Image Based Bio-CAD Modeling and Its Applications to Biomedical and Tissue Engineering

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Abstract

CAD has been traditionally used to assist in engineering design and modeling for representation, analysis and manufacturing. Advances in Information Technology and in Biomedicine have created new uses for CAD with many novel and important biomedical applications, particularly in tissue engineering in which the CAD based bio-tissue informatics model provides critical information of tissue biological, biophysical, and biochemical properties for modeling, design, and fabrication of complex tissue substitutes. This paper will present some salient advances of bio-CAD modeling and application in computer-aided tissue engineering, including biomimetic design, analysis, simulation and freeform fabrication of tissue engineered substitutes. Overview of computer-aided tissue engineering will be given. Methodology to generate bio-CAD modeling from high resolution non-invasive imaging, the medical imaging process and the 3D reconstruction technique will be described. Enabling state-of-the-art computer program in assisting the 3D reconstruction and in bio-modeling development will be introduced. Utilization of the bio-CAD model for the description and representation of the morphology, heterogeneity, and organizational structure of tissue anatomy will also be presented.

Categories and Subject Descriptors: CAD, Biomodeling, Tissue Engineering

1. Introduction

Recent advances in computing technologies both in terms of hardware and software have helped in the advancement of CAD in applications beyond that of traditional design and analysis. CAD is now being used extensively in the biomedical industry in applications ranging from clinical medicine, customized medical implant design to tissue engineering [HLC*00, SDS*04, LS04]. This has largely been made possible due to developments made in imaging technologies and reverse engineering techniques supported equally by both hardware and software technology advancements[KEP75, BCL96, MD96]. The primary imaging modalities that are made use of in different application include, CT/MRI, optical microscopy, micro CT, etc. each with its own advantages and limitations as described in [SDS04]. Using data derived from these images, computer models of human joints for stress analysis, dynamic force analysis and simulation; design of implants and scaffolds etc. have been reported in published literature [MMY94, TC03]. This effort to model human body parts in a CAD based virtual environment is also referred to as Bio-CAD modeling. This is a key first step in the field of computer aided tissue engineering [LS04, SDS04] which involves the application of enabling computer-aided technologies, including computer-aided design (CAD), image processing, computer-aided manufacturing (CAM), and rapid prototyping (RP) and/or solid freeform fabrication (SFF) for modeling, designing, simulation, and manufacturing of biological tissue and organ substitutes. An overview of the CATE approach is described in Figure 1. Specifically, CATE encompasses the following three major applications in tissue engineering: 1) computer-aided tissue modeling; 2) computer-aided tissue informatics; and 3) computer-aided tissue scaffold design and manufacturing. In this respect, Bio-CAD models are necessary for the field of Computer aided tissue scaffold fabrication since the outer shape of the scaffold is determined from the CAD model structure.

Several studies have been reported in literature that has made use of 3D reconstruction steps to help in a better understanding of anatomical functionality and morphological analysis. [HLC*00, MBB*03, HCM03]. All of the above literature focus more on the application of these image based techniques and less on the actual steps involved in the process. Up-to-date there has been no reported work focused on the different methods through which a CAD model is generated from image based data. This could be attributed to the fact that CAD models were not necessary for the different applications image based modeling was used for. However, with the growth in the field of tissue engineering and customized medical implant design, this has called for the need of Bio-CAD models to perform advanced modeling and analysis. These image based technologies can be used in the design and fabrication of biomimetic tissue scaffolds [SLF*03] since obtaining the outer architecture is critical to successful implantation of these scaffolds.

In this paper, we have described in detail methods by which CAD models can be obtained from CT/MRI images through a number of different process paths. The following section describes these process paths to follow in the generation of CAD models from CT/MRI images specifically for the medical prototyping industry and tissue engineering applications. They are 1) MedCAD interface path; 2) Reverse Engineering path; 3) STL interface method. The case study selected demonstrates the ability and advantages of different process paths in the generation of tissue and bone morphologies. The third section details the applications for Bio-CAD modeling and specifically on how it fits in the tissue engineering scenario. This is followed by a summary of the work that has been described in the paper.

