

DEVELOPMENT OF 3D BIT-MAP-BASED CAD AND ITS APPLICATION TO HYDRAULIC PUMP MODEL FABRICATION

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Abstract

A novel 3D bit-map-based CAD has been developed. This program, named CellCAD, relies on techniques which provides easy manipulation of huge sized 3D bit-map, poly-triangle and 2D bit-map data. It can be attached to various kinds of additional plug-in processors to extend its functions and to customize it highly for broad applications. CellCAD can be applied in fields using computed tomography digitizers and/or layering fabricators. The authors applied CellCAD to hydraulic pump model fabrication. This paper reports the basic design concept and implementation techniques of CellCAD from the viewpoint of design engineering, and also introduces the methods and results of an actual CellCAD application.

1. Introduction

Recently, many tools and methods for digital engineering are being developed and utilized in manufacturing. To obtain digital shape data from real objects, high energy X-ray computed tomography (CT) is very useful, because it can digitize entire shapes including interior regions accurately and automatically in very short time [1].

X-ray CT apparatuses obtain sectional images as two-dimensional (2D) bit-map data, while conventional CAD systems handle boundary representation (B-rep) data [2]. B-rep data contain geometrical and topological definitions, called "features", which are not contained in bit-map data. Therefore, there is poor compatibility between bit-map data and B-rep data, and it is very difficult to convert bit-map data into B-rep data.

The purpose of this study is to utilize piled-up X-ray CT sectional images, that is three-dimensional (3D) bit-map data, for various engineering activities. The authors developed a novel CAD program, named CellCAD, which can hold and manipulate 3D bit-map data as engineering shape data. This paper reports the design concept and implementation techniques for CellCAD.

2. B-rep data and 3D bit-map data

The difference in the two data formats, B-rep and bit-map, can be explained using Figure 1. A 3D B-rep datum is represented as a set of geometrical and topological definitions of shape elements like vertices, edges, faces and bodies. On the other hand, a 3D bit-map datum is represented as a three-dimensional array of tiny cells known as voxels (volume picture cells). Each voxel contains inside/outside discriminant or relative density at its position.

The greatest advantage of a 3D bit-map should be X-ray CT data acceptability. Sectional images obtained from X-ray CT apparatuses can be converted into 3D bit-map data by a piling-up method very easily. Additionally, the 3D bit-map has other two significant advantages, "uniqueness" and "compliance". Uniqueness is the characteristic that the same shapes must be represented with the same data. This is important for comparing two or more shapes to evaluate their sameness or to extract the difference between them. Compliance is the characteristic that the datum structure changes very little when a small deformation is applied to the shape. This is important for creating a shape by iterative computation like topology optimization.

Even with these advantages, there are severe issues to deal with the large data size of 3D bit-map. When representing even quite simple shapes, sometimes the 3D bit-map requires memory and storage capacity of 1 GB or more, while a B-rep requires less than 10 KB. Such a huge amount of data is very difficult to hold, manipulate and display. This is the main reason why all conventional CAD systems handle B-rep data.

However, the situation has been changing recently.

1. Computer performance has been drastically increased since the 1970s, when the first CAD system was developed. The latest PC models are able to handle huge amounts of 3D bit-map data in reasonable times.

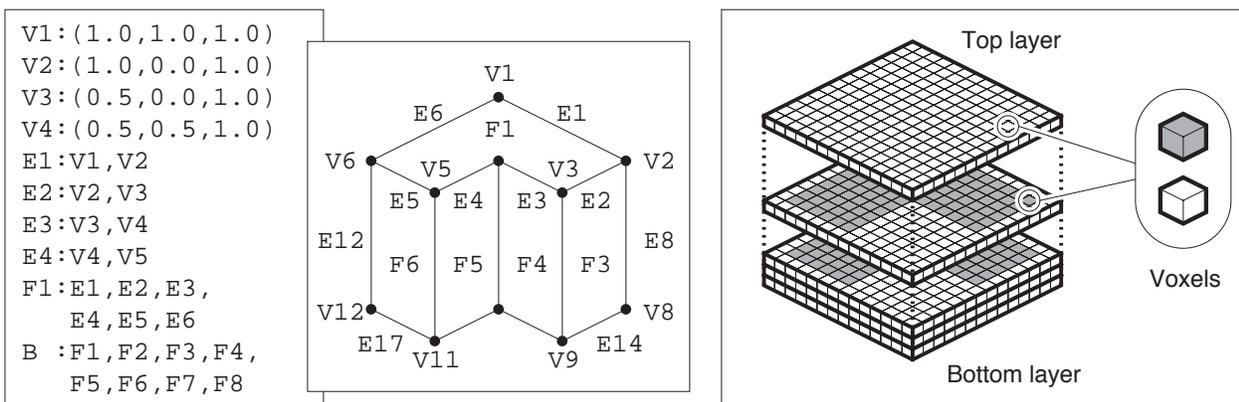


Figure 1. B-rep and bit-map formats

2. Many "layered manufacturing" tools have been developed. Rapid fabricators and "voxel engineering" programs give 3D bit-map great utility in engineering fields.
3. The quality and performance of X-ray CT has been greatly improved. 3D bit-map data containing even $2000 \times 2000 \times 2000$ voxels can be obtained in a few days, from target objects with a 1000 mm diameter.

