication materials, (2) hardware mechanism for deposition of materials, and (3) software system for object modelling and subsequent process control of multiple tools for object fabrication. These three issues are generally studied by researchers of specialised expertise. Nevertheless, the development of an integrated software system for modelling and fabrication of complex multi-material objects is particularly important as it has a huge impact on the overall efficiency and the fabrication quality, especially of large and complex objects.

In order to model and subsequently fabricate a multi-material object, both material and geometric information must be made available. Although STL is now a de-facto industrial standard file format for LM, it only contains geometric information. Therefore, some researchers have recently proposed CAD representation methods for multi-material objects to facilitate general CADCAM applications, including MRPII (Kumar et al., 1998; Morvan & Fadel, 1999).

A mathematical model, called r_m-object, was proposed by enhancing the theory of r-sets to represent heterogeneous objects. While this model suited DMM objects, it was not quite suitable for FGM objects (Kumar, 1999; Kumar et al., 1998). Chiu and Tan (2000) developed a modified STL file format in which a material tree structure was used to represent a DMM object. The modified STL file, however, became large and was slow to process. Hsieh and Langrana (2001) proposed a multi-CAD system for modelling DMM objects. Firstly, this multi-CAD system organized all component STL models generated from the traditional CAD modellers; secondly, it indicated materials to the STL models; and finally, it assembled them into a DMM model. They pointed that this approach could be very cumbersome for parts comprising a lot of materials at different locations because each material in the part required a separate solid.

Indeed, the work above has laid a solid base for extending the LM technology for fabrication of simple DMM objects. However, the representation methods for DMM objects cannot represent FGM objects; this hinders extending the LM technology for fabricating FGM objects. To overcome this, some researchers have attempted to develop different methods to represent FGM objects. The following section reviews some methods for modelling FGM objects.

Jackson (2000) presented a finite element-based approach to modelling FGM parts. This approach could represent an object with complex material composition distribution, but the process was computationally intensive and required much memory because it was necessary to generate a large amount of meshes to represent the object (Shin, 2002; Kou & Tan, 2007).

Samanta and Kou (2005) proposed a feature-based method to represent FGM objects, using free-form B-spline functions to model both geometry and material features. Cheng and Lin (2001) proposed a material feature-based approach for modelling of simple FGM biomedical objects. Kou and Tan (2005) suggested a heterogeneous feature tree (HFT) for constructive heterogeneous objects, based on which a recursive material evaluation algorithm was developed to evaluate the material compositions at specific location. However, the algorithm was computationally intensive and required large memory for handling complex objects.

Shin and Dutta (2001) proposed a constructive representation scheme for FGM objects. Constructive representations of the FGM objects were ordered binary trees whose nodes were heterogeneous primitive sets (hp-sets); an hp-set was the smallest component of an FGM object. Similar to CSG in solid modelling systems, a set of heterogeneous boolean operators, including material union, intersection, difference, and partition, was developed to construct a more complex FGM object from two or more simpler hp-sets. However, this scheme was not yet enough to model arbitrary material distributions as represented by CT or magnetic resonance imaging (MRI) images (Shin, 2002). Similarly, Kou et al. (2006) proposed a non-manifold cellular representation scheme for modelling complex FGM objects. This scheme needed huge computation efforts since the cellular model required more complicated data structures and algorithms for establishing and maintaining the spatial partitions. Kou (2005) proposed an adaptive sub-faceting method to generate mesh-based 2D slices with material composition variation information of an FGM object for visualization. It required huge memory to process complex FGM objects.

When fully developed and widely adopted, the proposed representation schemes above would be useful for MMLM. However, there are still some major problems to solve. These schemes tended to be computationally slow and needed large memory; they were not particularly suitable for complex multi-material objects for biomedical applications.

Most complex biomedical models, such as human organs and bone structures, are not designed using CAD systems. Instead, they are captured by laser digitizers, or CT/MRI scanners. Sun et al. (2005) reviewed the uses of CT/MRI techniques to model tissue scaffolds as CAD models that can be used for biomimetic design, analysis, simulation, and freeform fabrication of the tissue scaffolds. In general, the digitized images are normally processed to form a model in STL format with no material or topological information needed to extract the slice contours. Indeed, slice contours are random in nature without any explicit topological hierarchy relationship, and to process them for multi-toolpath planning remains a challenging obstacle that has yet to be surmounted. Most of the above representation schemes were incapable of modelling objects generated from CT/MRI scanners, and subsequent processing for fabrication of multi-material objects was ignored. Hence, it is worthwhile to develop an integrated computer system to represent and process multi-material biomedical objects for subsequent generation of toolpaths for fabrication control.

This chapter therefore describes a multi-material virtual prototyping (MMVP) system for modelling, visualization, and digital fabrication of discrete and functionally graded multi-material objects for biomedical applications. The MMVP system offers flexibility in representing objects designed by CAD systems or extracted from CT/MRI scan images. It also provides a virtual reality (VR) environment for digital fabrication, visualization, and quality analysis of multi-material biomedical objects. As such, the need for physical prototyping can be minimized, and the cost and time of biomedical product development reduced accordingly.

2. The Multi-Material Virtual Prototyping (MMVP) system

The MMVP system is an integrated software system for modelling, visualization, and fabrication of multi-material objects for biomedical applications. It consists mainly of (i) a discrete multi-material virtual prototyping (DMMVP) module for modelling, visualization, and process planning of DMM objects; (ii) a functionally graded multi-material virtual prototyping (FGMVP) module for modelling, and process planning for layered manufacturing of discrete and functionally graded multi-material objects; and (iii) a virtual reality (VR) simulation module for visualization and optimization of MMLM processes for digital fabrication and quality analysis of discrete and functionally graded multi-material biomedical objects. The following sections describe these modules in detail, with case studies given to demonstrate the design and digital fabrication of multi-material biomedical objects for possible applications like surgical planning, patient's education, and implantations.

2.1 The DMMVP module

The DMMVP mainly consists of a suite of software packages for design and visualization of multi-material objects and simulation of MMLM process. The software packages includes a colour modeller for colouring monochrome STL models, a slicer for slicing colour STL models, a topological hierarchy-sorting algorithm for grouping random slice contours of DMM objects, a topological hierarchy-based toolpath planning algorithm for generation of sequential and concurrent multi-toolpaths, and a virtual prototyping package for digital fabrication of DMM objects.

Figure 1 shows the flow of the DMMVP system. Firstly, a biomedical model created by CAD or a CT/MRI scanner is converted into STL format, which is the industry de-facto standard. As STL is monochrome or single-material, an in-house package is used to paint the STL model, with each colour representing a specific material.

Secondly, a few steps are taken to prepare for subsequent simulation of the MMLM process and visualization of the resulting digital prototypes: (a) slice the colour STL model into a number of layers of a predefined thickness. The resulting layer contours and material information are stored in a modified Common Layer Interface (CLI) file; (b) sort the slice contours with a contour sorting algorithm to establish explicit topological hierarchy; (c) based on the hierarchy information, multi-toolpath planning algorithms are used to plan and generate multi-toolpaths by hatching the slice contours with a predefined hatch space. The hatch vectors are stored in the modified CLI file for fabrication of digital prototypes and build-time estimation.

Thirdly, a virtual prototyping package is used for digital fabrication of multi-material objects and allows users to stereoscopically visualize and analyze the resulting digital prototypes, with which biomedical object designs can be reviewed and improved efficiently. The following section will use a human skull to demonstrate how the DMMVP module can model and fabricate multi-material objects for biomedical applications.

Figure 2 shows a monochrome STL model of a human skull constructed from CT or MRI images. Obviously, using such a monochrome STL model, it would not be easy for users to differentiate various parts or structures of the skull. To alleviate this, the colour STL modeller is used to paint the jaw, the teeth, and a part of spine in red, white, and blue, respectively, as shown in Figure 3. As such, surgeons can visualize and differentiate the various parts of the skull more vividly to explain and plan complex surgical operations. Moreover, each colour represents a specific type of material, and hence a colour STL model can provide both geometric and material information for planning the MMLM process. To fabricate this skull prototype with discrete multi-materials, a set of nozzles (N_i, i=1, 2, …n) would deposit specific materials on appropriate slice contours. It is necessary to identify and

