A Robust Object Modeling System Using a Range Finder

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Abstract

This paper presents a robust object modeling system that generates an object model from multi-viewing range data. The purpose of the system is to obtain an exact object model, overcoming a noise problem in range data. Our system computes object existence in voxel space by integrating observations form multi-viewpoints. The noise in range data is excluded by this integration process. Then, a triangular mesh is efficiently obtained by using adjacent relationships between voxels. Finally, a fine object model is acquired by associating brightness values in color image with the vertex on the mesh. Experiments are performed for plural real objects (dolls and a cup) and effectiveness of the system is shown.

1 Introduction

We have researched an automatic object modeling system to acquire a model for computer graphics. Automatic object modeling using a range finder has been studied actively since the later half of the 80's. To be used in computer graphics, an object shape definition needs to be made from its whole surface. [Nishino89], [Suenaga90] presented a modeling system based on cylindrical observation using a turntable. These systems observe only in the direction of the center of the turntable's rotation. The whole shape of a simple convex object can be generated by using the adjacent vertexes and the topological relationships of the measurements. On the other hand, [Sakaguchi90], [Sakaguchi91] computed object shape by shaving off a space between a measured surface and a range finder. But the space which an object actually occupies has a possibility to be shaven by the noise. [Hoppe92] has proposed a method creating a triangular mesh using a signed distance function from a collection of unorganized points on an object. However, a generated mesh may be under the influence of the noise, because the distance function should be accurately estimated for all points. Also [Turk94] presented an approach of fusing partial shapes generated from multi-view. This approach was applied to the generation of an entire shape from multiple observations well. But an integrated surface still contains the noise unless the filtering with the distance threshold is used. Thus, all of above approaches need to use the noise filtering with the adhoc threshold to acquire a good object model.

Our main purpose is to overcome the difficulty of the noise which comes from irregular reflections in using a range finder. We proposed an automatic object modeling system from multiple observation in

[Suzuki93]. In this paper, we present a robust modeling system to refine the system in [Suzuki93]. We compute "object occupancy space" by integrating "object occupancy candidate spaces" expected from each observation. The object occupancy candidate space is space behind a partial mesh generated using measured range data, and indicates space where it is expected that an object could exist. The object occupancy space is space supported from multiple observations. We can obtain a mesh covering an entire object surface without noise using range data in this object occupancy space. These two spaces are calculated in voxel space. The mesh is generated by using topological relationships between voxels in the object occupancy space. Therefore, our method can be applied to range data measured from multiple viewpoints. In addition, to achieve a fine object model, we associate brightness value in color image of an object with each vertex on the mesh. This associated brightness value is utilized as texture on the mesh, and we can display the shape with the real color of the target object.

2 System Overview

Our system measures an object on a turntable from multiple viewpoints and finally generates a mesh with brightness value. Figure 1 shows the configuration of the measurement equipment used in the system. In order to measure the entire object surface of a target object, the object is put on a transparent turntable. Every time the turntable revolves $\Delta\theta$, range data and an object image are obtained. A range finder shifts its position in x axis on the linear slider, and performs the scan in the Y-Z plane using a mirror. As a result, range data are obtained as 2D array of $n_x \times n_y$ from an observation. Each point in range data is classified as a surface point or a background point. A background point is a point on a background or a point which was not measured due to low reflection. Surface points are those not classified as part of the background. The transparent turntable was used in order not to measure the surface of the stand where the object is put. Then, brightness value (RGB value) in an object image is associated with surface points in range data. This brightness value is used as texture on the mesh generated finally.