Such significant changes have mitigated the weak points of the 3D bit-map, allowing its advantages to become the focus so there is a strong motivation for developing the 3D bit-map CAD.

3. Conceptual design of 3D bit-map CAD

As the first step to develop a 3D bit-map CAD program, the authors started with the conceptual design. In order to determine its functional requirements, the authors made a list of issues to be considered. Comparison of 3D bit-map CAD with conventional B-rep CAD led to identification of the following issues.

1. Large data size. A 3D bit-map datum containing $3000 \times 3000 \times 3000$ voxels requires memory and storage capacity of more than 2.5 GB. This issue in turn leads to the following derivative issues.
 - 1-1. Network capacity. In the case of cooperative work by many operators, a distributed CAD system may cause network congestion due to large data exchanges.
 - 1-2. Memory addressing limitation. Current Pentium-compatible 32-bit CPUs cannot address from a 4 GB memory space. Also the Windows OS cannot address from a 2 GB memory space.
 - 1-3. Long process time. 3D bit-map CAD operators have to wait for a long time until operations are completed. If the operators make a wrong operation, they experience a terrific loss of time.
2. Immature concept. The basic idea and methodology of engineering using 3D bit-map data have not been applied to many cases of practical production. Therefore, requirements for 3D bit-map engineering tools have not yet been clearly defined. Functional changes or additions may be required in the 3D bit-map CAD program.
3. Analytical usage. Conventional CAD operators know what they are handling, but this is different for 3D bit-map CAD operators handling X-ray CT data, because the target objects may not be their own products. The operators may want to use the 3D bit-map CAD for X-ray CT data analysis.

Many of these issues change the 3D bit-map CAD specifications. The authors found the following solutions for the issues.

1. PC cluster architecture (for issue 1). A PC cluster is a set of PCs connected by a high speed network. It is very useful for realizing scalable parallel processing. A bit-map datum is a set of local information, therefore parallel processing is very effective to reduce process time.
2. Client-server system (for issue 1-1). This consists of one server PC and one or more client PCs. The server holds 3D bit-map data and processes them upon receiving commands from the clients. In this system, large amounts of data are not delivered to all clients to avoid network congestion.
3. Partial loading and saving (for issue 1-2). Functions extracting partial data from 3D bit-map files and functions inserting partial data into 3D bit-map files are required for handling large amounts of data over 2 GB.
4. Pre-process and pre-load viewing (for issue 1-3). To avoid wrong operations, the results are shown to the operators before they start the operations. Additionally, it is also better to show the results of threads, that is sequences including two or more operations, before the operators start the threads.
5. Operation describing language (for issue 1-3). To reduce the operating time, sequential execution of many operations is very effective. A special language allows recording of operations and threads in literal scripts, modifying them using text editing programs, and executing them manually and automatically.
6. Plugged-in functional modules (for issue 2). It is very effective to define the interface between the kernel part and the plug-in modules to ease modification of the function set. Functions are attachable and removable when needed.
7. Multi-viewer system (for issue 3). Many other CAD programs assign one viewer for one datum, nevertheless, it is better to provide two or more viewers to ease three-dimensional shape recognition.
8. Analytical functions (for issue 3). Extracting information from 3D bit-map data is very important to handle X-ray CT data from unknown target objects. Analysis, measurement and recognition functions are very useful for this purpose.

4. Implementation of CellCAD

Considering the results of the conceptual design, the authors have built a multi-purpose 3D bit-map CAD program named CellCAD. It works on Windows NT 4.0 or Windows 2000 operating systems over IBM PC/AT compatible PCs.

CAD plug-in layer	CellCAD plug-in modules <ul style="list-style-type: none"> - Rendering (volume rendering, cut rendering, slicing, etc.) - Shape operation (primitive creation, transformation, cell operation, optimization, etc.) - Measurement (dimension measurement, shape comparison, density analysis, etc.) - Data conversion (rasterization, RP data export, simulation data export, etc.) - Feature extraction (geometric fitting, coordinate definition, alignment, etc.) - Poly-triangle manipulation (remeshing, inconsistency fixing, etc.) - Other functions
CAD kernel layer	CellCAD kernel module
Geometry handling layer	3D bit-map handling library CellGeom
Hardware layer	PC cluster architecture <ul style="list-style-type: none"> - PC cluster managing middleware ClusterWare Client-server system

Figure 2. 4-layer structure of CellCAD

CellCAD is designed as a 4-layer structure (Figure 2). The "hardware layer" realizes a computing environment for CellCAD. This layer contains the original middleware "ClusterWare", designed for Windows-based PC cluster management.

