Image-based bio-cad modeling: overview, scope, and challenges

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Abstract. CAD used to facilitate engineering design, modeling, simulation, analysis, and manufacturing. Recent advancement in computer graphics, medical imaging, and Image processing created new ways for CAD in the design, modeling, and development of many novels and essential biomedical and non-biological applications. The Biomedical use to develop implant, scaffold, prostheses, surgical guide, and other medical devices. The non-medical use in forensic, anthropology, passenger safety product design, and impact analysis. This review article gives an overview of various recent approaches for the development of virtual Bio-CAD models from high resolution medical images. It shows how to choose the appropriate path as per the application's requirement in terms of its complexity and capturing features. Key publications from the reputed peer-reviewed journals and books have been reviewed and presented a different approach to develop Bio-CAD models from non-invasive medical imaging data. Different methods used to develop the interfaces are biomedical software, STL interface, and reverse engineering discussed from various research study have been explored. Recent advances in state-of-art technology such as CAD, medical imaging, and image processing, and reverse engineering techniques made it possible to easily reconstruct the 3D CAD models, which will be useful for other downstream applications. This study concludes that the Bio-CAD model plays a dominant role in all downstream applications for the design, analysis, simulation, and manufacturing of complex biomimetic scaffold, patient-specific implants, surgical guides, prosthesis, organ bio blueprints, and other biomedical models. The outcome from the literature review strongly suggested that Bio-CAD modeling will soon be the future for all medical practitioners, biomedical engineers, and manufacturers and will use in all computer-assisted surgery and planning. This paper is beneficial to study the development of Bio-CAD models techniques and its applications in design, modeling, analysis, and manufacturing of biomedical and non-biological researchers.

1. Introduction

Recent advances in computer graphics, medical imaging, image processing, reverse engineering, biomaterial, and free form fabrication technique helped in the development of CAD for biomedical and non-medical applications. Hence CAD can be used to construct three dimensional (3D) bio model from primary medical imaging modalities. It includes computed tomography (C.T.) /micro-CT, Positron emission tomography (PET), Magnetic resonance imaging (MRI)/micro-MRI, optical microscopy each of these medical modality having its own some advantages and limitations [1]. Data derived from these therapeutic modalities use three dimensional (3D) reconstruction of virtual biomedical models, which
Further useful to design implants, analysis, and simulation and fabrication shown in the various published literature [2-3] shown in figure 1. The primary imaging modalities will not allow medical doctors to diagnose any disease and treatment plan to the patients quickly. Hence there is a need in research in constructing a virtual model to provide patient valuable medical information for a good understanding functionality of anatomy and morphology to diagnose disease and treatment process. The modelling of parts of human body in a CAD-based environment known to as virtual Bio-CAD modelling. These reconstructed 3D models have medical as well as non-medical applications. The therapeutic use includes computer-aided surgery, computer-aided tissue engineering (CATE), regenerative medicine, design of orthopedic devices and implants [4,5], Sports for gait analysis and BIO-Manufacturing [6-10] and non-medical applications like in the field of passenger design safety, impact investigation, forensic, anthropology, art and entertainment [11-13]. These reconstructed 3D models can provide important medical details and useful diagnostic tool for doctors to understand the patient's complicated internal human structure.

![Figure 1. Bio-CAD model and its application](image)

The general Image-based medical modeling process include the three necessary phases as acquisition of images, image processing, and segmentation, three dimensional (3D) reconstruction of 3D Bio-CAD robust model. Further, the process of developing 3D Bio-CAD models after image processing has three different routes are bio-medical software, reverse engineering, and stl interfaces [14]. However, as existing bio-cad modeling tools do not appear to be simple, accurate, efficient, and reliable for bio-image acquisition for the conversion into the mode for diagnosis and analysis of patient disease, currently, the challenges encountered, such as the lack of accuracy, active, efficient, and stable for robust design and modeling tools for analysis, simulation, printing, and prototyping customized complex and tiny features of the body part for biomedical implants and tissues scaffold. The growth in the biomedical application field needs very efficient and accurate methods as per the requirement for the conversion of non-invasive medical imaging data to CAD based virtual models that still having requirement to be develop.

