Building Octree Representations of Three-Dimensional Objects in CAD/CAM by Digital Image Matching Techniques

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ABSTRACT: Octree representations of three-dimensional (3D) objects in CAD/CAM are usually created by geometric modelers. But 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 which generates octree representations of 3D objects by digital photogrammetry. An algorithm for reconstruction of surfaces with discontinuities using area- and feature-based digital image matching has been developed. Interfaces between such digital surface models and octree representations have been realized. Applications of this method could be found in the fields of design and manufacturing in mechanical engineering, automobile industry, robot technology, and other industrial applications.

INTRODUCTION

IN COMPUTER AIDED DESIGN (CAD) and Computer Aided Manufacturing (CAM) systems, objects are described by geometric representations through which all geometric aspects of design and manufacture of products can be handled. Among geometric representations of three-dimensional (3D) objects, the octree representation has a 3D spatial data structure which can be applied to software packages that represent and manipulate geometric properties of products efficiently. Usually, such a geometric representation of a 3D object can be generated by a geometric modeler effectively and comfortably if a design concept and related necessary data are available. However, in cases where geometric information such as dimensions and shapes of objects are not available, measurements of the physically existing objects become necessary.

A typical example is prototyping. After the first prototype is produced, some tests have to be performed to acquire technical data. According to the test results, the shape of the prototype may be modified in order to achieve a better design model. The modified model is tested and improved again. This procedure repeats itself until an optimal design model is achieved. If the tests above concern only geometric characteristics of the product, the tests can be performed by computer simulation. If other factors are concerned, 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 model will be measured after each modification, so that corresponding geometric representations can be derived.

Photogrammetry is a technique which acquires 3D geometric data of objects without direct physical contact. Meanwhile, the digital photogrammetric measuring procedure is becoming very efficient and automated with recent developments in software and hardware technology and progress in computer vision. An algorithm for reconstruction of object surfaces with discontinuities using area-and feature-based digital image matching has been developed. By means of this algorithm, digital surface models are generated with a hierarchical structure of multi-resolution grids. An interface between the digital photogrammetry system and application systems in CAD/CAM makes it possible to convert the data acquired by digital photogrammetry to octree representations for further CAD/CAM procedures. Therefore, design and manufacturing procedures can be automated by applying digital photogrammetry which reduces processing time.

RECONSTRUCTION OF DIGITAL SURFACE MODELS BY DIGITAL IMAGE MATCHING

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 a matching procedure. Given transformation parameters between image and object space, locations of these image primitives in object space can be calculated.

Generally, image matching technique may be classified into three categories:

- Area-based image matching which uses directly intensity values of images that might be preprocessed, for example, by cross correlation, least-squares image matching, and other methods.
- Low level feature-based image matching which compares low level primitives, such as interest points, edges, or other features in images.
- High level feature-based image matching which uses processed primitives such as identified objects, object parts, and relationships 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 themselves are very difficult to resolve. Area-based image matching is widely applied in practice. This method achieves good results in cases where the surface relief is relatively flat and the surface is projected onto images with rich image texture (Ackermann, 1984; Foerstner, 1986; Wong, 1986). Inversely, the reconstruction of discontinuous surfaces and surfaces with few texture images by means of this method is problematic. However, in those 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 surface discontinuities. Therefore, edges can be extracted with help of digital image processing techniques; corresponding edges in stereo images are found by edge-based image matching (Marr, 1982; Ohta and Kanade, 1985; Ohta and Ikeda, 1988; Li, 1988; Li, 1990).

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RECONSTRUCTION OF DIGITAL SURFACE MODELS

The 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, 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 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 both 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 1 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 corresponding edges can be efficiently found by edge-based image matching (Li, 1990). Through image preprocessing, such as contrast enhancement and high and low pass filtering, 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.

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 of all grid points are calculated. *Z* values of grid points calculated at 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.

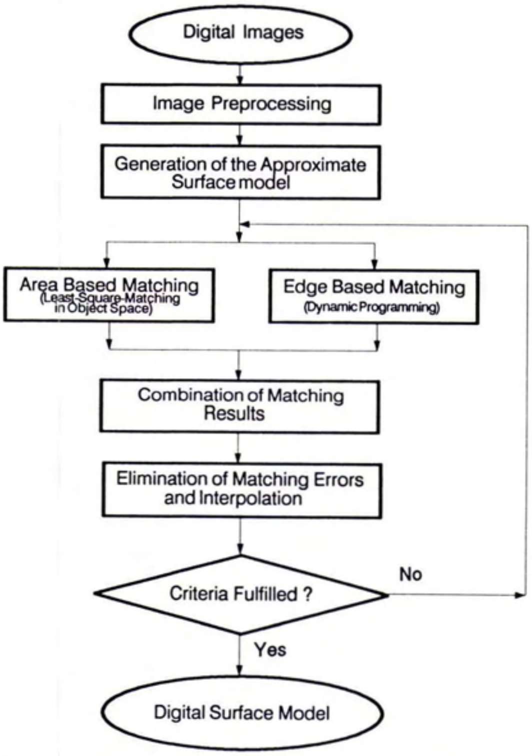

FIG. 1. A schema of the algorithm for reconstruction of a surface with discontinuities by digital image matching technique.