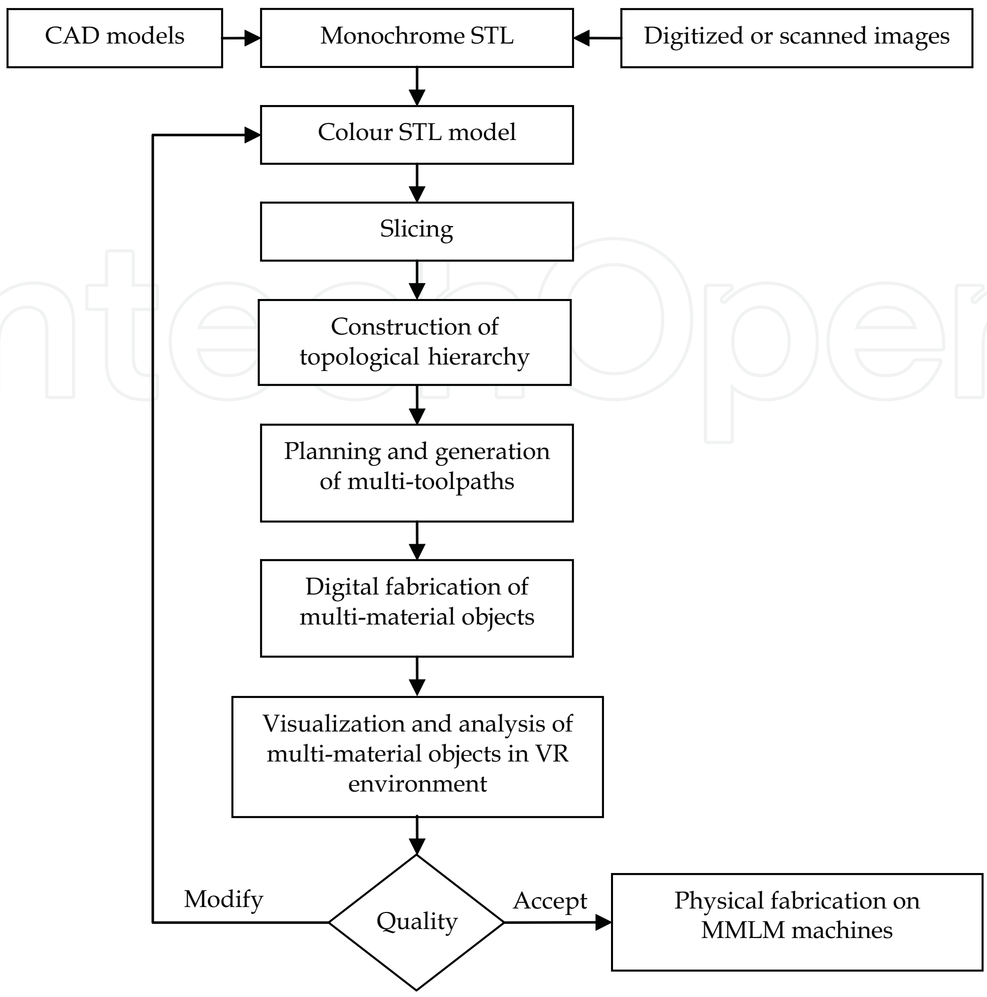


Fig. 1. The flow of the DMMVP module

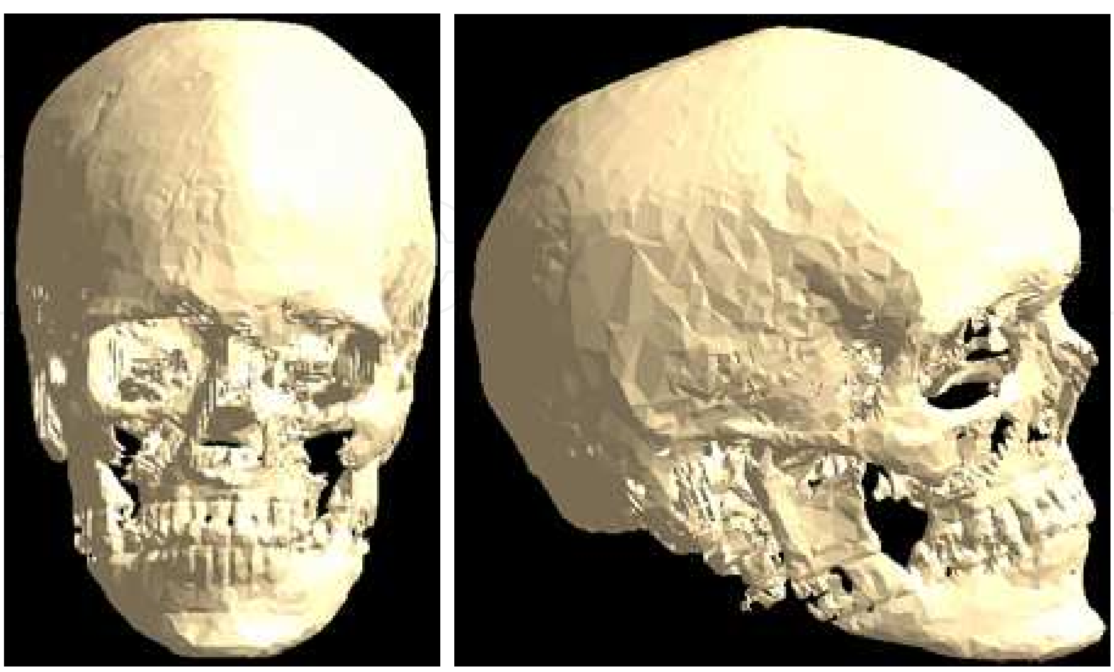


Fig. 2. A monochrome STL model of a human skull

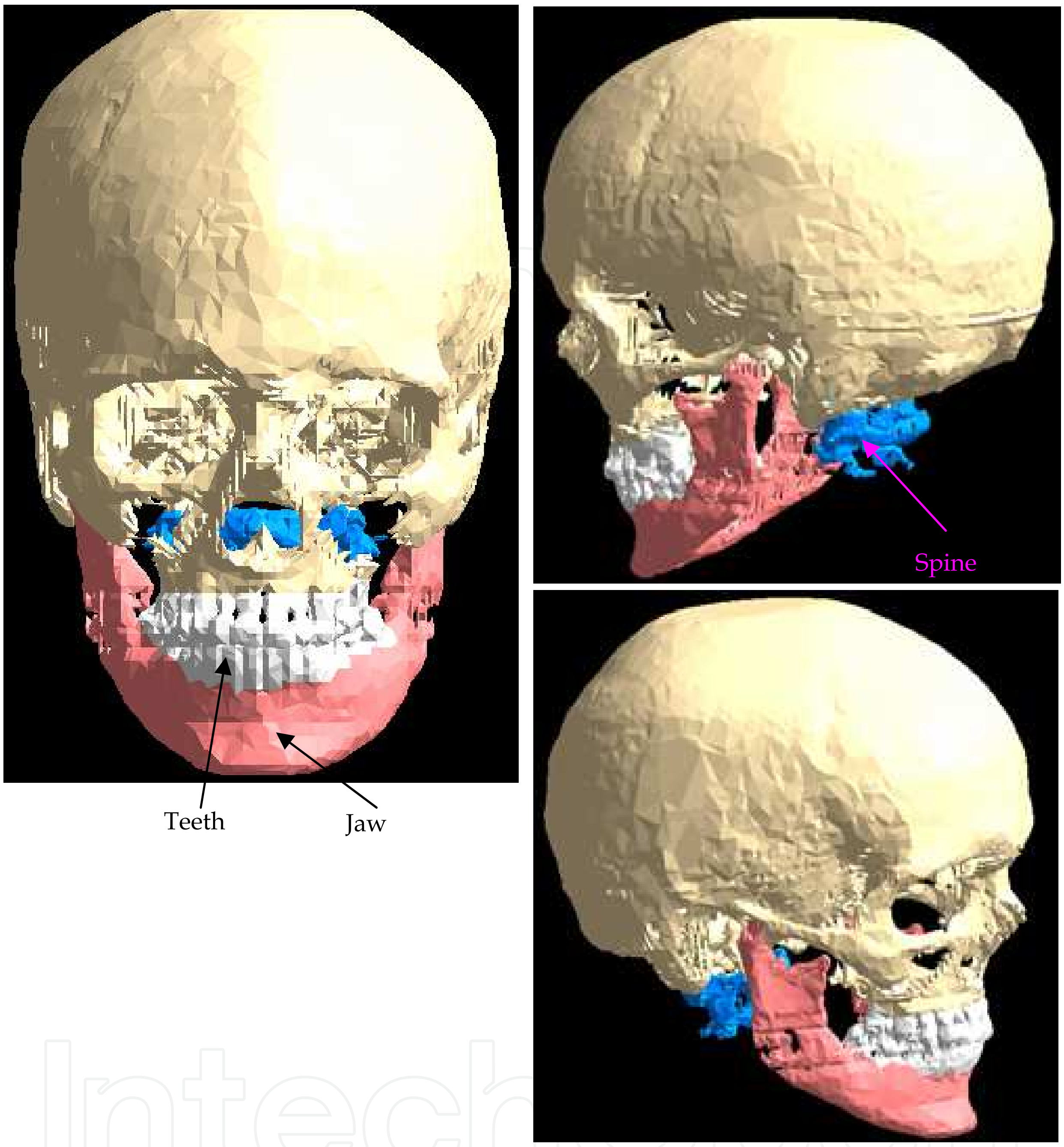


Fig. 3. A colour STL model of a human skull from different perspectives

relate specific contours of a slice to a particular tool and subsequently arrange the toolpaths to fabricate the prototype efficiently. This requires a multi-toolpath planning algorithm to generate efficient toolpaths without possible tool collisions. However, most multi-material objects tend to be complex and the slice contours do not possess any explicit topological hierarchy relationship. As a result, it is very difficult to associate specific contours with a particular tool. To tackle this problem, a topological hierarchy-based approach to toolpath planning for MMLM was proposed by the authors (Choi & Cheung, 2005; 2006a). This approach adopts a topological hierarchy-sorting algorithm to construct the topological hierarchy in terms of a parent-and-child list that defines the containment relationship of the contours of a slice. Thus, with the hierarchy relationship, it is no longer necessary to identify and relate contours to a particular nozzle one by one for multi-toolpath planning. Indeed, only grouping of the outermost contours is required. Besides, parametric polygons are used to construct tool envelopes for contour families with the same material property to simplify detection of tool collisions during concurrent movements of nozzles. As a result, concurrent toolpaths without collisions and redundant movements can be easily generated for controlling MMLM machines to fabricate physical multi-material prototypes.

The colour STL skull model is sliced into 180 layers of multi-material contours with a layer thickness of 0.619 mm stored in the common layer interface (CLI) file format. Figure 4 shows a layer containing 27 contours to be made of three materials, namely m_1, m_2, and m_3, respectively. The topological hierarchy relationship of the contours is listed in Figure 5. The contours are grouped into 24 contour families and 24 toolpaths (P_{C1}, P_{C2}, P_{C3}, P_{C4}, P_{C6}, P_{C7}, P_{C8}, P_{C9}, P_{C10}, P_{C11}, P_{C12}, P_{C13}, P_{C14}, P_{C15}, P_{C16}, P_{C17}, P_{C21}, P_{C22}, P_{C23}, P_{C24}, P_{C25}, P_{C26}, P_{C27}, and $P_{C5,18,19,20}$) are generated for these contours accordingly with a hatch space of 0.500 mm.

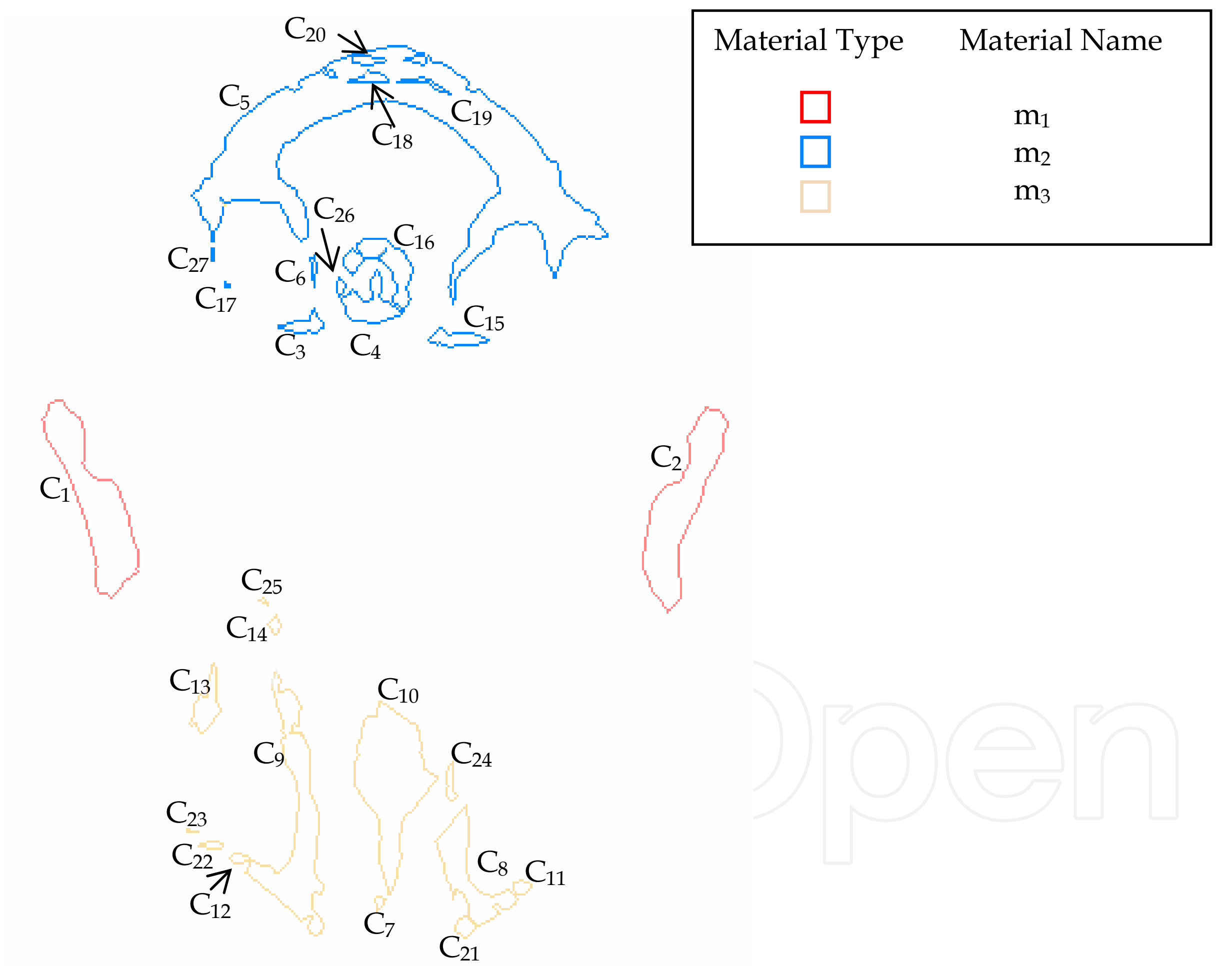
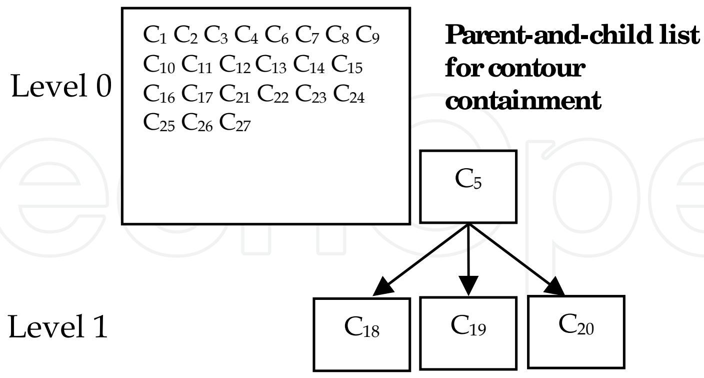