The "geometry handling layer" contains the original 3D bit-map handling library "CellGeom". This library provides hundreds of functions handling 3D bit-map, poly-triangle and 2D bit-map data. CellGeom works on both stand alone and client-server systems, on both single PCs and PC clusters.

The "CAD kernel layer" is implemented as the CellCAD kernel module. This module is an executable program provided with a graphic user interface (GUI). Figure 3 shows an example screen display. The kernel module provides essential functions of CellCAD including the following items.

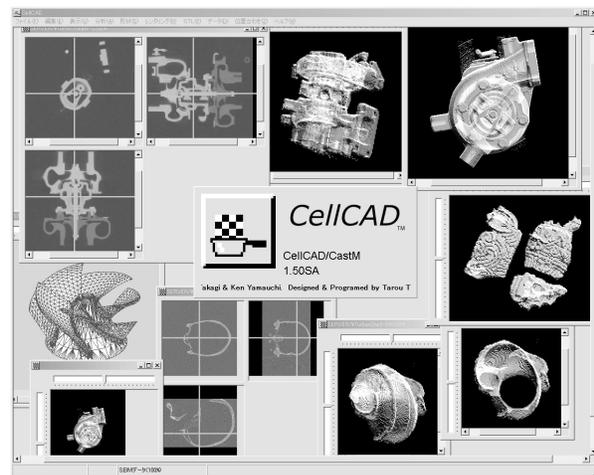


Figure 3. Example CellCAD screen display

1. Basic data management (data holding, memory management, display, etc.)
2. Basic user interface (command menu, information, help system, etc.)
3. Plug-in module interface
4. License control

The "CAD plug-in layer" consists of many CellCAD plug-in modules. They provide various useful functions, some of which are listed in Figure 2.

5. CellCAD applied to pump model fabrication

CellCAD has been applied to hydraulic pump model fabrication. The target object was an experimental model of a mixed flow pump impeller, designed with a 3D CAD program (Figure 4). The diameter and the height were approximately 100 mm and 74 mm. The object was fabricated by the selective laser sintering (SLS) method using metal material [3]. The SLS method, which is a rapid prototyping (RP) technique, included a furnace cycle to sinter the laminated objects to give them high strength. The final material density was 7.9 g/cm³.

This furnace cycle sometimes causes deformation of the objects, therefore a free-form shape validation method is required. For this purpose, the pump developer chose an X-ray CT apparatus (Hitachi HiXCT-6M). It worked very effectively to digitize the curved shape of the pump impeller into a set of 210 planes of sectional images, every one containing 900×900 cells. The total amount of the data was 162 MB.

The shape validation was achieved with the following sequence. Views of the data during this sequence are shown in Figure 5.

1. Input the sectional images. The sectional images were input and piled up to build a 3D bit-map datum (a).
2. Input the designed shape. A poly-triangle datum, with the designed shape, was input from the 3D CAD program (b).
3. Crop the 3D bit-map datum. The unused region around the object in the 3D bit-map datum was cropped to reduce the datum size (c). The cropped datum contained 360×360×210 voxels.
4. Adjust the scale of the poly-triangle datum. The 3D bit-map datum consisted of 0.35 mm-sized cubic voxels. The poly-triangle datum was resized to change its unit from mm to voxel.
5. Obtain the geometric relationship between the poly-triangle and 3D bit-map data. The poly-triangle datum was overlaid on the 3D bit-map datum. The alignment could be done geometrically

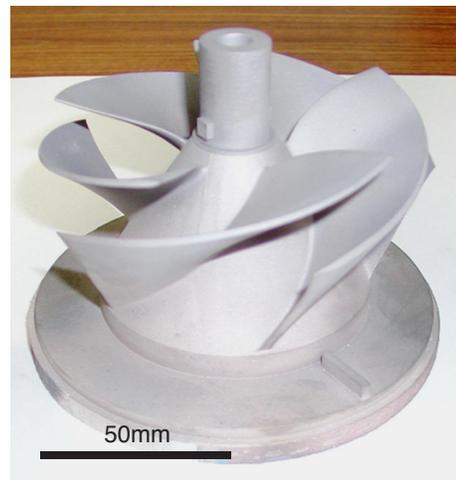


Figure 4. Target pump impeller

and visually.

