GENERATION OF OBJECT REPRESENTATIONS OF 3D OBJECTS IN CAD/CAM BY DIGITAL PHOTOGRAMMETRY

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ABSTRACT

3D object representations in CAD/CAM are usually created by geometric modelers. However, in cases where geometric information such as dimensions and shapes of objects are not available, measurements of physically existing objects become necessary. This paper presents a method of generating object representations of 3D objects by digital photogrammetry. Geometric parameters of primitives of 3D object representations such as Boundary Representation (B-rep) and Constructive Solid Geometry (CSG), and digital surface models are determined by digital image matching techniques. An algorithm for reconstruction of surfaces with discontinuities is developed. Interfaces between digital photogrammetric data and object representations are realized. Applications of this method could be found in fields of design and manufacturing in mechanical engineering, automobile industry, robot technology and others.

KEY WORDS: *3D object representation, Digital image matching, Photogrammetric interface, Spatial data base.*

1. INTRODUCTION

In Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) systems objects are described by object representations, by means of which the tasks associated with all geometric aspects of design and manufacturing of products can be handled. Usually, such an object representation of a 3D object can be generated by a geometric modeler effectively and comfortably if a design concept and necessary related data are known. But in some cases, where geometric information such as dimensions and shapes of objects are not available, measurement of physically existing objects become necessary.

A typical example of the above is prototyping. After the first prototype is produced, some tests have to be accomplished to acquire technical data. According to the test results, the shape of the prototype may be modified in order to reach a better design. The modified model is tested and improved again. This procedure repeats itself until the optimal design is achieved. If the tests above concern only geometric characteristics of the product, they can be done by computer simulation. In this case, modification of the prototype means just modifying its object representation. In other cases, non-geometric tests take place and a computer simulation may not be possible. In this circumstance, the model has to be modified physically. Thus the modified model will be measured so that a corresponding object representation can be derived.

Photogrammetry is a technique which acquires 3D geometric data of objects without direct physical contacts. Digital photogrammetric measuring procedure is becoming very efficient and automated with recent developments of software and hardware technology and progresses of computer vision. With help of digital image matching, geometric elements of primitives of 3D object presentations such as points, edges, curves and surfaces can be derived from stereo images. An algorithm for generation of digital surface models with surface discontinuities by area and feature based image matching is developed. An interface between the digital image matching system and CAD/CAM systems makes it possible to convert the data acquired by digital photogrammetry to 3D object representations. Therefore, design and manufacturing procedures can be automated and processing time can be reduced by applying digital photogrammetry.

2. BACKGROUND

2.1 Previous Work

Measuring machines are often utilized to measure 3D coordinates of objects in mechanical engineering (VW-GEDAS, 1989, Albertz, 1989). A surface point measured is touched by a contact point of the measuring machine. The position of the contact point can be determined by its 3D translation according to the origin of the coordinate system of the machine. Thus, the object can be measured point after point. Among others two drawbacks of this method are: a) physical contacts between objects and the measuring machine may limit its applications where such contacts are impossible; b) the long operating time makes it not suitable for measuring mass points, e.g. for digital surface models.

Close-range photogrammetry derives object positions in the object space by analyzing parallaxes of identical points in stereo images. This enables an optical measurement of objects without contacting objects. Digital photogrammetry, especially supported by digital image matching, can automate the measuring procedure (Kreiling, 1976, Cogan and Hunter, 1984, Ackermann, 1984, Helava, 1988, Wroble, 1987, Wong and Ho, 1986). Developments in pattern recognition, computer vision help analyze image features and identify objects. Surface features, e.g. surface edges (potential surface discontinuities), can be matched, so that their locations in the object space can be reconstructed (Ohta and Kanada, 1985, Ohta and Ikeda, 1988, Li, 1988, Li, 1990, Terzopoulos, 1986).

InduSURF system (ZEISS, 1987) is able to photograph objects by using analog metric cameras, and measure object surfaces from scanned images by digital image matching. Automatic capture of surface discontinuities is not included in the system.

This paper presents a method which applies digital image matching to generate 3D primitives of object representations and reconstruct digital surface models with discontinuities. An interface between the image matching system and CAD/CAM system is presented. The following brief introduction of 3D object representations and digital image matching may be helpful for understanding detailed discussions.