Fig. 4. A slice layer containing 27 contours to be made of 3 materials

According to the material information, the toolpaths with the same material are grouped into three toolpath-sets, namely S_1 to S_3, which are associated with three nozzles from N_1 to N_3, respectively. Subsequently, three work envelopes from E_1 to E_3 for each of these nozzles are constructed to facilitate planning of concurrent multi-toolpaths. Thus, with the hierarchy information and association relationship between the toolpath-sets and the nozzles, concurrent toolpaths without redundant tool movements and collisions can be easily generated and planned for fabrication control.



Contour Families	Toolpaths	Material
1. C_1	P_{C1}	m_1
2. C_2	P_{C2}	m_1
3. C_3	P_{C3}	m_2
4. C_4	P_{C4}	m_2
5. C_6	P_{C6}	m_2
6. C_7	P_{C7}	m_3
7. C_8	P_{C8}	m_3
8. C_9	P_{C9}	m_3
9. C_{10}	P_{C10}	m_3
10. C_{11}	P_{C11}	m_3
11. C_{12}	P_{C12}	m_3
12. C_{13}	P_{C13}	m_3

Contour Families	Toolpaths	Material
13. C_{14}	P_{C14}	m_3
14. C_{15}	P_{C15}	m_2
15. C_{16}	P_{C16}	m_2
16. C_{17}	P_{C17}	m_2
17. C_{21}	P_{C21}	m_3
18. C_{22}	P_{C22}	m_3
19. C_{23}	P_{C23}	m_3
20. C_{24}	P_{C24}	m_3
21. C_{25}	P_{C25}	m_3
22. C_{26}	P_{C26}	m_2
23. C_{27}	P_{C27}	m_2
24. $C_5 \rightarrow (C_{18}, C_{19}, C_{20})$	$P_{C5,18,19,20}$	m_2

Fig. 5. Topological hierarchy relationship of the contours in Fig. 4

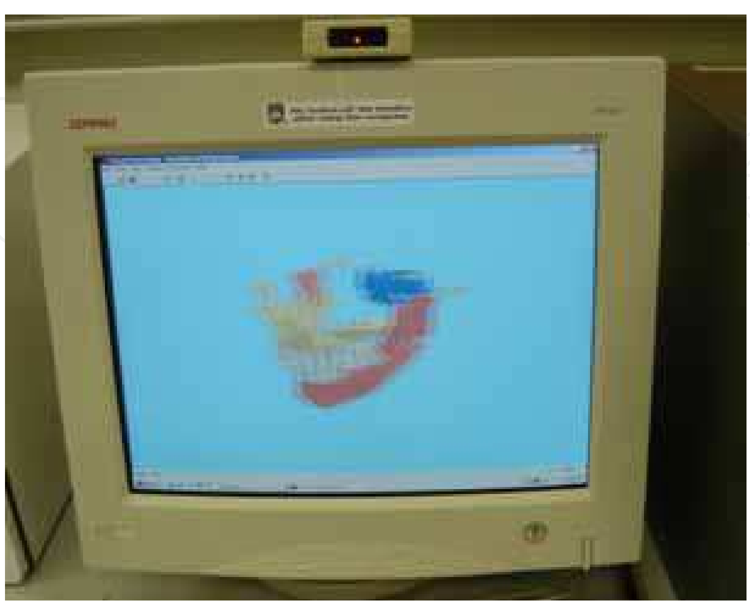


Fig. 6. Digital fabrication of a human skull prototype in a desktop VR system

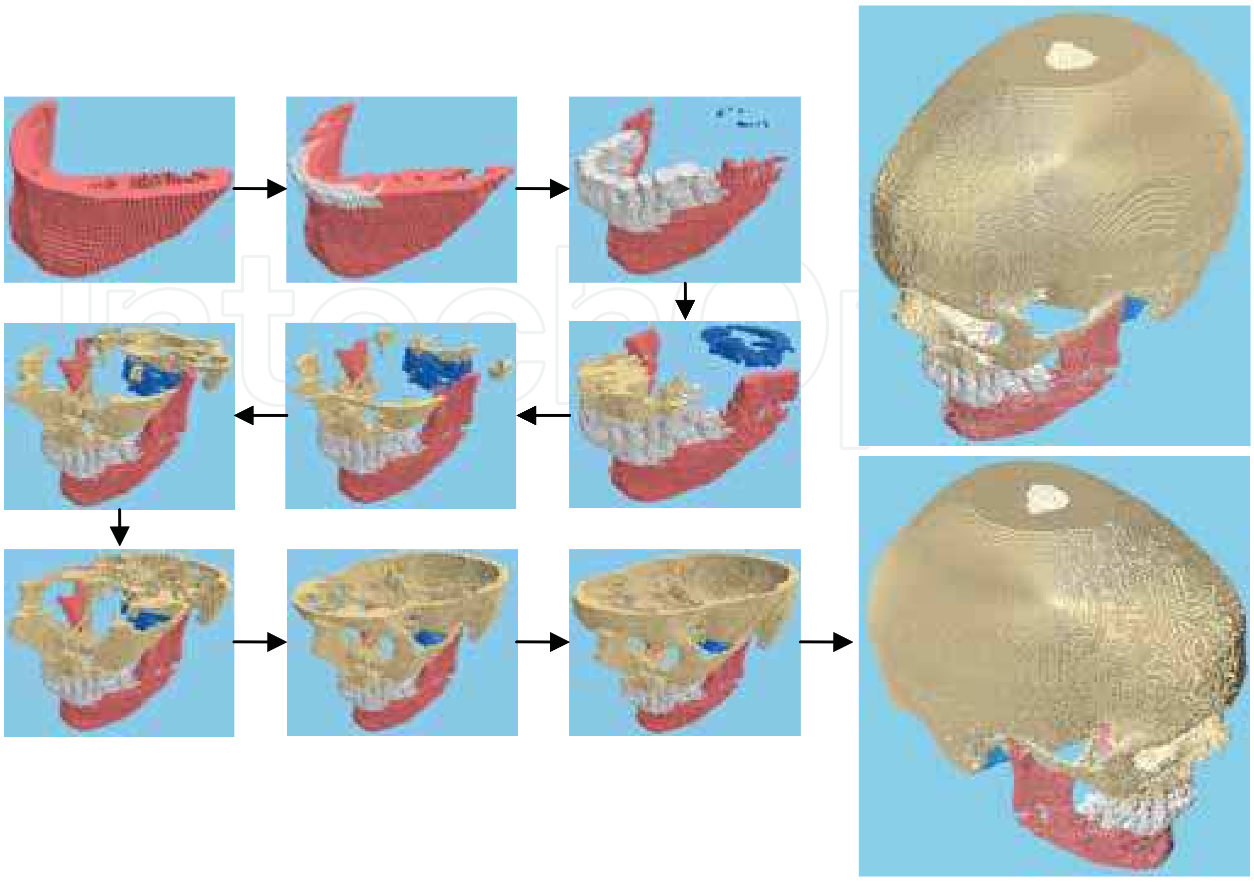


Fig. 7. Digital fabrication process of a human skull prototype

With the results of toolpath planning, a virtual prototyping system (Choi & Cheung, 2006b; 2008) is adopted to digitally fabricate the skull prototype for quality analysis through visualization in a VR environment, as shown in Figure 6. Figure 7 shows the digital fabrication process of a few layers of the skull. After fabrication, the resulting discrete multi-material skull prototype can be studied in a VR environment using the utilities provided to visualize the quality of the prototype that the MMLM machine will subsequently deliver. Besides, any dimensional deviations of the prototype beyond a tolerance limit can be identified by superimposing the colour STL skull model on its digital prototype. Therefore, using the DMMVP system, biomedical engineers can conveniently perform design iterations and quality analysis of the resulting prototype. Thus, an optimal combination of process parameters, such as layer thickness, build direction, and hatch space can be obtained for cost-effective fabrication of physical biomedical prototypes.

To repair or replace failing organs or tissues due to trauma or aging, biomedical prototypes may have to be made of functionally graded materials to mimic biological and mechanical characteristics of the organs or tissues. To achieve this, the proposed DMMVP system is enhanced to represent and fabricate FGM objects. The following section presents the FGMVP module for modelling and fabrication of FGM objects in detail.

2.2 The FGMVP module

The FGMVP module is used for modelling and fabrication of FGM objects. It is characterized by a contour-based FGM modeller, in which an FGM object is represented by material control functions and discretisation of layer contours with topological hierarchy.

Material control functions are specified across contour families of some representative layers in the X-Y plane and across layers along the Z-axis. The material composition at any location is calculated from control functions, and the slice contours are discredited into sub-regions of constant material composition. The discretisation resolution can be varied to suit display and fabrication requirements. Figure 8 shows the flow of the approach.

Firstly, it slices a monochrome STL model obtained from a traditional CAD design or digitized images, and sorts the resulting contours to build explicit topological hierarchy information.

Secondly, the contours are loaded into the FGMVP module for FGM object representation, with the following steps: (1) select a number of feature contour families in a representative layer; (2) specify control functions for material variations across layers along the Z-axis in the build direction; (3) specify control functions for material variations in the X-Y plane; and (4) discretise the slice contours into sub-regions of constant material composition.

Thirdly, the resulting contour-based FGM model containing both geometric and material composition variation information is processed for visualization, analysis, and fabrication of FGM objects.