6. Transform the 3D bit-map datum. The 3D bit-map datum was moved to the designed position, and rotated into the designed orientation (d).
7. Obtain the density distribution. To know the relative density threshold which separates the internal and external regions, the relative density for the air part and the metal part were measured, and their mean was taken as the threshold.
8. Remesh the polygon facets. The facets, which are elements of the poly-triangle datum, were divided into smaller facets (e). This process is important to distribute the measured points closed enough together.
9. Measure the surface offset. The original algorithm "virtual probe measurement (VPM)", which is a simulation of coordinate measuring machines, was applied to quantify the surface offset distribution between the 3D bit-map datum and the poly-triangle datum. The accuracy of the VPM was higher than the voxel size. In many cases, it was within 0.1 voxels. Measured offset was converted into a color and mapped on the facets.

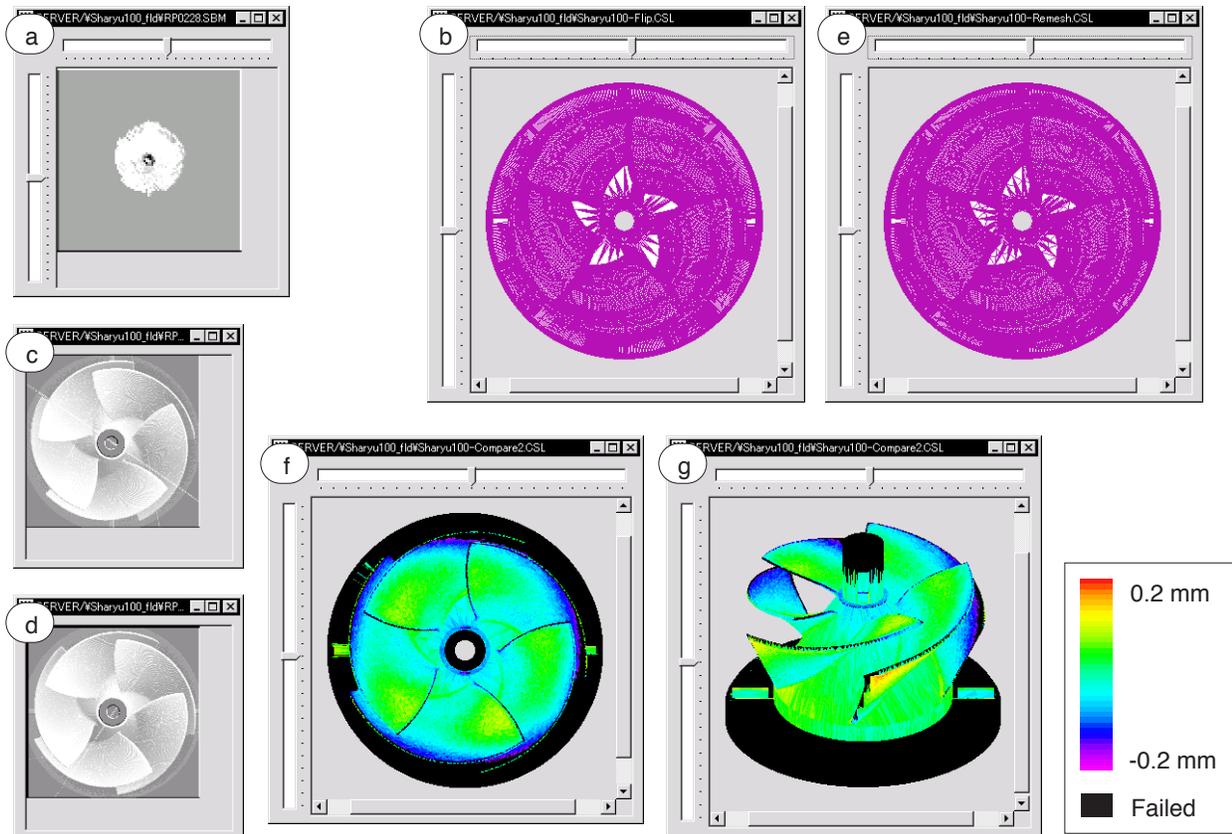


Figure 5. Views of data during the shape validation sequence

10. Render the colored poly-triangle datum. The color-mapped poly-triangle datum was rendered and the rendered images were pasted into a report which indicated the distribution of the deformation of the pump impeller (f, g).

Significantly, all of these 3D bit-map operations are carried out within a day using CellCAD. The report is very useful to analyze what happens during the furnace cycle and to improve the furnace conditions.

6. Conclusions

The conclusions of this paper are as follows.

1. A novel 3D bit-map CAD was developed, in order to utilize X-ray CT data and to enjoy the exclusive advantages of bit-map data.
2. Issues for realizing the 3D bit-map CAD were listed, and ways to deal with them were found.
3. The 3D bit-map CAD, CellCAD, was implemented as a 4-layer structure. It is powered on client-server systems and/or PC cluster architecture.
4. CellCAD was applied to hydraulic pump model fabrication. It is useful to analyze phenomena during the fabrication process of experimental models and to improve the conditions for their fabrication.

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