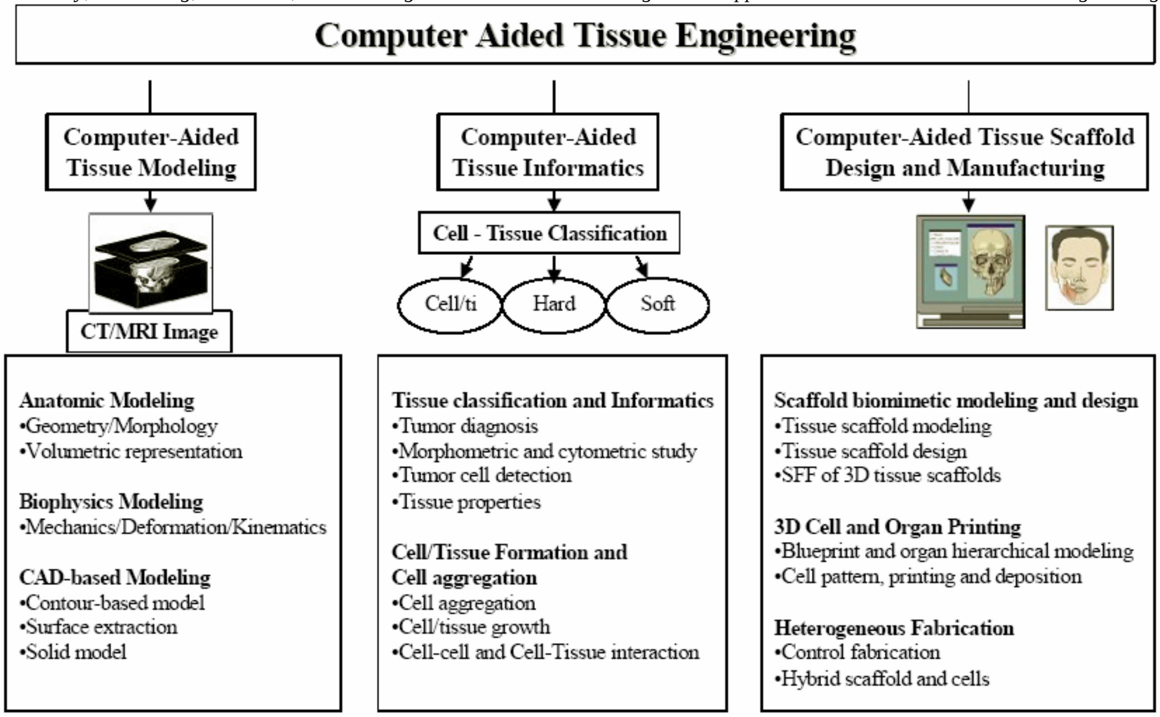


Figure 1: Overview of Computer Aided Tissue Engineering [SL02]

2. Image Based CAD Modeling

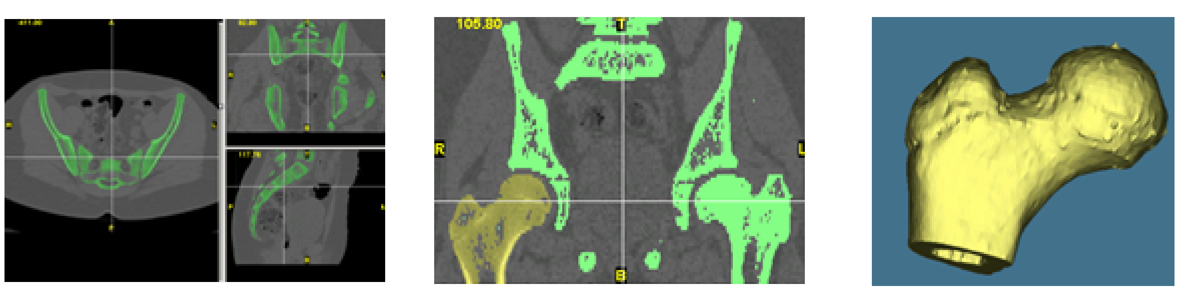
The image-based CAD design approach begins with the acquisition of noninvasive images and its subsequent processing of appropriate bone region of interest. This is followed by a three-dimensional reconstruction of anatomical structure using commercially available medical reconstructive and reverse engineering software (MIMICS, MIM02] and Geomagics [GEO02]). We have defined here the following steps in the CAD generation process.