In comparison with voxel-based representation schemes, this approach is computationally efficient and it requires little memory for processing relatively complex objects. More importantly, it facilitates physical fabrication on MMLM machines. The detail of the contour-based FGM modeller was presented in (Cheung, 2007; Choi & Cheung, 2009). In the

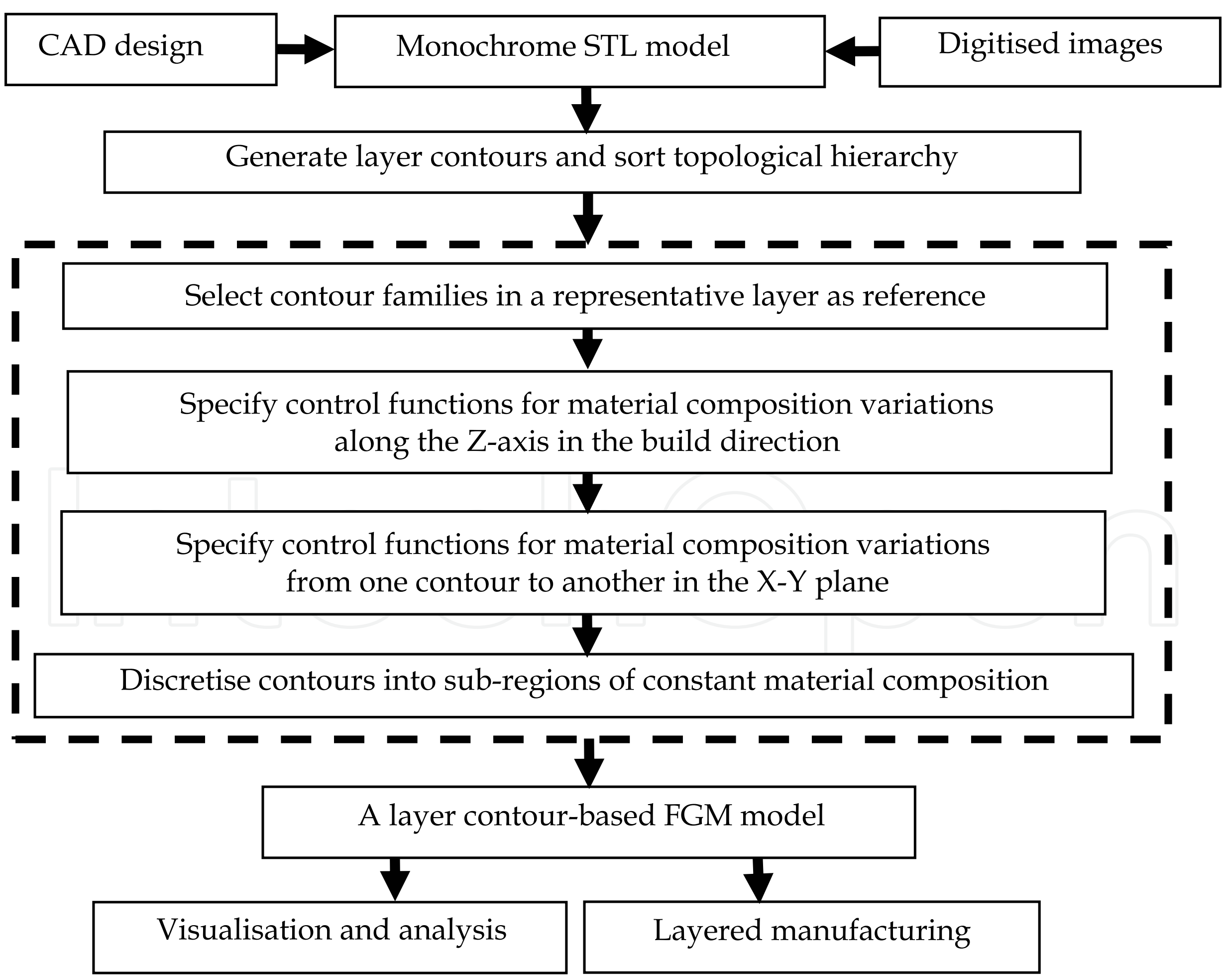


Fig. 8. The flow of processing FGM objects

following sections, a hip joint is processed to illustrate the use of the FGMVP module as a tool for design and fabrication of FGM biomedical objects.
Figure 9 shows an assembly of a prosthetic hip joint (Anné et al., 2005), which consists of three main components, including an acetabular cup, a femoral ball head, and a stem. Figure 10 shows a CAD model of the prosthesis assembly. While the fermoral ball head can be made of a single, mechanically tough material, such as titanium (Ti), the acetabular cup and the stem are preferably made of functionally graded materials to achieve desirable properties (Heida et al., 2005; España et al. 2010). The acetabular cup should have a biocompatible material at the outer surface and a mechanically tough material at the internal surface; the stem should have a biocompatible material at the lower region and a mechanically tough material at the upper region along the Z-axis. The following section

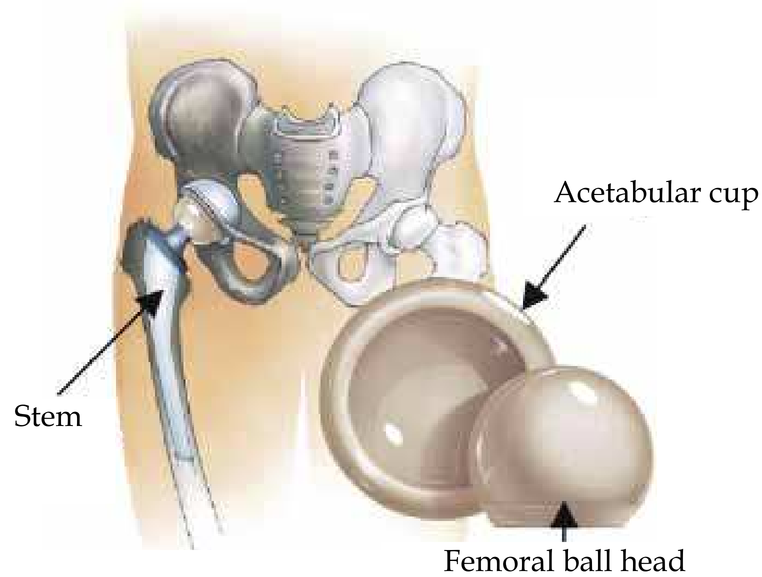


Fig. 9. An artificial joint for hip prosthesis (Anné et al., 2005)

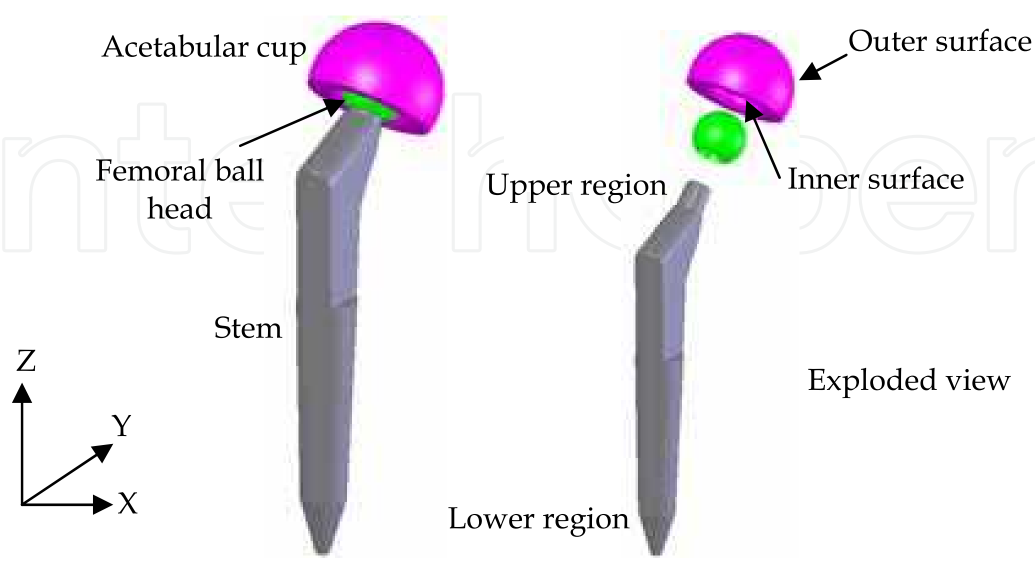


Fig. 10. Prosthesis assembly of an acetabular cup, a femoral ball head, and a stem for hip joint replacement

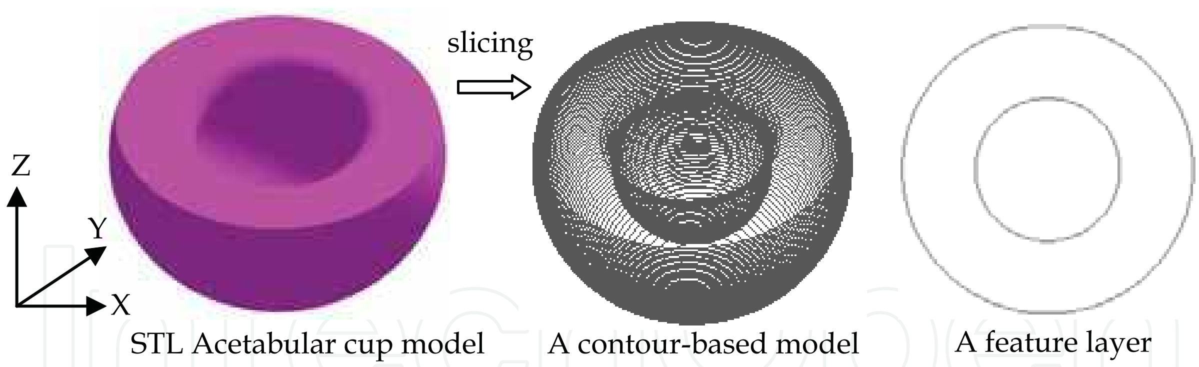


Fig. 11. Slicing an acetabular cup into a contour-based model; a feature layer is selected for assigning primary materials and material control functions

briefly demonstrates how the models of the acetabular cup and the stem are processed to represent material variations.

Using the FGMVP module, an STL model of the acetabular cup is firstly sliced into a contour-based model consisting of a number of layers, as shown in Figure 11; secondly, the topological hierarchy information of each layer is established, and a feature layer is selected for assigning primary materials and material control functions for calculation of property values of material composition; thirdly, each layer is discretised into sub-regions of constant material composition. Subsequently, the resulting geometric contours and material information are used for visualization and digital fabrication of the FGM acetabular cup prototype. Figure 12 shows a layer of the FGM acetabular cup prototype in wireframe and rendered displays, respectively. This layer has a purple/green graded variation in the X-Y plane to represent a gradual change of material composition from hydroxyapatite (HAP) at the outer surface to Ti at the inner surface, giving the desirable biocompatible properties at the surface and the desirable mechanical properties at the core of the acetabular cup. Moreover, the discretisation resolution can be easily changed accordingly to control the smoothness of material composition variations. Figure 13 shows a finer material composition variation compared with the one in Figure 12, and Figure 14 shows a contour-based FGM model of the acetabular cup from two perspectives. The digital fabrication process of an FGM acetabular cup prototype is shown in Figure 15. Therefore, the proposed FGMVP module is a practical tool for design of FGM objects and simulation of MMLM process for biomedical applications.

Similarly for the stem, its material composition changes gradually along the Z-axis from HAP at the bottom to Ti at the top, as shown in Figure 16. This variation can be represented by repeating the steps above.