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 relatively 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 the 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; and (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 supression of surface discontinuities due to global interpolation.

Because of a 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. At this point, a complex surface model is generated.

In the image matching procedures, area- and edge-based image matching modules run separately (Figure 1). That is, the result from one image matching module does not benefit the

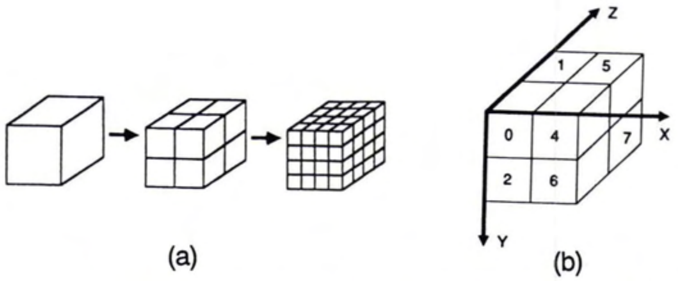

FIG. 2. (a) Octant subdivision and (b) correspondence between the Cartesian coordinate system and suboctants.

other directly. In fact, area-based matching improves the digital surface model and could provide better geometric constraints 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 are satisfied, for example, the number of iterations and/or the percentage of total mismatched points. The final result is a digital surface model which approximates the real object surface as closely as possible.

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

CONVERSION FROM A DIGITAL SURFACE MODEL TO AN OCTREE REPRESENTATION

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; Spur *et al.*, 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 2a, at first level, the original octant is divided into eight suboctants by halving it in three directions. Each suboctant is then checked to see 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 Cartesian coordinate system (Figure 2b). 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 3 shows an example of octree representation. In order to create the octree representation, the simple object of Figure 3a is subdivided twice. The first level contains the root or the original octant (Figure 3b); 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 3c shows a linear octree of the object.

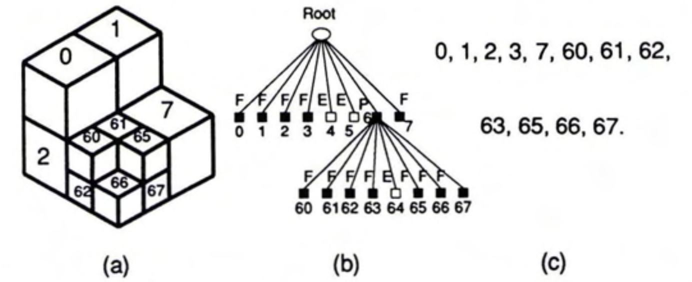

FIG. 3. An example of octree representation: (a) a 3D object, (b) its octree, and (c) its linear octree.

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 4 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. However, 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.

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 5, 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

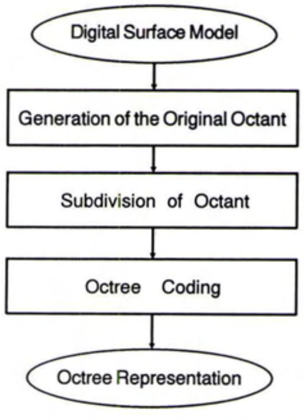

FIG. 4. A concept for conversion from a digital surface model to an octree representation.

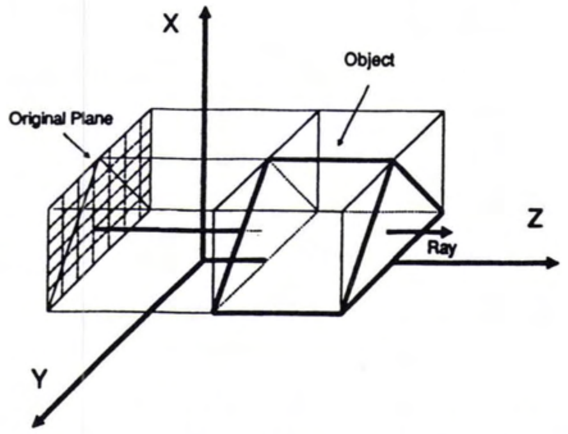

FIG. 5. Building the original octant by ray tracing technique.