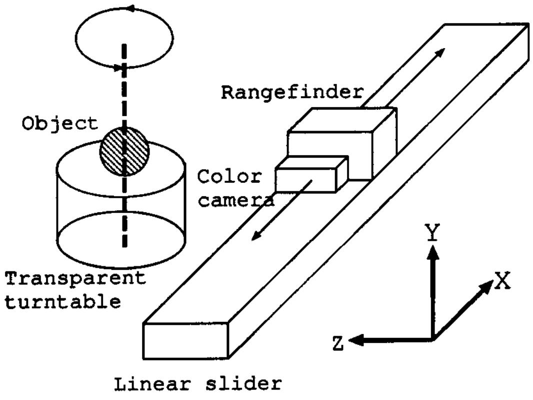

Figure 1: Configuration of measurement equipment

We generate the mesh on the object using these measured data. First, a partial mesh is calculated by connecting surface points in range data observed from each observation. This partial mesh is used to obtain object occupancy candidate space in the voxel space. Object occupancy candidate space is space behind the partial mesh from the viewpoint of the range finder. Object occupancy candidate space supported from most observations is determined as object occupancy space which corresponds to the whole shape of the object. Vertexes on a mesh are calculated from range data in this object occupancy space. Also, topology of the mesh is generated with adjacent relationships between voxels in the object occupancy space. Finally, we assign brightness value of each surface point in range data to vertex on the mesh.

3 3D Shape Reconstruction

3.1 Object Occupancy Space

The range finder used by the object modeling system measures the three dimensional position of where the reflection of the laser happened. On the locus of the laser light, it is unknown whether an object occupies the rear space of the reflective position on the object surface, although it can be easily determined that the object does not exist in the front space of the position. We refer to this rear space as "object occupancy candidate space" where it is expected that an object exists. Object occupancy space is determined from object occupancy candidate space according to multi-viewing results. Even if the object occupancy candidate space is mistakenly determined by the noise in one observation, there are few possibilities that the same space will be determined as object occupancy candidate space according to the other observations. Thus the noise at measurement can be removed. Object occupancy candidate space and object occupancy space are computed in two voxel spaces; temporal voxel space and common voxel space. Temporal voxel space is used to calculate object occupancy candidate space temporarily for each observation. And common voxel space is employed to determine object occupancy space. This common voxel space is modified every time object occupancy space is computed. These voxel spaces express the same space, having the same voxel size.

A process determining object occupancy space is shown in Figure 2. Figure 2(a)-(c) indicate object occupancy candidate space obtained when a circle-like object is observed from three orientations, and the arrow head indicates the orientation of observation. Assuming that some noise is contained in observation of Figure 2(a). Figure 2(d) is a result of integrating object occupancy candidate spaces computed from each observation. In this case, that object's occupancy space can be successfully obtained without influence from the noise.

Formally, determination of object occupancy space is performed in four steps: (Figure 3).

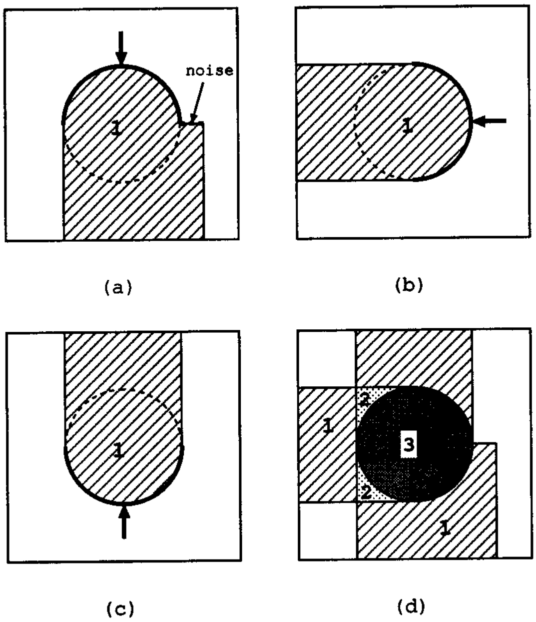

Figure 2: The outline of the process by which object occupancy space is determined. (top view)

step1 A partial mesh is generated from range data obtained from an observation.

step2 For each triangle in the generated mesh, perspective space which spreads from a viewpoint of the range finder in the rear of the triangle is calculated. This perspective space is object occupancy candidate space.

step3 The object occupancy candidate space is associated with voxel space.

step4 Object occupancy space is determined according to the judgements of object occupancy candidate space.

Each step will be explained in detail below. In step1, a mesh used to obtain perspective space is calculated. The mesh is reconstructed using range data from an observation. Because range data are acquired as 2D array, the mesh can be generated easily. Each point has a flag which indicates

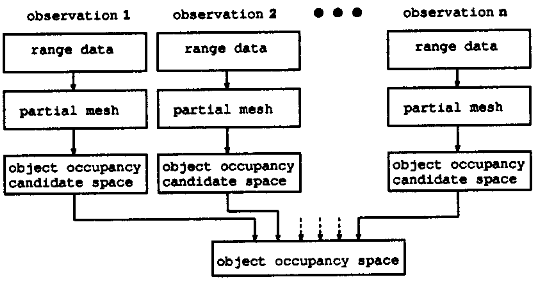

Figure 3: The determination process of object occupancy space.