2.3 The virtual reality simulation module

The DMMVP module and the FGMVP module above are integrated with a VR simulation module to form an MMVP system for modelling and digital fabrication of discrete and functionally graded multi-material objects for biomedical applications. The MMVP system provides a platform for stereoscopic visualization and analysis of digital fabrication process of multi-material objects in a VR environment (Choi & Cheung, 2005, 2006a; 2008). Through simulations, design validation and modification of a biomedical product can be iterated without incurring any manufacturing and material costs of physical prototyping. Therefore, the cost and time of product development can be reduced considerably.

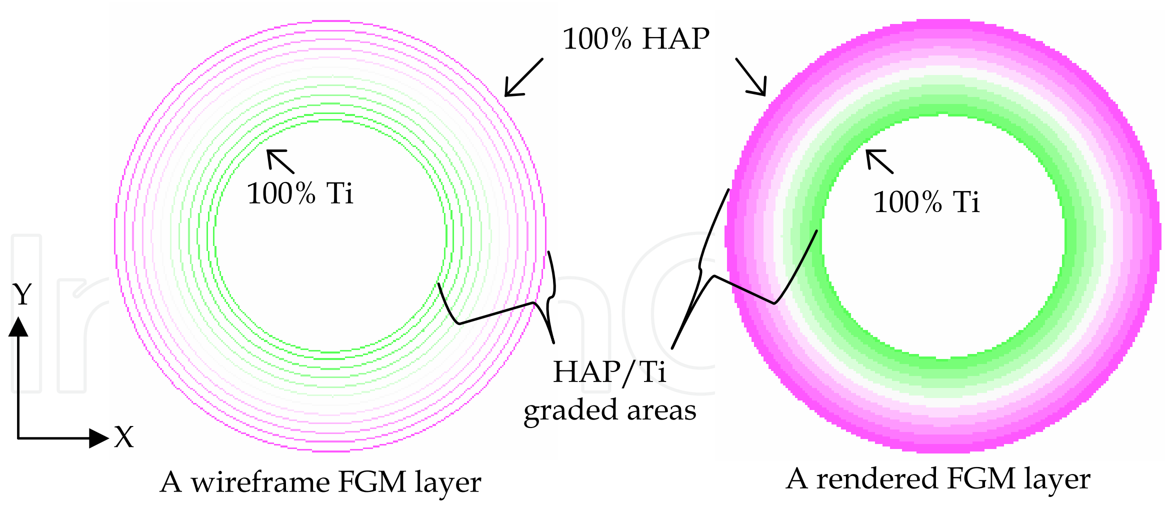


Fig. 12. The resulting FGM layer of the acetabular cup in Fig. 11

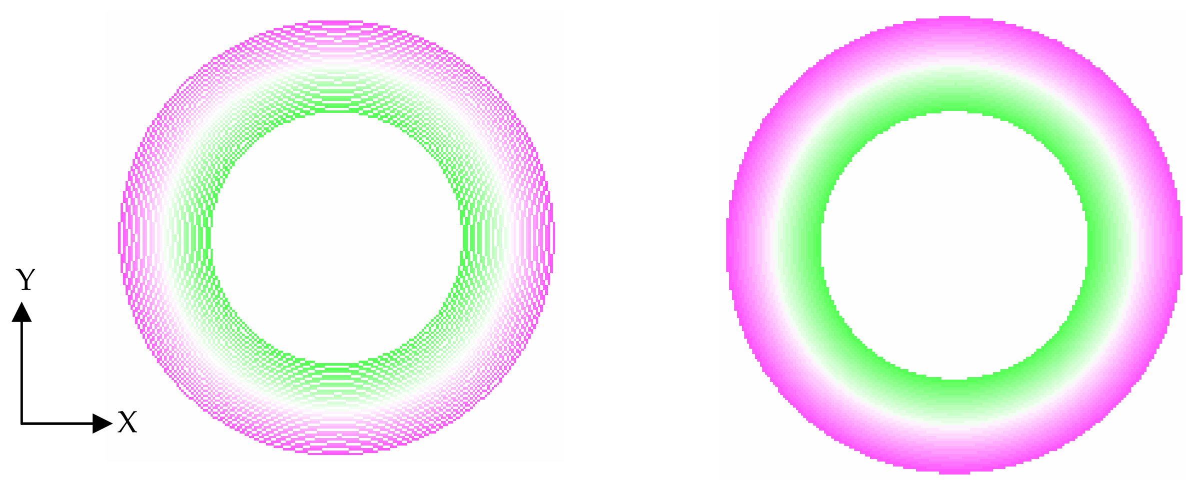


Fig. 13. A layer with a finer material composition variation

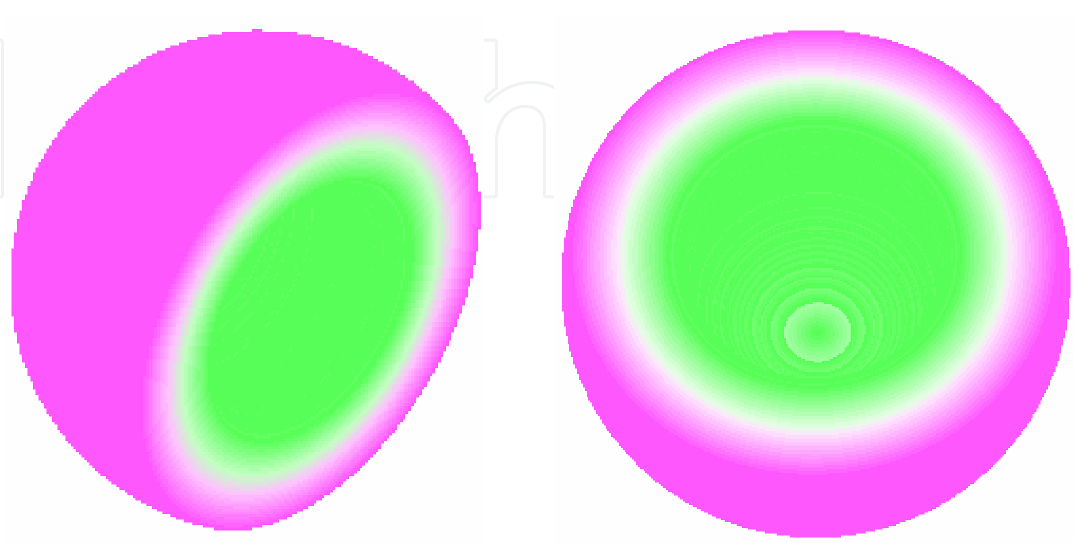


Fig. 14. A contour-based FGM model of the acetabular cup from two perspectives

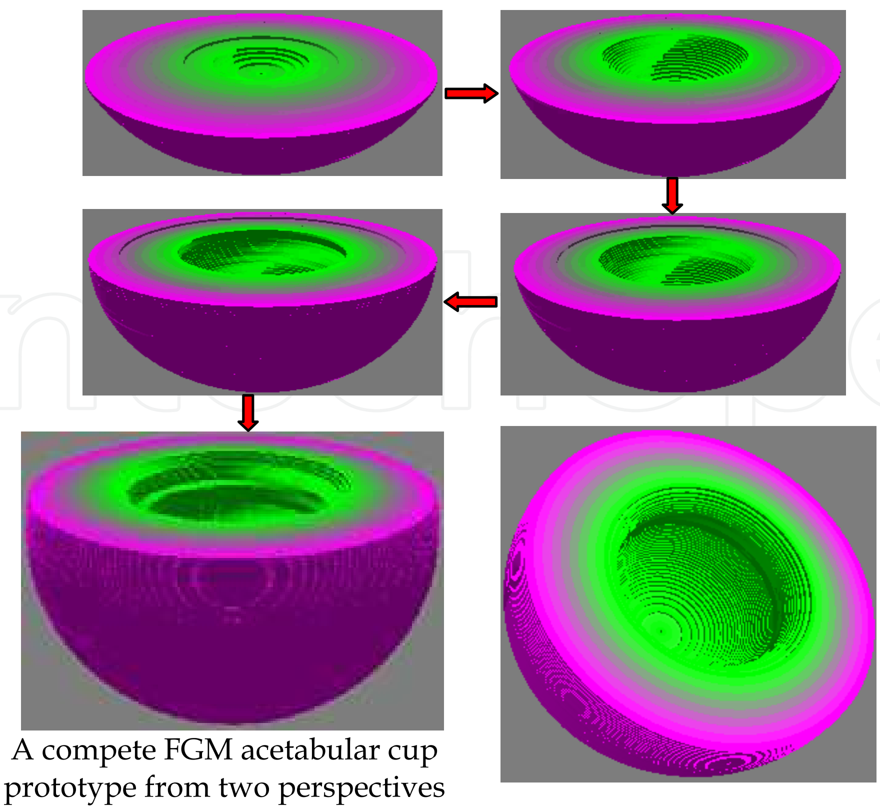


Fig. 15. Digital fabrication of an FGM acetabular cup prototype

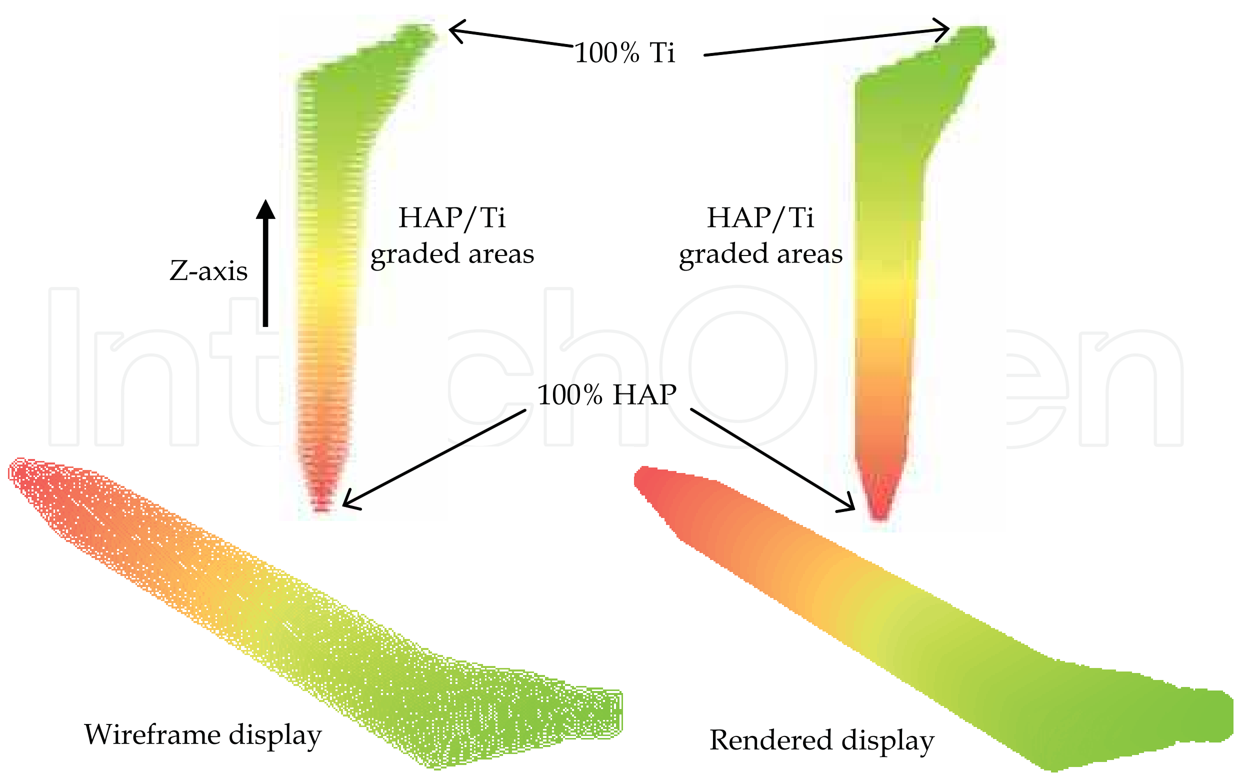


Fig. 16. A contour-based FGM model of the stem in wireframe and rendered displays

3. A case study

A functionally graded assembly for dental implant

In clinical surgery, it would be desirable to have dental implants made of functionally graded materials, such as Ti and HAP, to satisfy both mechanical and biocompatible properties. The MMVP system would be a practical tool for modelling and digital fabrication of functionally graded dental implants for such purposes.