2. 3D Bio-CAD Modeling Process
The literature review found that the most efficient technique to construct the Bio-CAD model is from medical imaging modalities. In this technique, the model created from appropriate medical imaging modalities data captured and process these data through an image processing algorithm. The medical image based Bio-CAD modeling includes three important phases, as shown in figure 2: i) Image data acquisition, ii) imaging processing, and iii) geometric Bio-CAD modeling.

![Figure 2. General steps in image base Bio-CAD modelling](image)
2.1 Data acquisition
In Bio-CAD modeling, the primary imaging modalities use Planar X-ray, CT/micro C.T., optical microscopy, MRI/ micro MRI, PET with its advantages and limitations [2, 3, 6, 7, 27].

2.1.1 Computed tomography (C.T.)/Micro C.T. In CT and micro-CT scans require exposure of ionizing radiation and then it gets detected by absorption. The series of 2D images for which display the density map of sample. Overlaying these series of 2D images construct 3D model. Differentiation of tissue in C.T. scans accomplished through contrast segmentation, the grayscale values of each voxel decide by density of tissue [8, 9, 14]. It is more useful in the case of hard tissues as well as where density changes abruptly at the interface between soft and hard tissue. The recent development of micro-CT technology used effectively to determine the functionality of microstructure relationship of tissues involves characterizing micro-architecture of scaffolds of tissues [1, 5, 8]. Also, to helps the design and manufacturing [11, 12], to find the bone morphology of tissue and strain-stress nature [13-15] and to know the porosity of biomaterials [16] non-destructively and to model the tissue of lung of 10–50-micron resolutions [6, 17, 27]. Due to the high resolution of CT and micro-CT it is suitable for to capture image very preciously.

2.1.2 Magnetic resonance imaging (MRI)/Micro-MRI. It is a medical imaging technique used in radiology to build images of the physiological and anatomy of the body. It has proven to be a versatile imaging technique in medical diagnosis. The scanners use very strong magnetic fields and fields gradients as well as radio waves to developed images of the body part or organ. Then the series of 2D images display a density of sample map. Overlaying these images used to construct the 3D representation of model. Classification of tissue scans accomplished through contrast, the black and white value of these voxel used by density of tissue [8, 9, 18]. It is more helpfull in the case of classification of different soft tissues. It is most prominently useful in diagnostic medicine and biomedical research, it also may be used to form images of non-living objects. MRI scans are capable of producing a variety of chemical and physical data, in addition to detailed spatial images. The advantage is that no radiation exposed as in case of CT. In scan required longer time and patient may discomfort during scan period and people with some medical implants or other non-removable metal inside the body may not recommended for MRI.

2.1.3 Ultrasound Imaging. It is uses high frequency sound wave to create image of tissue, organ or blood flow inside the vessel. The sound waves are transmitted to the area to be examined and the returning echoes are captured to provide the physician with a ‘live’ image of the area. It is safe as it is not utilized ionizing radiation nor contrast agent as compared to X-ray or CT. The Ultrasound is used to visualise and create images of the heart valves and blood flow. Ultrasound has several advantages which make it ideal in numerous situations, in particular, studies of the function of moving structures in real-time. It can be used to examine many parts of the body, such as the abdomen, heart and blood vessels, breasts, muscles, carotid arteries, and female reproductive system including pregnancy and prenatal.

2.1.4 Hybrid modality approach. A hybrid modality approach is more precise for 3D Bio-CAD model construction on the same specimen to make more accurate instead from any single modality of deficiencies. The 3D model constructed from C.T. and MRI, as for combined heterogeneous soft tissue for which MRI is functional and for high-resolution skull C.T. is best. A combination of C.T. and PET provides structural and metabolic information for the precise location of cancer for clinical application. A combination of C.T. and optical microscopy use in histological distortion correction from physical sectioning of optical microscopy. The CT angiography-derived vascular tree may be a means to help correct this histological distortion in the final model. When comparing the optical base vascular model and the CT based vascular model, the histological distortion can be correctable. The study of development a hybrid from micro-CT and optical microscopy, in this vascular tree from a micro-CT.
angiography used to correct the distortion from image from section of optical microscopy shown in Figure 3 [19]. The hybrid imaging modalities use and its application, as shown in Table 1[19].