2.2 Three Dimensional Object Representations

3D object representations are basic elements in CAD/CAM systems. With proper definitions and applications of these object representations many tasks can be simplified and accomplished efficiently and comfortably. For instance, a part of design problems can be transformed to a description of products by predefined primitives; furthermore, manufacturing process may be simulated by operations of object representations. Generally, an object can be represented by two principal techniques, namely by its boundary and by its interior. Following are some well known and mostly used object representations in the mechanical engineering (Spur and Krause, 1984, Morthenson, 1985, Samet, 1990):

- Boundary Representation (B-rep): an object is represented by its boundary elements, which are decomposed into a set of volume, face, edge and point subelements hierarchically (Figure 1).
- Constructive Solid Geometry (CSG): predefined solid primitives of objects, such as cubes, cones, cylinders and others, are combined to form complex objects by geometric transformations and Boolean set operations.
- Cell decomposition: the object space is decomposed into cells with different sizes. For example, Octree is a regular decomposition variant of this representation, where an object can be approximated by cubes of different sizes.

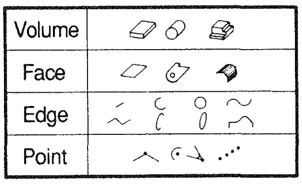


Figure 1. Subelements of Boundary Representation.

Generally, it is recognized that B-rep and CSG are more appropriate for design applications. While cell decomposition based methods are more advantageous for manufacturing applications.

Figure 2 shows a simple part described by (a) B-rep, (b) CSG, and (c) octree representation.

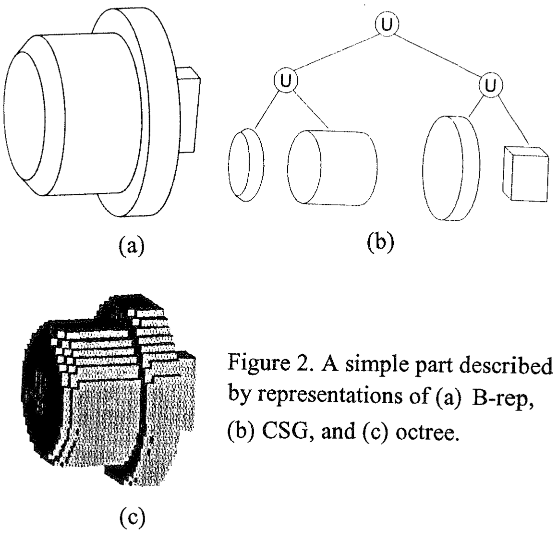


Figure 2. A simple part described by representations of (a) B-rep, (b) CSG, and (c) octree.

2.3 Digital Image Matching

Digital image matching is a powerful method for matching geometric information in stereo images. Identical primitives in different images can be found automatically by the matching procedure. Given transformation parameters between image and object space, locations in the object space can be calculated. Generally, image matching technique may be classified into three categories:

- Area based image matching which uses directly gray scale of images that might be preprocessed.
- Low level feature based image matching which compares low level primitives such as interest points, edges and other features in stereo images.
- High level feature based image matching which uses processed primitives such as identified objects, object parts and relations between them.

High level feature based image matching supplies reliable and stable results, but the extraction of high level features and the identification of objects itself are very difficult problems. The area based image matching is widely applied in practices. This method achieves good results in cases where the surface relief is relative flat and the surface projects rich texture in images. Inversely, the reconstruction of discontinuous surfaces and surfaces with few texture is problematic. However, in such cases image features such as edges are often available. Edges are usually only a small percentage of the whole image content, but they imply a great deal of information about the surface discontinuity. Edges can be extracted by using digital image processing. Corresponding edges in stereo images are found by edge based matching (Marr, 1982, Ohta and Kanade, 1985, Li, 1990).

Because of its high precision, least squares image matching (Ackermann, 1984) is applied to locate point position in stereo images. Given good approximate positions of points in stereo images with sufficient image texture, least squares image matching provides high matching precision. But the accuracy of the matched points in the object space are mainly dependent of image resolution (pixel size), image quality, matching algorithm, transformation model between image and object spaces, and others. A method of least squares matching in object space (Li, 1990) is developed which includes the image-object-space constraint in the image matching model in order to achieve more plausible results.

Edge based image matching searches identical image edges in images. An algorithm for edge matching by dynamic programming has been developed, under considerations of edge continuity and geometric constraint of the approximate surface model (Li, 1988, Li, 1990). The result of the edge based image matching is combined with that of area based image matching, so that discontinuous parts of the surface can also be represented in the reconstructed digital surface model. An iterative procedure is employed. This results in an improved digital surface model which is closer to the real object surface.