Figure 17 shows a dental implant assembly consisting of a Ti abutment and a dental implant. To satisfy the desirable mechanical and biocompatible properties, the material composition of the dental implant is to change gradually from 100% HAP at z = 0 mm to 100% Ti at z = 15 mm along the Z-axis. The volume fraction for HAP, V_{HAP}, is expressed as

$$V_{HAP} = (\frac{L-z}{L})^{\alpha}, \qquad 0 \le z \le L \tag{1}$$

where L and z are the length of the dental implant and the height along the Z-axis, respectively; α is the volume fraction index.

The volume fraction for Ti, V_{Ti}, is thus denoted as

$$V_{Ti} = 1 - V_{HAP}. \tag{2}$$

With the FGMVP module, an STL model of a dental implant assembly, as shown in Figure 18, is sliced to obtain a contour-based model of 80 layers, for which the explicit topological hierarchy information is built accordingly. The first 56 layers comprise the dental implant, while the remaining layers belong to the abutment of a discrete material, Ti. The material composition of the dental implant changes from 100% HAP at the first layer to 100% Ti at the 56th layer along the Z-axis, controlled by Equations (1) and (2).

Hence, the lst layer contours and the 56th layer contours are selected as the two feature layers for assigning these primary materials and volume fraction equations to control the material composition of the dental implant. Figure 19 shows the resulting FGM dental implant assembly, with material variation represented by blending of red (100% HAP) and green (100% Ti) colours. Indeed, this approach can represent assemblies of both FGM and discrete materials conveniently.

The dental implant model now contains geometric and material information which can be conveniently processed for visualization, and inspection of internal material variation of each layer, multi-toolpath planning, and simulation of MMLM process. Figure 20 shows the process of digital fabrication of an FGM prototype of the dental implant assembly. The MMVP system can adjust the resolution of material composition to suit practical visualization and fabrication requirements, simply by changing the discretisation of layer contours, which is the number of layers in this case. It is therefore a practical tool for modelling and digital fabrication of biomedical objects with FGM and discrete materials.

To further demonstrate the capability of the proposed FGMVP module, it is used to design and process an artificial tooth as shown in Figure 21a, which is assumed to have material variations along the Z-axis and in the X-Y plane to mimic the desired properties of a human tooth.

A natural human tooth has material variations along various directions in order to achieve the desired properties. The enamel of a tooth can be regarded as a functionally graded natural biocomposite (He & Swain, 2009). The inner enamel has lower elastic modulus and

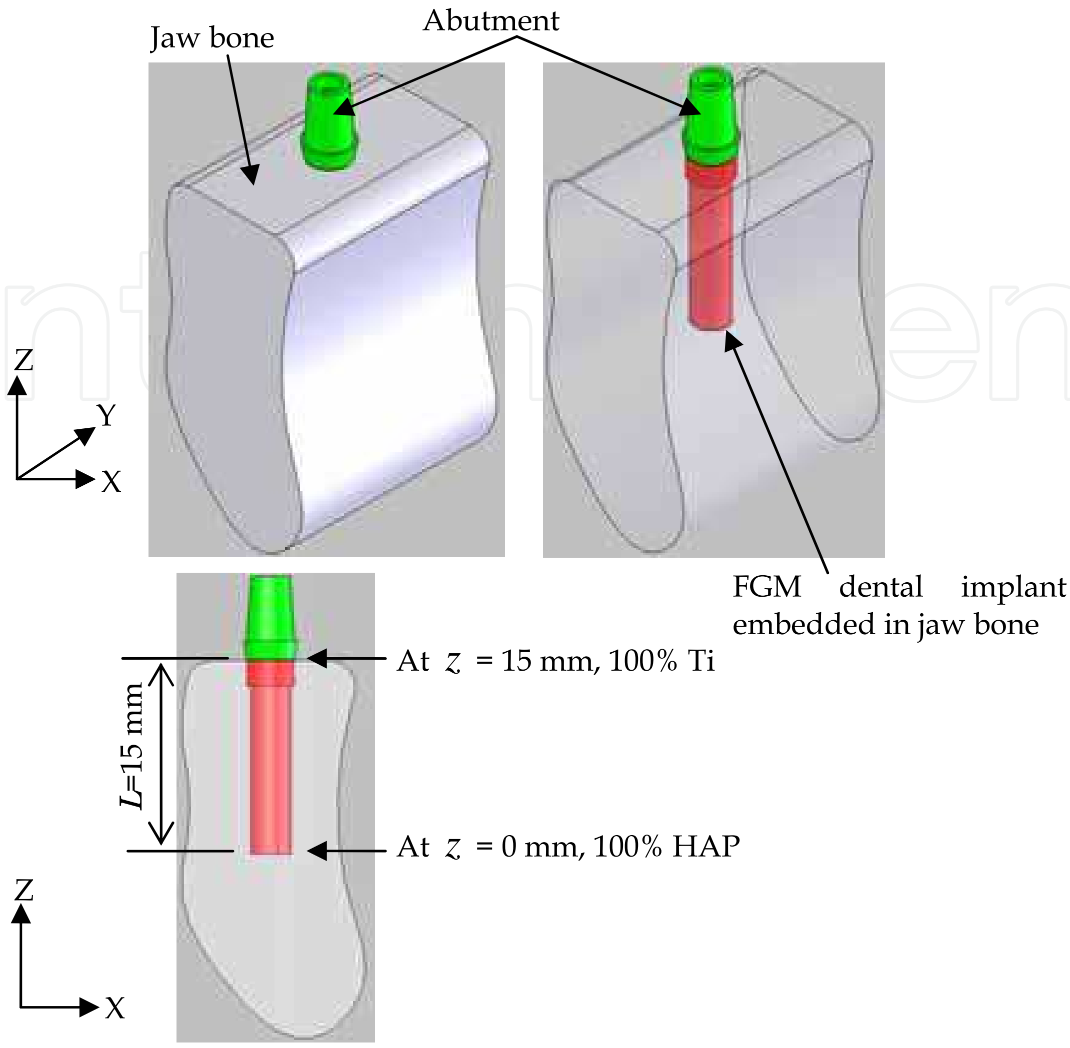


Fig. 17. A dental implant in a jaw bone

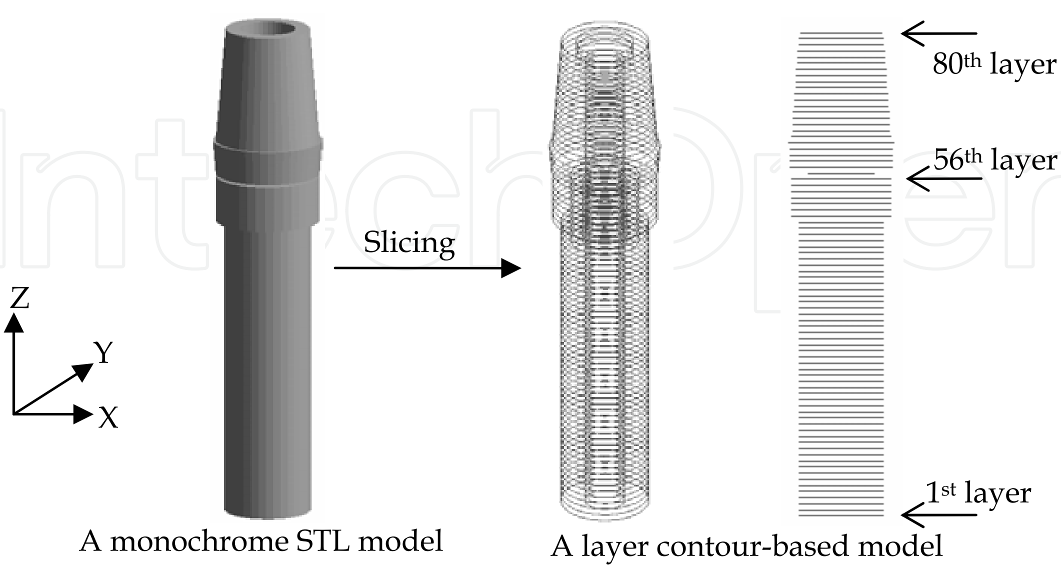
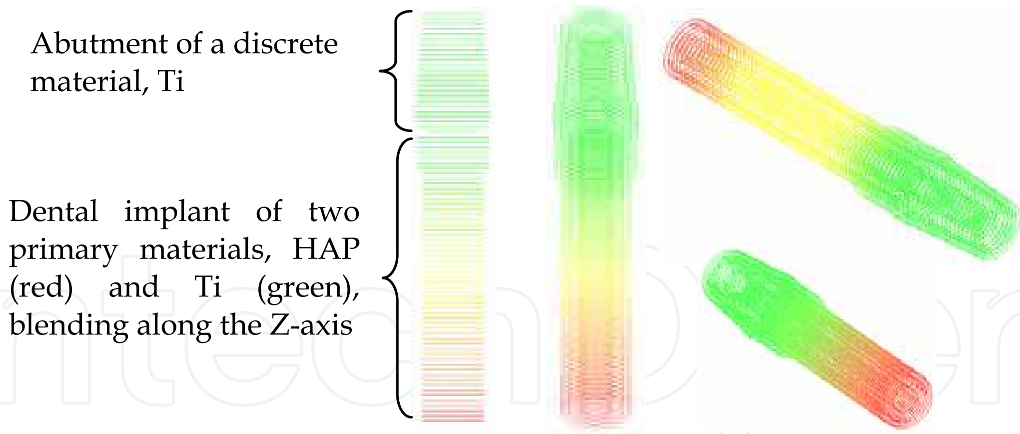
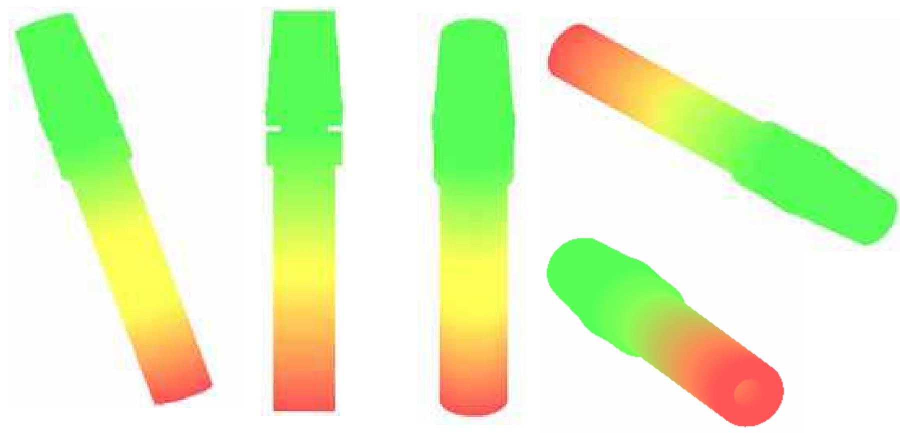


Fig. 18. Slicing an STL model of a dental implant assembly into a contour-based model for FGM modelling



(a) Wireframe display mode



(b) Rendered display mode from various perspectives

Fig. 19. Layer contour-based representation of an FGM dental implant assembly

hardness but higher creep and stress redistribution abilities than the outer counterpart, which is related to the gradual compositional change through the enamel.