Step 1: Image Acquisition, Processing and 3-D reconstruction

Our region of study involved the CT images obtained from that of a proximal femur bone of a small child. In all, 34 slice images were obtained each of 2mm sliced segmentation for a height of 68mm of the proximal femur bone. Once loaded into the software, all images were properly registered and aligned for its orientations. Next, the region of interest was identified and a 3D voxel model of the bone under study had to be made. As a first step, an appropriate threshold range was found that could best capture the relevant information contained in the femur. Using this threshold value, all pixels within this range were grown to a color mask and hence the segmentation process achieved by making use of region growing techniques available in the software. This color mask acts as the input to the 3-D reconstruction process. The process is depicted in Figure 2.

Step 2: Reverse Engineering Based CAD model generation

A reverse engineering approach that converts 3D reconstructive image data to a NURBS-based CAD model is developed. We have evaluated and compared three different process paths for generating a CAD model from MRI/CT data as shown in Figure 3. The comparison and comments of these three paths are also listed in Table 1.



a) CT images are loaded into and properly registered for their alignment with respect to image orientations.

b) Region of Interest (ROI) is identified and given an appropriate differentiating color mask.

c) A Three dimensional voxel reconstruction of the segmented images

Figure 2: Image Registration, 2-D segmentation, 3-D reconstruction process

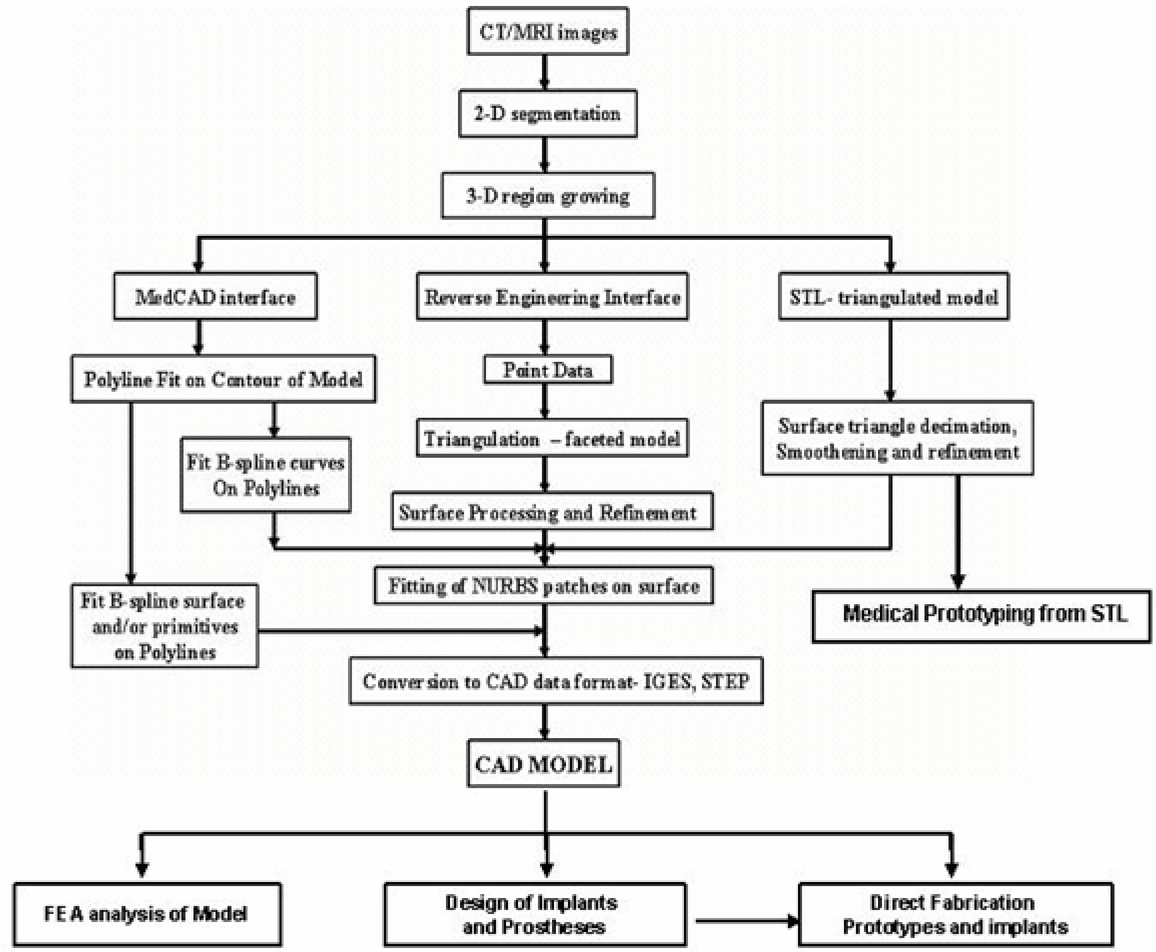


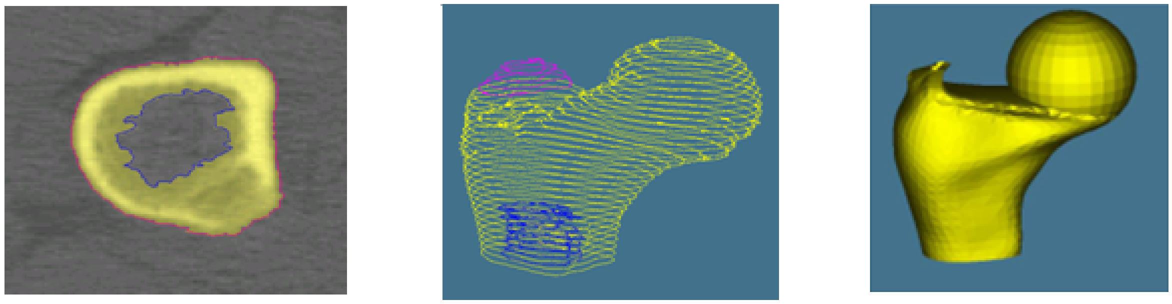
Figure 3: Process Definition to arrive at a CAD model from CT/MRI data

Process Path 1: MedCAD interface

This interface bridges the gap between medical imaging and CAD design software. This means that the interface can export data from the imaging system to the CAD platform and vice versa. The International Graphics Exchange Standard (IGES) format or the Standard for Exchange of Product (STEP) model can be used for models to be exported to CAD and the STL format used to import models from CAD to the MedCAD system interface. The interface provides for the fitting of primitives such as cylinders, planes, spheres etc on the CT image slices. It also provides us with the ability to model freeform shapes using B-spline surfaces. In our example, we have used both primitives and freeform shapes to model the femur bone. The process is as shown as follows in Figure 4. It is important to realize that not all features or details of the image can be exported to CAD due to the limitation of this interface, particularly for features with complex geometry. Most likely if surface models are generated, then they need to be closed if a solid model is desired.