3. GENERATION OF 3D OBJECT REPRESENTATIONS BY DIGITAL IMAGE MATCHING

3.1 Measuring Primitives of B-rep and CSG

After photographing, objects are projected onto stereo images. Objectives are a) to analyze the images, b) to identify object shapes, and c) to locate geometric positions in the object apace. Geometric data thus obtained can be used to generate object representations. Although progresses in digital photogrammetry and computer vision have been made, automatic recognition of objects with any geometric forms still remains as a research area. Therefore, interactive operations are some times necessary.

A B-rep or CSG representation of an object is composed of a lot of primitives among which point, edges, and curves are basic elements. Other primitives can be derived from these basic elements. The following describes how to reconstruct basic elements and some primitives from digital images.

Points in an image displayed are located on a monitor with a cursor interactively, as long as the areas which contain the points are not lacking texture. By means of least squares image matching corresponding points in other images can be found provided that their approximate locations are pointed out by an operator.

On the monitor, definition of a point in the left image of a stereo pair by the cursor provides the accuracy of one pixel. If a point is depicted by a artificial pattern, e.g. a marked control point, a matrix which digitally represents the artificial pattern can be built. Through a matching between the matrix and the image area of the point, the definition of the point can be reached in subpixel precision. Because the corresponding point on the right image is found by least squares image matching, it is also located in subpixel precision. The matching precision is presented by standard errors of image coordinates after matching procedure is performed (Ackermann, 1984). The photogrammetric forward triangulation transforms the matched points from the image space into the object space.

A straight line can be determined by measuring two points. Parameters of curves with regular forms such as circles, ellipse etc. can be determined analytically if a certain number of points on the curves are visible in images and are measured by digital image matching. Curves with irregular forms (free forms) are reconstructed by measuring points on the curves which represent changes of the curvature. These points are used to generate polygons or to estimate parameters of B-spline functions.

Faces are located by measuring boundaries and auxiliary points. For example, a cylinder face may be described by a circle and two central points on the top and the bottom respectively. Similarly, volume primitives can be determined by the obtained faces.

Thus, primitives of B-rep and CSG are reconstructed in object space from stereo images. These reconstructed primitives are combined by using geometric modelers in order to generate B-rep and CSG representations.

3.2 Generation of Digital Surface Models

The above procedure for reconstruction of primitives of B-rep and CSG by digital image matching is mostly performed interactively. Generation of an octree representation from digital images can be automated because of its hierarchical data structure. The presented algorithm first reconstructs a digital surface model from digital images, and then convert it to an octree representation.

Generation of digital surface models by means of digital image matching has been researched in the last few decades (Kreiling, 1976, Claus, 1983, Foerstner, 1986, Wong and Ho, 1986). But handling discontinuities of surfaces still remains as a difficult problem. However, objects with discontinuous surfaces often occur in CAD/CAM applications. Thus, image matching must be able to reconstruct both continuous and discontinuous portions of surfaces in this method.

In order to reconstruct a complete digital surface model, area based image matching is used to acquire surface information in relatively flat areas of the surface, and edge based image matching is applied to extract discontinuities of the surface. The results of these two processes are combined, so that continuous and discontinuous parts of the surface can be reconstructed. At the same time the efficiency of digital image matching can be improved (Li, 1988, Li, 1990).

Figure 3 illustrates a schema of the method by means of which continuous and discontinuous portions of a surface can be reconstructed from digital stereo images.

Digital stereo images may be acquired directly by using CCD cameras or indirectly by scanning analog photographs. If edge based image matching is used, one must consider the camera-object-geometry during the design of the photograph arrangement, so that the object edges in stereo images intersect mostly at epipolar lines and more correspondent edges can be efficiently found by edge based image matching (Li, 1990). Through image preprocessing methods such as contrast enhancement and high and low pass filtering, the image quality can be improved for further image processing and image matching. Edge detection and edge following supply edge elements which are correlated during edge based matching.