![Figure 3. Hybrid micro C.T./Optical Microscopy [17]](image)

Table 1. A Hybrid imaging modality and its application.

| Hybrid imaging modality                  | Applications                                             |
|------------------------------------------|----------------------------------------------------------|
| CT and MRI                               | Skull and its surrounding tissue                         |
| C.T. and PET                             | Clinical application for example cancer detection        |
| C.T. and Optical Microscopy              | Histological distortion correction                       |
| Micro-CT and Optical Microscopy          | Histological distortion correction vascular tree for     |
|                                          | Angiography                                             |

2.2 Image processing

In digital image processing digital computer is use to process digital images through an algorithm. Hence it is the digital processing of any 2D data. Depending on whether the image resolution is fixed, it may be of vector or raster type, by itself, the term “digital image” usually refers to raster images or bitmapped images. The generation and development of digital image processing are mainly affected by three factors: first, the development of computers; second, the development of mathematics; third, the demand for a wide range of applications in industry and medical science has increased. A digital image is a 2D array of pixels. The medical image acquiring the patient is in the standard format of DICOM (Digital Imaging and Communication in Medicine) of medical imaging modalities [20]. Its has some important advantages are its remove noise, correct density and contrast helps to easily store and retrieve in computer, image can be made available in any desired formats like black and white, negative, color. The main processing of image steps, as shown in figure 4: image pre-processing, image enhancement, segmentation, extraction of feature, classification of image, and post-processing of image.

![Figure 4. Image processing steps](image)
Image Enhancement is one of the most important and complex techniques in image processing technology. In image enhancement the quality of image improve and also perceptibility as well. It include both point and local operation, the local operation depends on input pixels value and transform technique works on Fourier technique. Image classification is one of the most important methods of image mining. Image classification is process of finding model from database of image features which predict unknown class label. The image classification technique categorized into three namely: texture classification, neural networks and data mining techniques respectively. Neural network are very useful alternative to different conventional classification methods

The most important step in medical image processing is segmentation where image classified voxels into object. It makes possible to developed 3D object which can be use further to perform analysis of size, density and other important parameter of interest. The input raw 3D image of CT, MRI or microscopic image are in 3D array of pixels or voxels. Each voxel has its greyscale value range. 16 bit is use to generate most of images. For the processing of segmentation and image recognition the 3D image is required huge computer processing speed due to large number of pixels. Image segmentation provides simpler description of objects for the creation of 3D models. Because of the importance of identifying objects from an image, there have been extensive research efforts on image segmentation for the past years. A number of image segmentation methods have been developed using fully automatic or semi-automatic approaches for medical imaging and other applications. Image segmentation works in three methods, which are region, border, and edge. Region method is used to examine images and region class of neighboring pixels. Thresholding segmentation uses the histogram and threshold value of pixels. Image edge techniques are used to analyze the images at borders or discontinuing

2.3 3D Geometric Modelling

The 3D geometrical modeling process conducts to develop a 3D CAD model from medical image data which use to design the medical device, implants, surgery planning by segmenting the patient's region of interest (ROI). Design, analysis and simulation of an anatomical model need to carry out in a vector-based modeling environment like CAD system. In CAD system the construction of these 3D geometric solid modelling methods used to represent as B-REP (boundary representation) and mathematically described as NURBS (Non-Uniform Rational B-Spline) functions. To convert medical imaging data into its NURBS based model is not simple process. In recent years, open source as well as commercial software available which shown in table 2.

| Medical Image processing Software | CAD Software | Simulation Software |
|----------------------------------|--------------|---------------------|
| Med-Link                         | Solidworks   | Ansys               |
| MIMICS                           | Catia        | Abacus              |
| Med-CAD                          | Creo         | Comsol              |
| Surgi-CAD                        | Fusion 360   | LS-Dyna             |

This medical software is not very much useful if the object is very complex and to capture minimal feature at the micro-level. Hence practical approach for the development of medical image into Bio-CAD models needs development. Three different geometrical modeling routes suggested by some researchers in their article [1, 21], which used depending on capturing of microscopic and complexity features as per the requirement of application are (1) Medical CAD software interface (2) Reverse engineering interface and (3) STL interface. The outline of the processes shown in Figure 5 [19, 22, 27].
Figure 5. Process flow chart for the development of the Bio-CAD model [17, 20]
2.3.1 Medical CAD software interface.