Process Path 2: Reverse Engineering Method

The 3D voxel model created after segmentation is used as the starting point for this method. The 3D voxel dataset of the bone structure is converted to point data form and then these points are loaded into any reverse engineering software. Commercially available software Geomagic Studios (Raindrop Inc) [GEO02] are then used to process these data points for surface processing and refinement. This is perhaps the best approach that can be followed since the process starts from the base level, i.e., points. The imported points first needs to be cleaned of noise points and decimation of points maybe necessary depending on the number of points. The points are then triangulated to form a faceted model. Further surface refining and enhancement (Figure 5(c)-5(d)) is required to reduce file sizes and unwanted features maybe removed at this stage. To generate out the CAD model, it is necessary to model the bone using freeform surfaces. Figure 5(e)-5(f) show NURBS patches used to fit across the outer shape of the model. Although the process did have a comparatively longer processing time, the results obtained are significantly better than the other two methods. The CAD model is much more aesthetic and stable in configuration. The process when started from this level also reduces the error in data transfer formats and can reduce complication arising in CAD FEA analysis such as during the meshing stage.

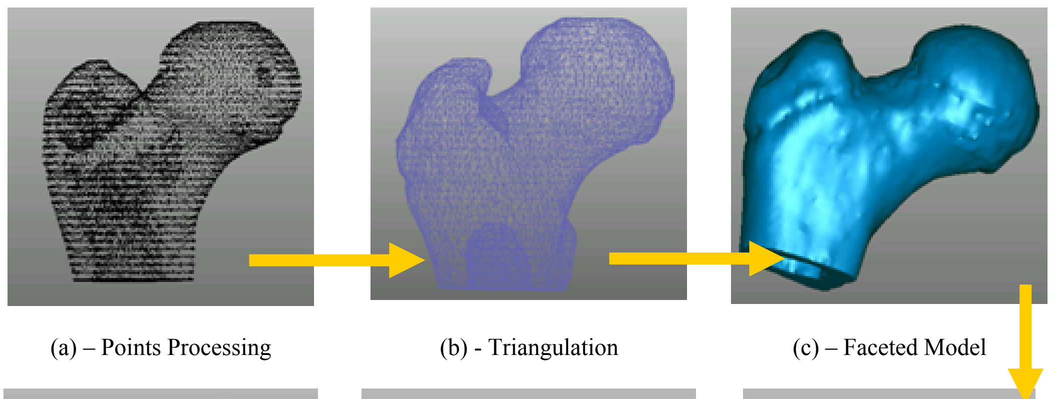


a) Polylines contours used to demarcate boundary regions

b) Polylines are grown through the segmented images

c) B-spline surfaces and primitives (sphere) used to construct surface model.

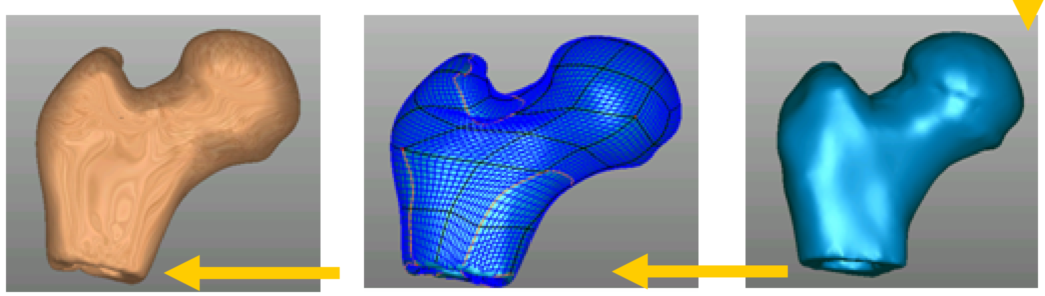
Figure 4: Surface Model reconstruction using MedCAD interface



(a) – Points Processing

(b) - Triangulation

(c) – Faceted Model



(f)– NURBS fit (CAD)

(e) – Grid Generation

(d)–Surface Cleaning

Figure 5: From Points to CAD

Process Path 3: The STL interface.