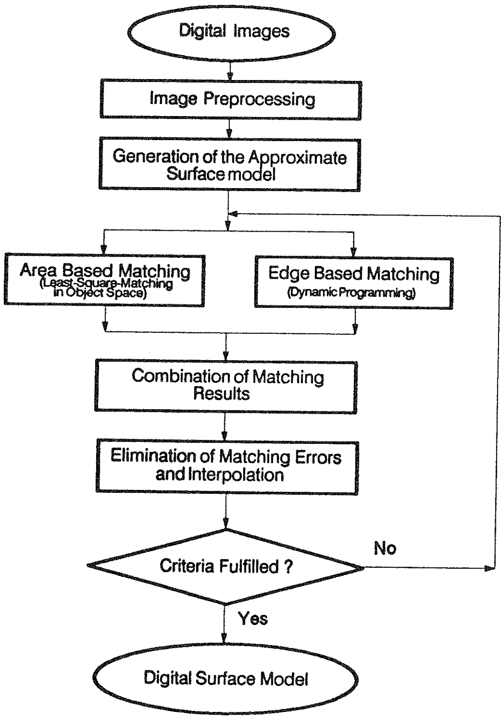


Figure 3. A schema of the algorithm for reconstruction of a surface with discontinuities by digital image matching technique.

An approximate surface is built hierarchically with a pyramid structure by digital image matching. This process begins with an image pair of reduced resolution and a sparse grid on the XY plane in the object space. At every grid point in the object space, Z values are determined by Vertical Line Locus (VVL) Matching (Cogan and Hunter, 1984, Li, 1990). The image pair with a larger format size is used and the grid is densified after Z values for all grid points are calculated. Z values of grid points calculated during the previous iteration, are used to estimate approximate values in the current iteration. This procedure continues until the image pair reaches its original resolution. This insures a reliable approximate surface and reduces computing time.

With the approximated surface model, an area based image matching module, namely a least squares matching in object space (Li, 1990), is used to calculate grid points in the object space point after point. This refines the Z values at all grid points in relative flat regions. At the same time edges are extracted and matched by a dynamic programming procedure to determine discontinuities of the surface. In this procedure, there are three similarity criteria for recognizing identical edges in the objective function: a) similarity of gray value distributions near edges, b) differences between edge directions, and c) image texture characteristics. This edge matching procedure (using dynamic programming) is constrained by edge continuity and geometric consistence with the obtained object surface. The first condition requires that a pair of correctly matched edges should be matched at all intersection points between these edges and epipolar lines. The second constraint implies that correctly matched edges in the object space should be within a proper tolerance to the calculated surface model. Thus, elimination of a part of mismatched edges is included in the matching procedure itself. A detailed description of this edge based image matching can be found in Li (1990).

In order to acquire a complete surface model in continuous and discontinuous regions, results achieved by the area based and edge based image matching methods have to be combined. One of most important considerations is the preservation of local surface discontinuities during the integration of the results. It is realized in such a way that a) unmatched points along an edge are linearly interpolated; b) points with matching failures, which often appear near surface discontinuities are interpolated separately on both sides of edges. This local interpolation method makes it possible, to prevent depression of surface discontinuities due to global interpolation.

Because of lack of image texture, effects of object-camera-geometry, and surface discontinuities, mismatches are unavoidable. False matches are detected by checking points in their neighborhood. They are then replaced by values calculated according to their neighborhood. Until here, a complex surface model is generated.

In the image matching procedures, area and edge based image matching modules run separately (Figure 3). That is, the result from one image matching module does not benefit the other directly. In fact, area based matching improves the digital surface model and could provide better geometric constrains for the edge based matching. Conversely, the reconstructed discontinuities may improve the estimation of surface points near edges (potential surface discontinuities) by area based matching. In that sense, it is necessary to restart the image matching procedure with the improved digital surface model as an approximate surface, and to refine the digital surface model iteratively. This iterative procedure continues until some criteria such as the number of iterations and/or the percentage of total mismatched points are satisfied. The final result is a digital surface model, which approximates the real object surface as closely as possible.

The presented algorithm for the reconstruction of digital surface models is applied successfully to different image types, e.g. aerial photography, close-range photography and electron-microscopic images (Li, 1990).