It is special purpose medical image processing software developed to bridge the gap between medical digital image processing and CAD design software. The input to this interface is primary medical imaging data which may be in the form of standard DICOM and finally it export the out file in the standard CAD format like STEP (Standard for Exchange of Product (STEP), IGES (International Graphics Exchange Standard), or STL format. The fitting of primitive done by this interface at slices of 2D image segmentation. The limitation is that it provide very limited facility to developed freeform shape or surface by using B-spline. Both primitives and freeform shapes used to model femur bone anatomy shown in figure 6 [23]. Another main limitation which is very useful for biomedical application is that it has not capability to capture features which are very complex and having small details. The application example showed a C.T., imaged based CAD model for the femur of a small chilled [23]. In all, 34 slice images obtain with each of 2 mm sliced segmentation for a height of 68 mm. Once loaded into the MIMICS software, all images were registered correctly and aligned for its orientations. Next, the region of interest (ROI) identify, and a 3D voxel model of the femur made. In doing so, an appropriate threshold range found that could best capture the relevant information contained in the femur. Using this threshold value, all pixels within this range collected to a color mask within the given segmentation level. A region growing technique was applied to form a 3D femur anatomic representation, shown in the figure. 6 [19].

![Figure 6. Model reconstruction using Med CAD interface [19]](image)

2.3.2 Reverse engineering approach

The second path is the traditional way for geometric modelling called reverse engineering or it is also called NURB based method. In this interface the conversion of 3D voxel data of 3d volumetric construction into the point cloud data which is further exported in any reverse engineering software for the creation of polygonal mesh which again finishes by using NURBS curves [24]. It is divided into four steps: preprocessing, polygonal mesh generation, mesh refinement and best fitting of curve. In preprocessing noise and errors are removed of the point cloud data, triangulation of the point cloud used to create faceted model, then mesh refinement is to be done and finally best fitting of curve generated using NURBS [25]. Some mesh refinement software available are Mesh Lab, PolyMLib [26] can be used for mesh refinement. The final optimized mesh model concerted into STL file for manufacturing by 3D printing for surgery planning and NURBS surface model can be used for design of surgical guides, implant, scaffolds [25]. The main advantage of this method is that smooth curves, high quality data, control on implant thickness, less error in transfer of file, stable Configuration and use for complex anatomy [23, 28-31]

The disadvantages of this methods are it is very time consuming and tedious [20, 21] and many control points on waved surface generates waved due to which numerical computation process in CAD is very complex [20]. The final result of CAD model is always better than Med CAD and STL interface. The BIO-CAD model is less error in transfer of data file, good aesthetic, and configuration is stable and suitable for integrated with CAM and CAE applications. 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, stable in configuration, and less error in data transfer formats,
particularly for an integrated CAD and FEA application. The generation of femur both by this reverse engineering method is shown in figure 7 [19].

![Figure 7. CAD Model construction by Reverse Engineering [17]](image)

### 2.3.3 STL Interface.

Third route is called STL interface which the simplest as compared to the previous two to avoid complexity and small featured to be captured. In this interface 3D volumetric data convert to STK triangulated mesh model and if required can be export into reverse engineering software for further refinement of mesh and error to be corrected and smooth generation of the surface model by using best fitting of curve NURBS [21,23]. Third route is called STL interface which the simplest as compared to the previous two to avoid complexity and small featured to be captured. In this interface 3D volumetric data convert to STK triangulated mesh model and if required can be export into reverse engineering software for further refinement of mesh and error to be corrected and smooth generation of the surface model by using best fitting of curve NURBS [21,23]. It use input as the STL triangulated surface instead of point cloud data point. The processing is efficient for the generation of the model which can further prototype however it has all the limitations of the STL file generation format. The figure 8 [19] shows the conversion of model from voxel based to STL.