The 3D voxel model can also be converted to the STL file and this STL file can then be imported into Geomagics for surface refinement and NURBS surface generation. The difference between this and the point data method is that here a triangulated model is the input format rather than in point data form. The process time involved is less but may suit for only certain kinds of surfaces. This interface is more or less used when rapid prototypes of the desired medical component are so desired. It must be noted that this process is however not fool proof in conversion to CAD due to the inherent defects present in the STL representation. As seen in the Figure 6, the CAD model of the femur bone did not fully reconstruct well. This can however be corrected, if the surface is refined, leading to more triangle counts and hence bigger file sizes. This may not be an economical approach in the generation of CAD models; however for certain models that do not involve complicated features, this approach do present another option to generate CAD models.

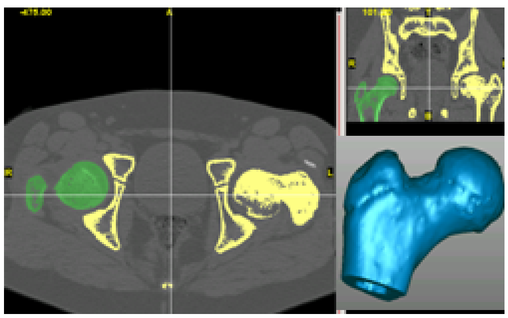
As can be seen from Table 1, the second approach seems to the best but however this can vary with model shapes and applications. The first method would generally be preferred when surface models are required because they provide the easiest approach to surface generations. The second approach, the reverse engineering based method is suitable for models if they need to be meshed provided a stable and accurate data transfer format is supported such as STEP or IGES. The third process is suitable when medical rapid prototypes need to be made since the .STL format remains to be the industry standard for medical rapid prototyping.

3. Applications for Bio-CAD modeling

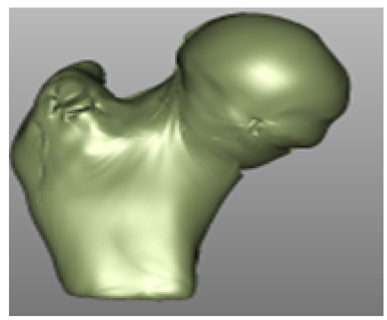
Once CAD models are generated and saved in an IGES or STEP format, these then can be used for a variety of other different design applications. For example, the reconstructed femur bone can be used to design patient specific hip implants using CAD

Table 1: Process Comparison – Conversion from CT/MRI images to CAD of the proximal femur

Process	Qualities	File Size Comparisons	Overall
MEDCAD	Easiest and quickest, but may not be suitable for complex models.	Doesnot involve huge file sizes and only involves the IGES conversion process time. IGES : 266KB	Poor
Reverse Engineering	A longer process but suitable for complex shapes since control is achieved at every level.	Initial file sizes in the point form are not high but final CAD model may involve comparatively higher file sizes. Point : 256KB (7732points) IGES : 266KB (102 NURBS patches)	Best
STL method	Quick method to arrive at a CAD Model but may not work if triangulated surfaces contain errors.	Initial STL file size maybe high resulting in more CAD model IGES file size. STL : 1.82 MB (38252 triangles) IGES : 9.83MB (2316 NURBS patches)	Average



a) Voxel model converted to STL based models.



b) Improper reconstruction from STL based models.