3.3 Conversion from a Digital Surface Model to an Octree Representation

3.3.1 Octree Representation

Octree representations describe objects by a spatial numerical structure. Octree micro cells approach geometric details of objects hierarchically. An original octant is defined as a cube which contains the object to be described by an octree representation (Spur et al., 1989, 1990, Samet, 1990, Li, 1991). The original octant is then divided into suboctants which fit the object shape by their hierarchical spatial structure. As shown in Figure 4(a), at first level, the original octant is divided into eight suboctants by halving it in three directions. Each suboctant is then checked whether it is occupied by the object. The suboctants are classified into three categories: a) F=Full (occupied by the object); b) E=Empty (no object element in the suboctant); and c) P=Partial (the suboctant is partially occupied by the object). On the other hand, these eight suboctants correspond to eight digits from 0 to 7, which enable the suboctants to be related to the 3D

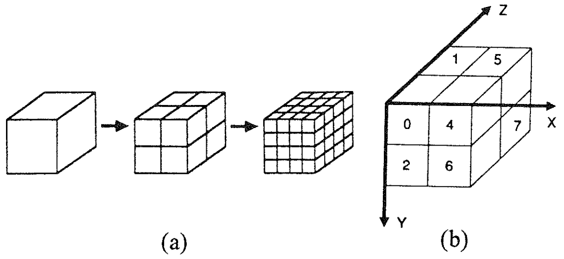


Figure 4. (a) Octant subdivision and (b) correspondence between the Cartesian coordinate system and suboctants.

Cartesian coordinate system (Figure 4(b)). P-octants are further subdivided into eight suboctants at the next level, which are again classified. The partition procedure continues until all suboctants are categorized as F- or E-octants. These final octants are presented by their octree codes. Those octree codes are listed with digits representing octants at different levels. After decoding information from the octree codes, a suboctant can be reoriented in the Cartesian coordinate system, and its size can be determined.

To save memory, E-octants are not registered. A linear octree data structure that lists only octree codes of F-octants is used in this algorithm. Figure 5 shows an example of octree representation. In order to create the octree representation, the simple object of Figure 5 (a) is subdivided twice. The first level contains the root or the original octant (Figure 5 (b)); the second level contains five F-octants, two E-octants and one P-octant. This P-octant is further divided at the third level into eight suboctants. Among these are seven F-octants, one E-octant and no P-octants. Figure 5(c) shows a linear octree of the object.

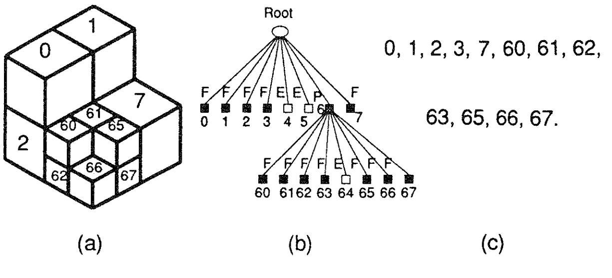


Figure 5. An example of octree representation, (a) a 3D object, (b) its octree and (c) its linear octree.

3.3.2 Interface between Digital Image Matching and CAD/CAM Systems

An interface between digital image matching and CAD/CAM systems is developed to convert the digital surface model into an octree representation. Figure 6 demonstrates the concept of this conversion.

The digital surface model is transformed by a regular gridded data structure into voxel elements (an extension of pixels) of the original octree. From the original octant, subdivision of suboctants begins. After the octree is coded, its representation is built.

Usually, the digital surface model consists of regularly distributed grid points. Although in some cases, the calculated surface points are relatively sparse where the surface relief varies slowly. In other cases, dense surface points are available where the surface has rapid changes. For building a digital surface model with regular grid intervals from irregularly distributed grid points, interpolation and resampling methods may be utilized. The resulting digital surface model is a single valued function, i.e. for any (x, y) point coordinates, there is only one Z value. However, surfaces of 3D objects in CAD/CAM are often multi-valued. In this case, for some grid points there may be more than one Z value. The Z values have been estimated by digital image matching from several stereo pairs.

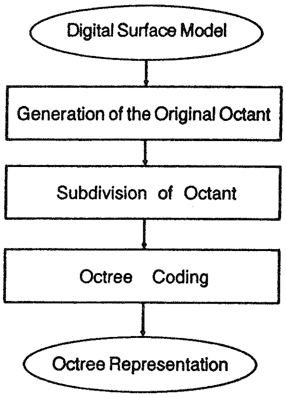


Figure 6. A concept for conversion from a digital surface model to an octree representation.