The STL tooth model is firstly sliced as a layer-contour based model of 120 layers, as shown in Figure 21. Subsequently, material functions are associated with feature layers to control material variations. The resulting FGM tooth prototype with gradual material changes along Z-axis and in the X-Y plane is shown in Figure 22. Figure 23 shows the digital fabrication of an artificial FGM tooth.

4. Conclusion

This chapter presents a multi-material virtual prototyping (MMVP) system for modelling, process planning, and subsequent digital fabrication of discrete and functionally graded material objects. The MMVP system is characterised by its topological hierarchy-based toolpath planning algorithm and contour-based approach to representation of FGM objects. Case studies showed that the system can conveniently process CAD models and CT/MRI images to represent complex multi-material objects for biomedical and dental applications. It is computationally efficient and requires relatively little memory for processing complex objects. More importantly, it facilitates visualization of the resulting multi-material objects in a VR environment. The system may be adapted to control MMLM machines with appropriate hardware for physical fabrication of biomedical objects.

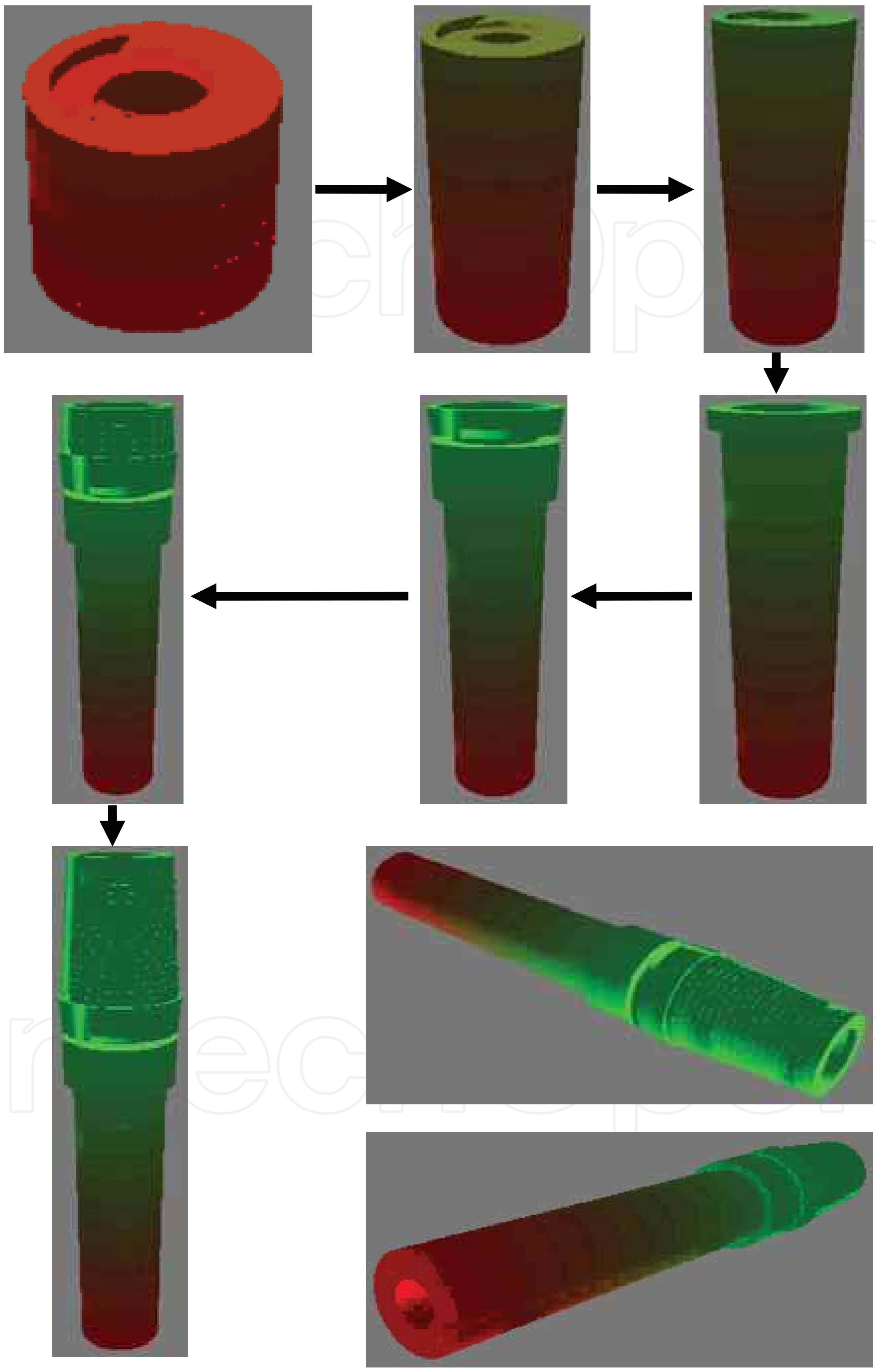
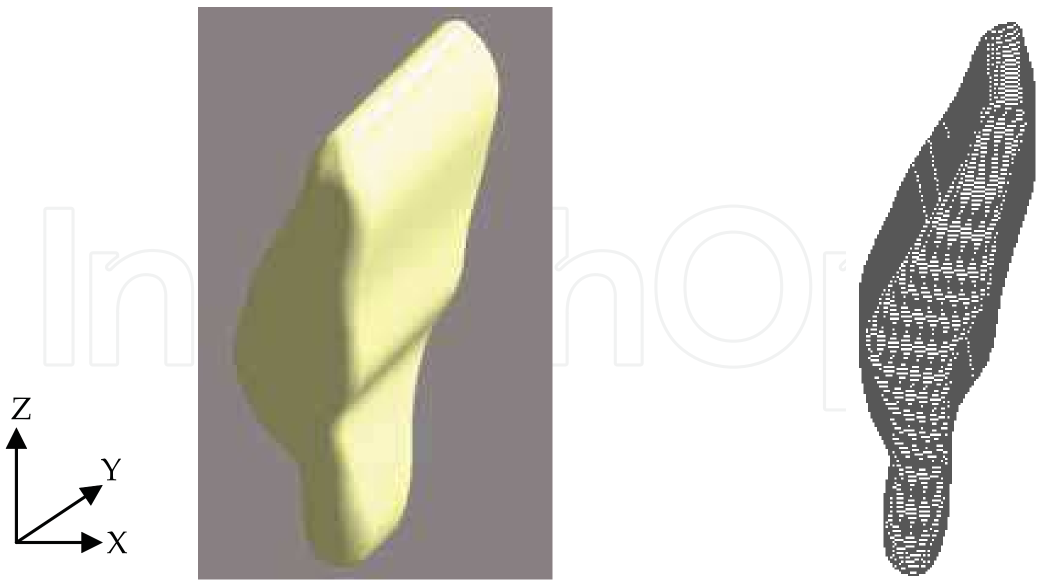


Fig. 20. Digital fabrication of a multi-material prototype of a dental implant assembly



(a) A monochrome STL tooth model (b) A homogeneous layer contour-based tooth model

Fig. 21. Slicing an STL model of a human tooth into a homogeneous contour-based model for FGM representation