Figure 6: Conversion from Voxel Model to CAD model via STL interface

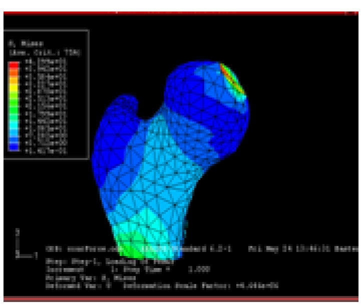


Figure 7(a) FEA analysis of Femur

Figure 7(b): Dynamic analysis of hind foot

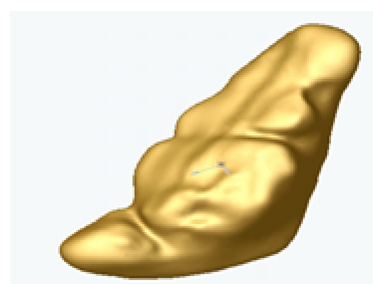


Figure 7(c): Sinus graft model designed with the help of CAD

software. These CAD models can also be used for FEA or dynamic force analysis using CAD based software. Fig 7(a) depicts a stress analysis performed on the femur bone using FEA software ABAQUS and Fig 7(b) gives an example to show how the CAD model of the hind foot reconstructed from CT/MRI images was used for dynamic force analysis using ADAMS. Fig 7(c) displays a sinus graft model that was designed based on CAD model reconstructions of the sinus region. All of these models were generated starting from points to NURBS surfaces followed using the reverse engineering approach.

Bone tissue scaffolds need to have certain characteristics of their own in order to function as a true bone substitute that satisfies the biological, mechanical and geometrical constraints [SSD*04, SLS*03]. The approach presented here addresses the third requirement of anatomical fitting since the bone scaffold to be made is reconstructed from CT/MRI images of the area that needs to be filled. Example of how a basic unit cell was intersected within Geomagics software with a bone structure that needs to be replaced to form a tissue scaffold of the exact internal architecture and external anatomy is schematically illustrated in Figure 8(a). The model was then fabricated using 3D Printing solid freeform fabrication technique. Sample of a tissue scaffold is shown in Figure 8(b).

A biomimetic based design approach has been described in [SSD*04, ZMV99] where the mechanical properties of bone in terms of its Young's

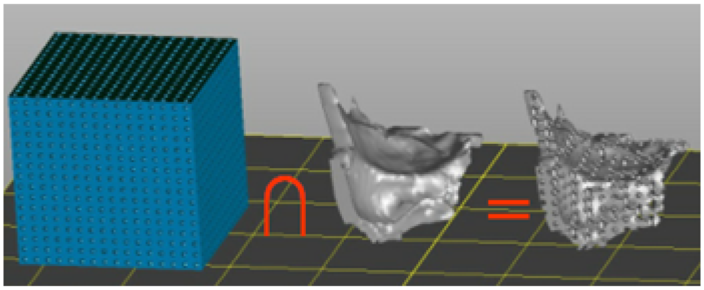


Figure 8(a): Example of using Boolean operation to achieve bone scaffold anatomical geometry

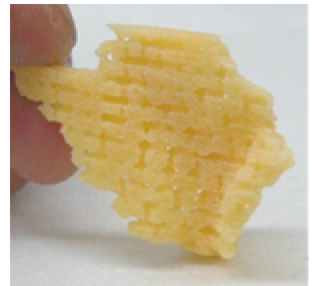


Figure 8(b) – Fabrication of Scaffold

modulus have been retrieved from the CT images using a QCT based approach. A layer based CAD model is then developed with each layer associated with a definite property. The layers of the CAD model were then associated to specific unit cells with matching mechanical properties to generate a biomimetic bone structure.

4. Conclusion

The authors have explored the bioengineering application of reverse engineering (RE) technology in converting CT/MRI based images to CAD models and have brought forward different process paths in which this can be achieved. Each process path selected depends on the particular application it is intended for. This approach can aid in the development of biomimetic bone structures which in turn would be used in the design of heterogeneous scaffold structures. The CT/MRI image based reconstruction provides a technique in which the outer shape of the scaffold structure can be retrieved for appropriate anatomical fitting and compatibility. Once this is done, freeform fabrication of CAD models using the method of direct slicing [SLS*03] can be made use of so that these can be then transferred as process planning instructions to any one of the solid freeform fabrication technologies.

5. Acknowledgements

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