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 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 $2^n \times 2^n \times 2^n$. Here, n is determined by the defined resolution of the octree and the dimensions of the object. Voxels in the extended part of the original octant are filled with the value 0. So far, the control as to whether a voxel belongs to the object is simplified by checking 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 $2^n \times 2^n \times 2^n$. 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 an 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 database of octree representation. This database may be used for further database conversions or directly for geometric processing and simulations.

EXPERIMENTS

Programs for 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.

Figures 6a and 6b illustrate a stereo image pair of a test model which simulates a discontinuous surface. The test area has a dimension of about 0.70 by 0.55 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 about 1.5 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, least-squares image matching in object space was started to refine surface points in relatively flat regions. The processing of the surface discontinuity began with a Sobel-Filtering. Figure 6c shows that a lot of small spots remain after the filtering, which makes edge following more difficult. For better edge detection, a median filtering was performed prior to edge enhancement (Figure 6d) so that the small spots and a part of image noise were filtered out. Figure 6e shows the result of the edge extraction by using a Sobel operator on the image of Figure 6d. 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 6f 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 64 by 64 by 64 was defined. A ground Z value was added to the digital surface model in Figure 6f. 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 7a, 7b, and 7c show octants of 2nd, 4th, and 6th level. Figure 7d 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 7, 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, for col-

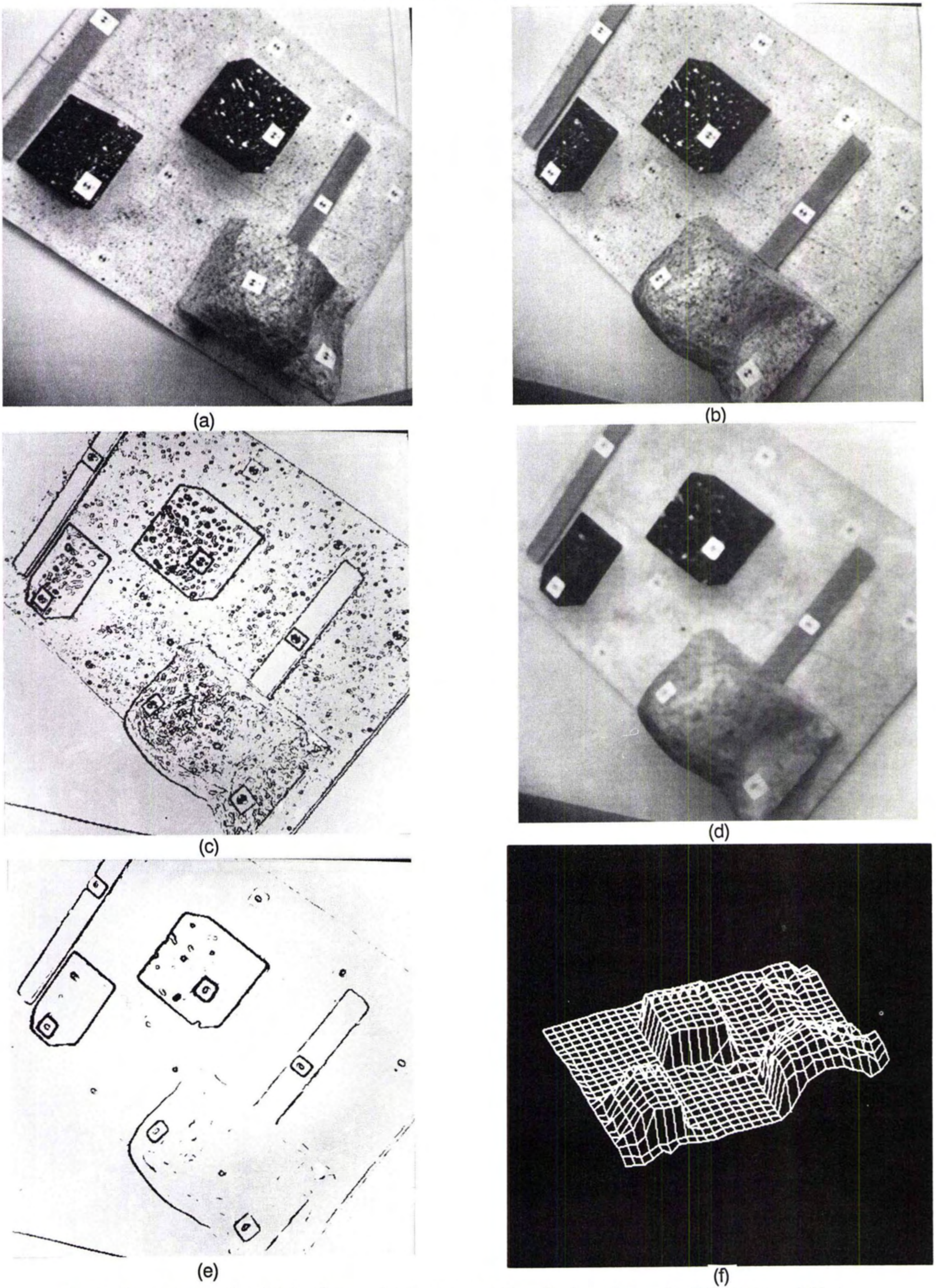

FIG. 6. Reconstruction of a digital surface model of a test model from its stereo images by digital image matching.