For generating the octree, a 3D array B is defined. It describes an object in such a way that if an element b_{ij} is inside the object or on its surface, it has the value 1 ($b_{ij}=1$); otherwise $b_{ij}=0$. Actually, this is a 3D binary image of the described object. To transform a multi-valued regular grid into a 3D-array, a ray tracing technique has been applied (Li, 1991). As shown in figure 7, in the Cartesian coordinate system the smallest box is defined as the box that contains the object (described by the digital surface model) and whose faces are parallel to the three principal planes of the coordinate system. This box, also referred to as the original box, is projected onto one of the three principal planes, for example the XY-plane. The projected area on the XY-plane is named "original plane", where a grid is defined. The grid interval is identical to that of the surface model and the dimension of octants at the deepest level (voxels). From each grid point on the original plane (x,y,0), a ray is sent in the Z-direction. Intersection points between the ray and surfaces of the object, which are also the intersection points between the ray and the digital surface model, are calculated. Segments on the ray between two intersection points that lie within the object can be derived by the analysis of indices of intersection points and surface normal vectors. Extreme cases are a) the ray lies within a face of the object and b) the ray intersects the surface tangentially. In the former case, it can be mathematically calculated that the ray has unlimited intersection points with the face. Therefore, the segment on the ray within the face is defined to be on the object surface. These two intersection points at the ends of the segment are considered as indexed intersection points on the ray. In the latter case, the ray intersects the surface model at only one point. The voxel containing this intersection point is defined as being on the object surface. An auxiliary index intersection point, which is the duplication of the intersection point, is added in order to keep analytical consistency of the indices of all the intersection points on the ray.

All voxels of the original box begin with 0. Generally, voxels

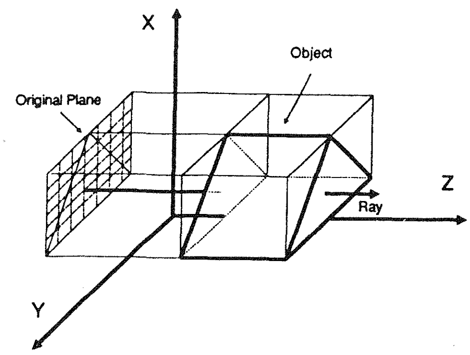


Figure 7. Building the original octant by ray tracing technique.

of the calculated segments parallel to the Z-direction on the ray inside the object are set to one. After generating the ray on the original plane, voxels that are inside the object or on the object surface have the value 1. As a result, the information about the solid object is presented in discrete form in the original box where voxels with value 1 represent the object and complementary voxels with value 0 describe the background.

The original box is further extended to the original octant with dimensions 2^nx2^nx2^n. Here, n is determined by the defined resolution of octree and the dimensions of the object. Voxels in the extended part of the original octant are filled with value 0. So far, the control as to whether a voxel belongs to the object is simplified to check whether or not the voxel has the value 1. Actually, the solid information of the object is not saved in the way that every voxel is registered, because this would need a memory of an array with the dimension of 2^nx2^nx2^n. The memory requirement increases rapidly as n rises. Therefore, the run length coding technique is applied in the algorithm. For every ray coming from the original plane, only those segments on the ray with value 1 are saved. Suppose a segment begins at (x,y,z_1) and ends at (x,y,z_2). Its run length is $RL=z_2-z_1+1$. Instead of storing RL voxel elements, only the coordinates (x,y,z_1) and the run length RL are registered. Thus, the algorithm does not need to use enormous amount of memory to code every voxel (proportional to the object's volume), but only to record run length parameters (proportional to the object's surface).

The following functions and subroutines are programmed and applied to generate an octree from the original octant:

UNIDEF:	defining an original octant
SUBDIV:	subdividing an octant into its eight suboctants
CLAOCT:	classifying an octant to one of the three categories (F, E and P)
OCTCOD:	generating octree codes.

After the octree is coded, objects are represented by their octree codes and saved in the data base of octree representation. This data base may be used for the further data base conversions or directly for geometric processing and simulations.