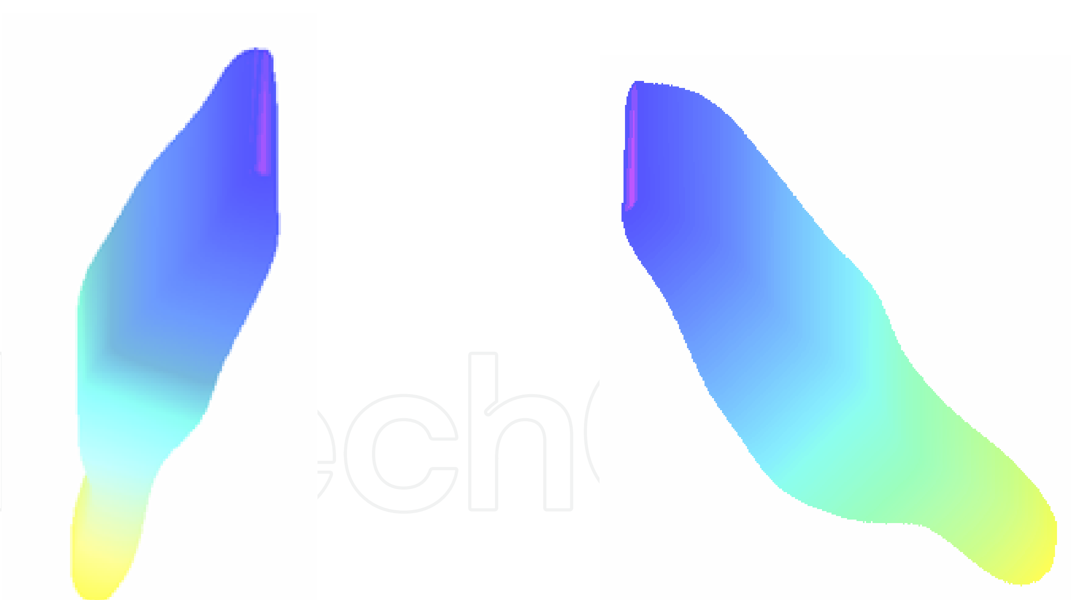


Fig. 22. An FGM tooth prototype from two perspectives

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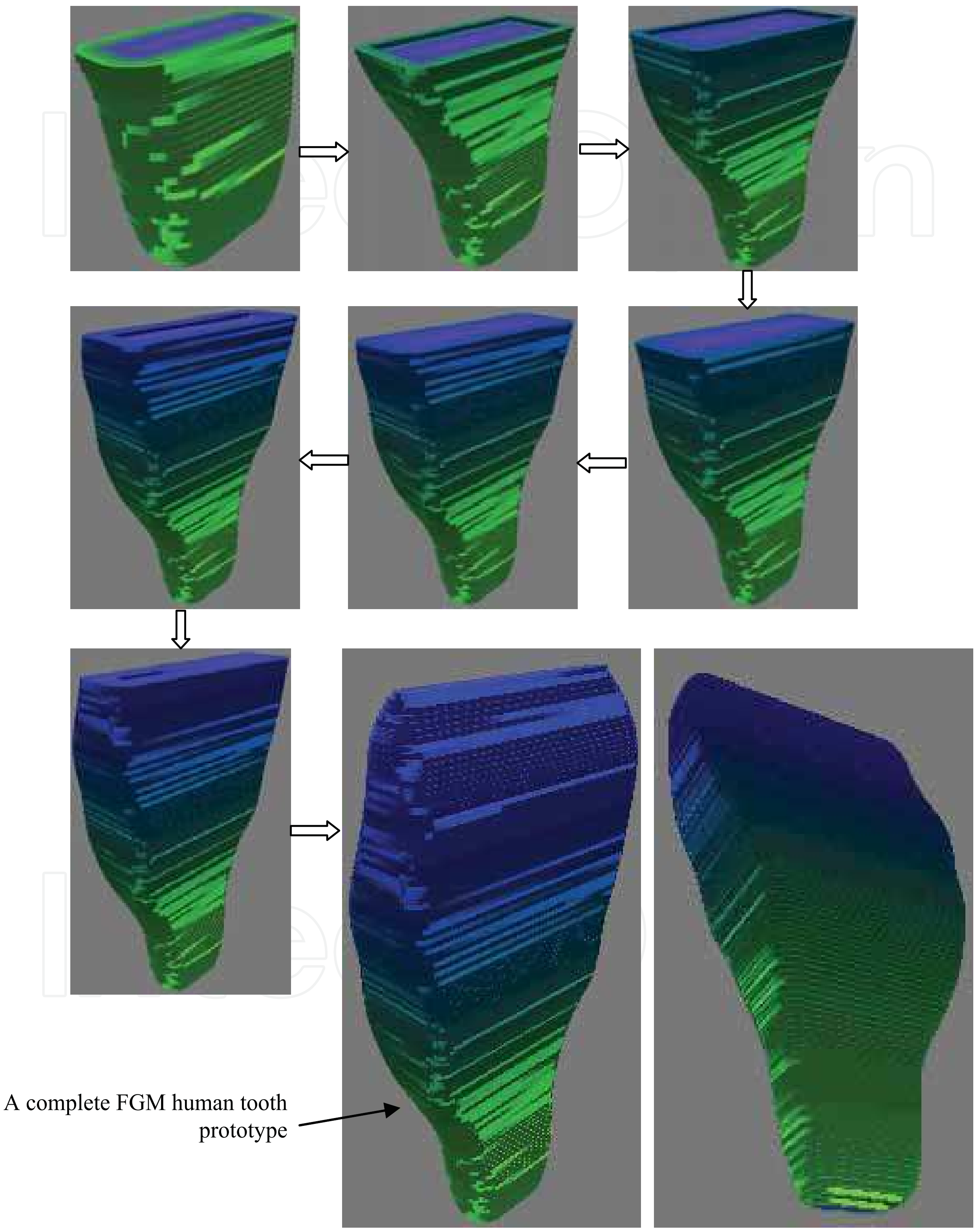


Fig. 23. Digital fabrication of an FGM human tooth

6. References

Anné, G.; Vanmeensel, K., Vleugels, J. & Biest, O.V.D. (2005). Electrophoretic deposition as a novel near net shaping technique for functionally graded biomaterials, In: *Biest, O.V. D., et al. (Eds.), The 8th International Symposium on Multifunctional and Functionally graded Materials (FGM 2004)*, pp. 213-218. Leuven, Belgium, July 11-14, 2004.

Cheng, T.H. & Langrana, N.A. (2001). A system approach in extrusion-based multi-material CAD, In: *Bourell, D.L., et al., (Eds.), Solid Freeform Fabrication Symposium*, pp. 313-321. Austin, Texas, The University of Texas.

Cheung, H.H. (2007). A versatile multi-material virtual prototyping system. *Ph.D. Thesis*. The University of Hong Kong, Hong Kong.

Chiu, W.K. & Tan, S.T. (2000). Multiple material objects: from CAD representation to data format for rapid prototyping. *Computer-Aided Design*, Vol.32, No.12, 707-717.

Cho, W.J., Sachs, E.M., Patrikalakis, E.M. & Troxel, D.E. (2003). A dithering algorithm for local composition control with three-dimensional printing. *Computer-Aided Design*, Vol.35, No.9, 851-867.

Choi, S.H. & Cheung, H.H. (2005). A multi-material virtual prototyping system. *Computer-Aided Design*, Vol.37, No.1, 123-136.

Choi, S.H. & Cheung, H.H. (2006a). A topological hierarchy-based approach to toolpath planning for multi-material layered manufacturing. *Computer-Aided Design*, Vol.38, No.2, 143-156.

Choi, S.H. & Cheung, H.H. (2006b). A CAVE-based multi-material virtual prototyping system. *Computer-Aided Design and Applications*, Vol.3, No.5, 557-566.

Choi, S.H. & Cheung H.H. (2008). A versatile virtual prototyping system for rapid product development. *Computers in Industry*, Vol.59, No.5, 477-488.

Choi, S.H. & Cheung, H.H. (2009). A topological hierarchy-based approach to layered manufacturing of functionally graded multi-material objects. *Computers in Industry*, Vol.60, No.5, 349-363.

España, F.A., Balla, V.K., Bose, S. & Bandyopadhyay, A. (2010). Design and fabrication of CoCrMo alloy based novel structures for load bearing implants using laser engineered net shaping. *Materials Science and Engineering C*, Vol.30, No.1, 50-57.

Fessler, J.R., Nickel, A.H., Link, G.R., Prinz, F.B. & Fussell, P. (1997) Functional gradient metallic prototypes through shape deposition manufacturing, In: *Bourell, D.L., et al. (Eds.), Solid Freeform Fabrication Symposium*, pp. 521-528. Austin, Texas, The University of Texas.

He, L.H. & Swain M.V. (2009). Enamel – a functionally graded natural coating. *Journal of Dentistry*, Vol.37, No.8, 596-603.

Hedia, H.S., EI-Midany, T.T., Shabara, M.A.N. & Fouda, N. (2005). Development of cementless metal-backed acetabular cup prosthesis using functionally graded material. *International Journal of Mechanics and Materials in Design*, Vol.2, No.3-4, 259-267.

Hsieh, C.T. & Langrana, N.A. (2001). A system approach in extrusion-based multi-material CAD, In: *Bourell, D.L., el al., (Eds.), Solid Freeform Fabrication Symposium*, pp. 313-321. Austin, Texas, The University of Texas.

Jackson, T.R., Liu, H., Patrikalakis, N.M., Sachs, E.m. & Cima, M.J. (1999). Modelling and designing functionally graded material components for fabrication with local composition control. *Materials & Design*, Vol.20, No.2-3, 63-75.

Jackson, T.R. (2000). Analysis of functionally graded material object representation methods. *Ph.D. Thesis*. Massachusetts Institute of Technology, USA.

Jafari, M.A. & Han, W. (2000). Mohammadi, F., Safari, A., Danforth, S.C., Langrana, N.: A novel system for fused deposition of advanced multiple ceramics. *Rapid Prototyping Journal*, Vol.6, No.3, 161-175.

Jepson, J., Beaman, J.J., Bourell, D.L. & Wood, K.L. (1997). SLS processing of functionally gradient materials, In: *Bourell, D.L., et al. (Eds.), Solid Freeform Fabrication Symposium*, pp. 1-8. Austin, Texas. The University of Texas.

Kou, X.Y. (2005). Computer-Aided design of heterogeneous objects. *Ph.D. Thesis*. The University of Hong Kong, Hong Kong.

Kou, X.Y. & Tan, S.T. (2005). A hierarchical representation for heterogeneous object modelling. *Computer-Aided Design*, Vol.37, No.3, 307-319.

Kou, X.Y., Tan, S.T. & Sze, W.S. (2006). Modelling complex heterogeneous objects with non-manifold heterogeneous cells. *Computer-Aided Design*, Vol.38, No.5, 457-474.

Kou, X.Y. & Tan, S.T. (2007). Heterogeneous object modelling: a review. *Computer-Aided Design*, Vol.39, No.4, 284-301.

Kumar, V., Rajagopalan, S., Cutkosky, M. & Dutta, D. (1998). Representation and processing heterogeneous objects for solid freeform fabrication. *The 6th IFIP WG 5.2 International Workshop on Geometric Modelling: Fundamentals and Applications*. Tokyo, Japan. The University of Tokyo, 1998.

Kumar, V. (1999). Solid modelling and algorithms for heterogeneous objects. *Ph.D. Thesis*. The University of Michigan, USA.

Lappo, K., Jackson, B., Wood, K., Bourell, D.L. & Beaman, J.J. (2003). Discrete multiple material selective laser sintering (M^2SLS): experimental study of part processing, In: *Bourell, D.L., et al. (Eds.), Solid Freeform Fabrication Symposium*, pp. 109-119. Austin, Texas, The University of Texas.

Merz, R., Prinz, F.B., Ramaswami, K., Terk, M. & Weiss, L.E. (1994). Shape deposition manufacturing, In: *Bourell, D.L., et al. (Eds.), Solid Freeform Fabrication Symposium*, pp. 1-8. Austin, Texas, The University of Texas.

Morvan, S.M. & Fadel, G.M. (1999). Heterogeneous solids: possible representation schemes. In: *Bourell, D.L., et al., (Eds.), Solid Freeform Fabrication Symposium*, pp. 187-198. Austin, Texas, The University of Texa.

Samanta, K. & Koc, B. (2005). Feature-based design and material blending for free-form heterogeneous object modelling. *Computer-Aided Design*, Vol.37, No.3, 287-305.

Shin, K.H. & Dutta, D. (2001). Constructive representation of heterogeneous objects. *Journal of Computing and Information Science in Engineering*, Vol.1, No.3, 205-217.

Shin, K.H. (2002). Representation and process planning for layered manufacturing of heterogeneous objects. *Ph.D. Thesis*. The University of Michigan, USA (2002).

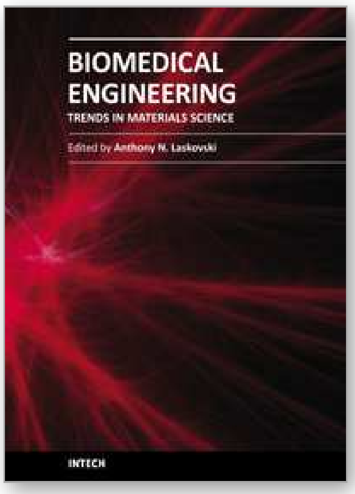
Sun, W., Starly, B., Nam, J. & Darling, A. (2005). Bio-CAD modelling and its applications in Computer-aided tissue engineering. *Computer-Aided Design*, Vol.37, No.11, 1097-111.

Wang, F., Shor, L., Darling, A., Khalil, S., Sun, W., Gűçeri, S. & Lau, A. (2004). Precision extruding deposition and characterization of cellular poly-ε-caprolactone tissue scaffolds. *Rapid Prototyping Journal*, Vol.10, No.1, 420-429.

Wang, J.W. & Shaw, L.L. (2006). Fabrication of functionally graded materials via inkjet colour printing. *Journal of the American Ceramic Society*, Vol.89, No.10, 3285-3289.

Watari, F., Yokoyama, A., Saso, F., Uo, M. & Kawasaki, T. (1997). Fabrication and properties of functionally graded dental implant. *Composites Part B*, Vol.28B, 5-11.

Zeng, W., Ruan, F. & Zhou, T. (2008). Fused deposition modelling of an auricle framework for microtia reconstruction based on CT images. *Rapid Prototyping Journal*, Vol.14, No.5, 280-284.



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Rapid technological developments in the last century have brought the field of biomedical engineering into a totally new realm. Breakthroughs in materials science, imaging, electronics and, more recently, the information age have improved our understanding of the human body. As a result, the field of biomedical engineering is thriving, with innovations that aim to improve the quality and reduce the cost of medical care. This book is the second in a series of three that will present recent trends in biomedical engineering, with a particular focus on materials science in biomedical engineering, including developments in alloys, nanomaterials and polymer technologies.