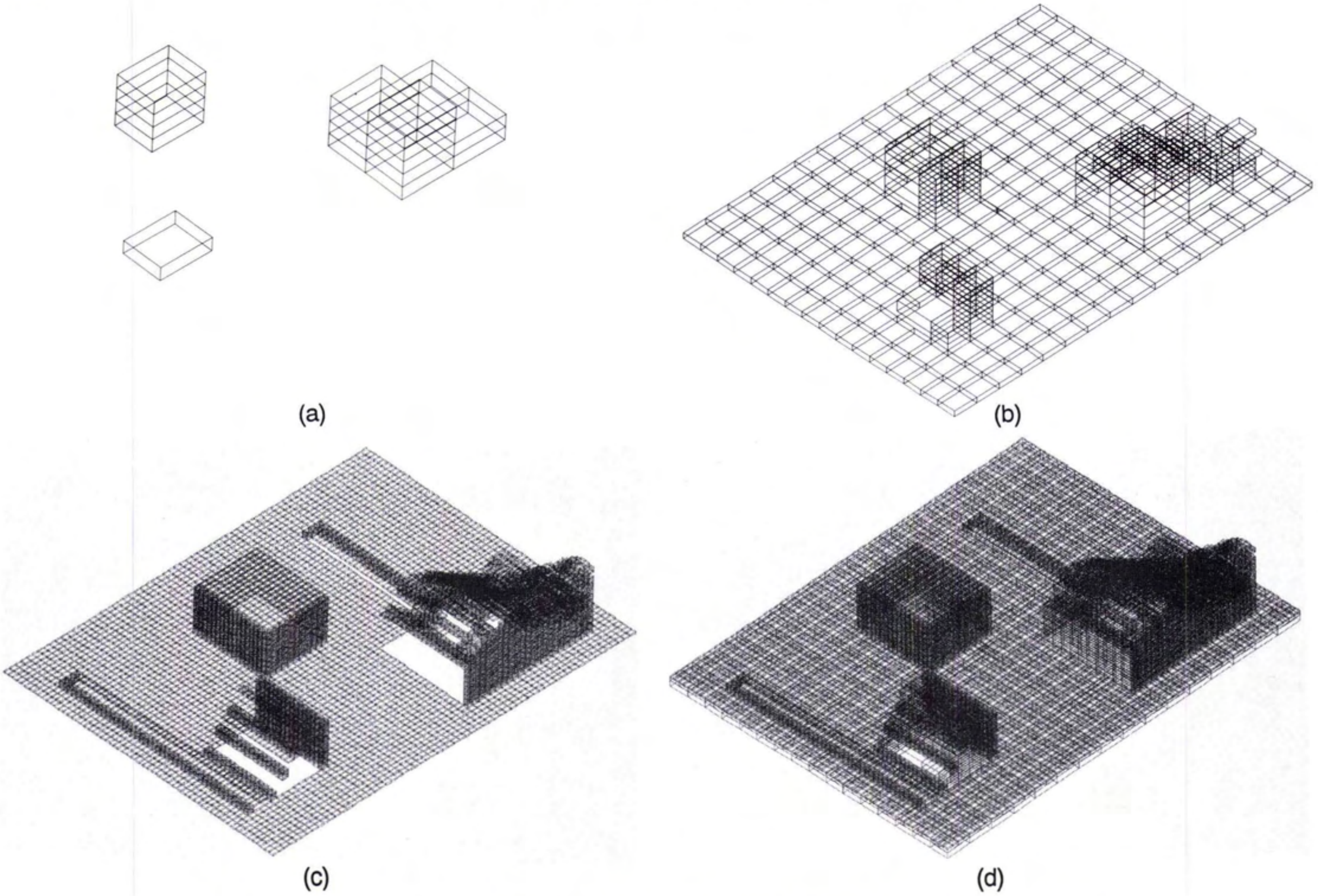

FIG. 7. Octants at 2nd (a), 4th (b), and 6th (c) level, and the octree representation of the test model (d).

lision control for industrial robots, and for path planning of mobil robots.

CONCLUSIONS

Digital photogrammetry can be applied to acquire 3D geometric data for the generation of octree 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 an octree representation. The presented method may be applied in the fields of design and manufacturing in mechanical engineering, automobile industry, robot technology, and others.

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