4. EXPERIMENTS

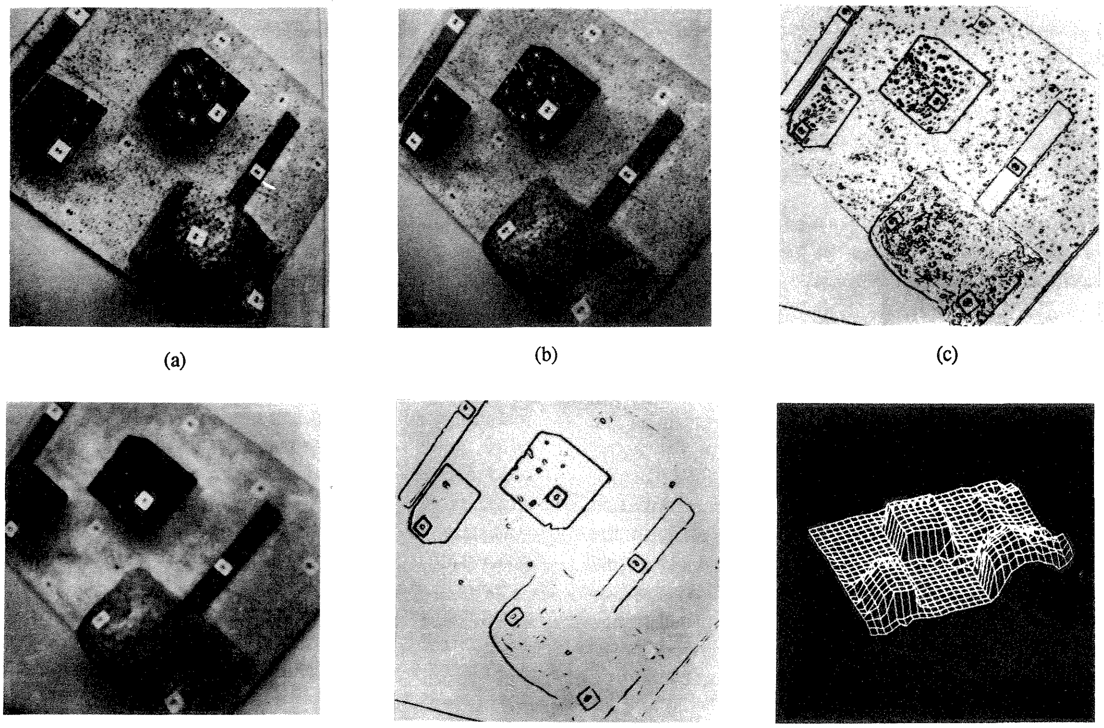
Programs for measuring primitives of B-rep and CSG, and 3D surface reconstruction from digital images by digital image matching and the interface for conversion from digital surface models to octree representations have been written in FORTRAN on a VAX/VMS system. The following example demonstrates the method presented.

Figure 8(a) and (b) illustrate a stereo image pair of a test model which simulates a discontinuous surface. The test area has a dimension of about 0.70x0.55 m and consists of objects with different shapes including a box, a wedge and a free form object. Eleven marked control points were measured geodetically. The mean square error of points was 0.15 mm. The model was photographed by a video camera (Sony AVC-3200 CE) with a depth distance of about1.5 m. The distance between the two camera positions was about 0.3 m. In order to obtain more image texture for area based image matching, an artificial texture pattern was built by spraying color spots on the model. Area based image matching produced an approximate surface model. From this first surface model, the least square image matching in object space was started to refine surface points in relative flat regions. The processing of the surface discontinuity began with a Sobel-Filtering. Figure 8(c) shows that a lot of small spots remain after the filtering, which make edge following more difficult. For better edge detection, a median filtering was performed prior to edge enhancement (Figure 8(d)), so that the small spots and a part of image noise were filtered out. Figure 8(e) shows the result of the edge extraction by using a Sobel operator on the image of Figure 8(d). Obviously, the preprocessing by median filtering improves the edge extraction. The extracted edge elements were then processed by edge following and edge based image matching.

The combination of results from area and edge based image matching provides a digital surface model with extracted discontinuities. In order to obtain fine surface structures, two more photographs were taken at different locations. With these images, the area and edge based image matching were also carried out. Figure 8(f) is the reconstructed 3D digital surface model made from the combination of results from these two stereo-image pairs.

To generate an octree representation of the test model, an original octant with a dimension of 64x64x64 was defined. A ground Z value was added to the digital surface model in figure 8(f). Therefore, the digital surface model became a digital solid description of the test model and was transformed into the original octant. After the subdivision of the original octant and octree coding, a linear octree representation was built. Figure 9(a), (b) and (c) show octants of 2nd, 4th and 6th level. Figure 9(d) displays a wire frame model of the final octree representation. In this figure, the meaning of octant is extended, i.e. octants can have different dimensions in the three directions of the Cartesian coordinate system. From the data structure of octree representation in figure 9, we can see that objects are partitioned hierarchically into octants of different sizes. At first, an object is approximated by large octants for a rough description, and then by smaller octants for finer structure of the object. These characteristics can be used especially in the simulation of manufacturing processes, collision control for industrial robots and for path planning of mobile robots.