![Figure 8. Construction of CAD model via STL interface [17]](image)

### 3 APPLICATIONS

The Bio-CAD models are 3D anatomical virtual models of human body parts that are agreement with formats of CAD standards. These models can use for measuring and simulation for analysis to improve the design and development of medical devices. Due to recent advances in additive manufacturing, biomaterial technologies, the CAD model is beneficial for the precise biocompatible fabrications for biomedical applications. Hence, Bio-CAD models can use some essential applications as a primary input to other downstream applications for design, analysis, simulation, and manufacturing. It including the planning of surgery, tissue engineering, and regenerative medicine, implants, medical devices, prostheses, bio-models, forensic science and anthropology, art and entertainment, passenger safety, crash analysis.
4 SCOPE AND CHALLENGES
None of the available medical application software has been effectively and broadly used by the biomedical and regenerative medicine research and development community due to the inherent complex nature of the anatomical structures of tissues. Hence there is a scope to develop more efficient approach for the development of medical imaging modalities data into Bio-CAD model.

AI, machine, and deep learning technology [32-36] utilizes in the future research trends of CAD in the biomedical field and transform it into the next most higher area called computer-aided diagnosis (CADx). The need for the hour is to combine multiple images from various modalities, as explained in section 1.1.3 hybrid modality approach to evaluate the patient's condition holistically, which is a great challenge for researchers, designers, and manufacturers. It may be an exciting area for future research. Hence there is a need and hence scope in research in constructing a virtual model to provide patient valuable medical information for better understanding of anatomical functionality and morphology to diagnose disease and treatment process.

Soon, Bio-CAD based CATE can use for scaffolds design which utilize as mini bioreactors. Complex scaffolds from micro to macro level could design to use bioactive materials for the interaction with the cells and the external pores to provide physical access to the scaffold for drug monitoring and administration

Hence as existing bio-cad modeling tools is complex, not so accurate, inefficient, and not much reliable for medical image input for the conversion into the mode for diagnosis and analysis of patient disease. Also, the currently developed, active, efficient, and reliable for robust design and modeling tools for analysis, simulation, printing, and prototyping customized complex and very small features of the body part for biomedical implants and tissues scaffold. The growth in biomedical applications, particularly in computer-aided surgical guides, tools, or devices development. It needs very efficient and accurate methods as per the requirement for the conversion of non-invasive medical images into CAD based solid models need to be develop.

5 CONCLUSION
In this review article, an overall view of recent research approaches used to develop the Bio-CAD model from biomedical imaging modality as per the requirement of a particular application discussion. The outcomes-based on literature review, discussed in this paper, strongly suggest that the most efficient route for the development of Bio-CAD model is reverse engineering route which is very efficient for the development of the small and complex tissue scaffold and biomedical devices which might become part of the standard protocol in various design and manufacturing processes soon. After elaborate scrutiny of the published research, the main conclusions can summarize as follows:

- The Medical CAD interface could be used for the development of surfaces models with less overall complexity. These models used for visualization of 3D biomodel.
- The Reverse engineering approach preferred for 3D robust model that is very complex and small features need to capture. These robust model needs to design and fabricate and used for dynamic analysis.
- The STL interface selected in the generation of the complex surface model, but no small features need to capture. Such models used for the rapid prototyping of bio models.

Application benefit of Bio-CAD modeling allows:
- To understand the biological physical properties of the ROI of the model of study for dynamic simulation.
- Better design of implants and prostheses.
- Using these virtual models, customize patient-specific prostheses and implants can design with improvement in comfort and quality.
- STL interface used to develop a rapid prototyping model, which can be useful for surgical planning or visualization or training purposes.
To study many new methods in design, simulation, and manufacturing of complex tissue scaffold for the enhancing of functionality and improvement interactions with the cells.

Hence, the generation of Bio-CAD model useful for biomedical applications such as patient-specific implants, prostheses, surgical guides, and other medical devices. It will also be useful in non-biomedical applications such as forensic, anthropology, passenger safety design, and crash analysis. The Bio-CAD model gives an important base and facility to the advancement of in regenerative medicine.

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