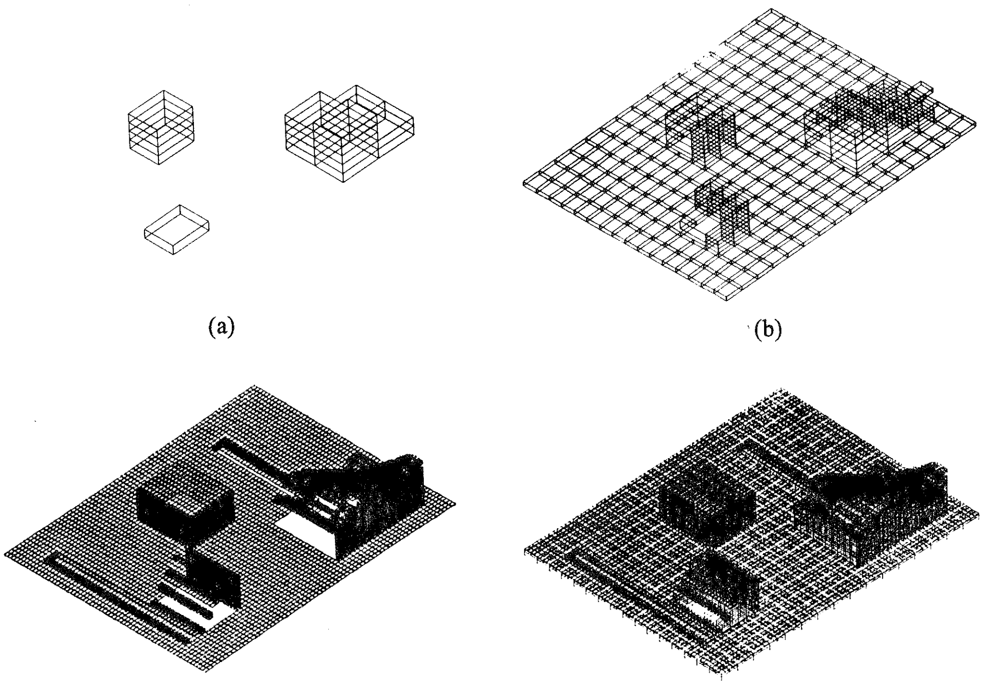
In order to generate a B-rep of the test model dimensions and parameters of shapes and locations of regularly shaped objects were measured interactively on a monitor by using least squares image matching. In addition, 36 surface points of the



(a) (b) (c)

(d) (e) (f)

Figure 8. Reconstruction of a digital surface model of a test model from its stereo images by digital image matching.



(a) (b)

(c) (d)

Figure 9. Octants at 2nd (a), 4th (b) and 6th (c) level, and the octree representation of the test model (d).

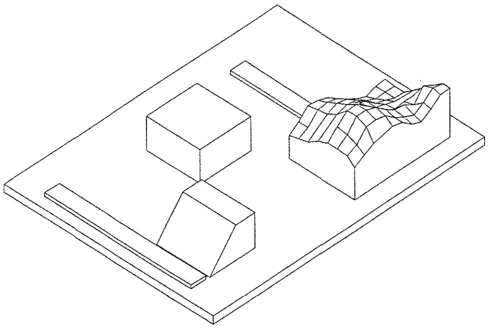


Figure 10. Boundary representation of the test model.

free form object were also determined by image matching. This geometric information was used as input to a B-rep based geometric modeler. Figure 10 illustrates the resulted B-rep of the test model by the geometric modeler.

5. CONCLUSIONS

Digital photogrammetry can be applied to acquire 3D geometric data for the generation of object representations in CAD/CAM. The method which uses both area and edge based image matching for reconstruction of digital surface models is very efficient, especially for objects with surface discontinuities. The interface between digital image matching and CAD/CAM systems makes it possible to transform the acquired digital surface model directly into 3D object representations. The presented method may be applied in the fields of design and manufacturing in mechanical engineering, automobile industry, robot technology and others.

Further efforts should be made in automatic recognition of Primitives of B-rep and CSG representations from digital images. Conversion from octree representation to other object representations is also an interesting topic.

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