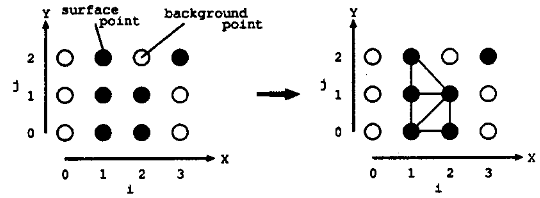

Figure 4: Triangulation

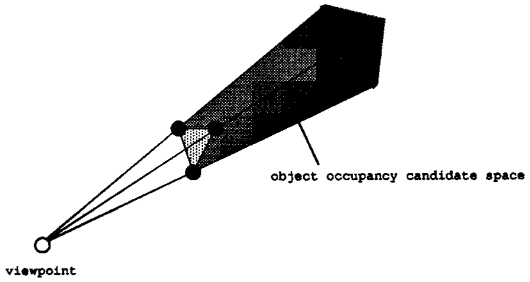

Figure 5: Object occupancy candidate space

whether it is a background point or a surface point; only surface points can express the object surface. The 3D shape is reconstructed with these surface points. When n_x points are measured in the direction of x axis and n_y measurement in the direction of y axis is performed, a point is expressed as P(i,j); i=0,..., n_x-1 and j=0,...,n_y-1. Triangles generated in this step are temporal data for computing object occupancy candidate space and the triangles are not used in a final mesh. We use a very simple triangulation algorithm. Because P(i,j), P(i,j+1), P(i+1,j+1), and P(i+1,j) are neighboring points, triangles which are generated from these points can be considered to be on the surface of the target object. The triangulation algorithm is as follows (Figure 4).

- When there are two or less surface points, a triangle is not generated.
- When there are three surface points, a triangle is generated using the three points.
- When there are four surface points, two triangles are generated.

This triangulation is performed for any given (i,j).

In step2, each triangle generated by step1 is projected from the viewpoint of the corresponding observation. Space behind the triangle is calculated as object occupancy candidate space. Our range finder performs the scan in the Y-Z plane using a mirror. We use perspective projection to build object occupancy candidate space solely because of the material constraints (Figure 5). This object occupancy candidate space is obtained by checking the intersection between voxel and a line projected from a point on a triangle. Object occupancy candidate space obtained from each observation is computed in temporal voxel space.

Step3 is where the object occupancy candidate space obtained in temporal voxel space is related to a common voxel space. Each voxel in this common voxel space has a "score of object occupancy space". This score is the number of observations by which the voxel is judged as object occupancy candidate space. In the beginning of the determination process of the object occupancy space, the scores for all voxels are set to 0. Then, the scores are accumulated according to object occupancy candidate space in temporal voxel space obtained from each observation.

Step4 is executed after performing the step1-3 for all observed range data. The final determination of object occupancy space is carried out according to the score of object occupancy space for each voxel in common voxel space. The determination is performed by using a common threshold value for all voxels.

3.2 Mesh Generation

After calculating the object occupancy space in voxel space, it must be converted into the mesh data to be used as shape data. Marching cubes method [Lorensen87] is a well-known approach to extract isosurface of triangular mesh from 3D scalar data. However, the marching cubes method cannot be applied to the mesh generation connecting the scattered 3D points, directly. To apply the marching cubes method to scattered 3D points, it is necessary to use a scalar function as [Hoppe92]. But the calculation of the scalar function requires the adjustment of some parameters for each data. We use an original mesh generation method which can generate 3D surface without both the calculation of the scalar function and the adjustment of the parameters. In our system, the mesh is generated by checking all the voxels in voxel space to see whether the adjacent voxels are part of the object occupancy space. Mesh generation is composed of three following steps:

step1 Surface shape of an object is generated from voxel space in which object occupancy space was computed.

step2 By associating coordinate of multi-viewing range data with the voxel space, vertex coordinate value of each triangle is calculated.

step3 Smoothing process is performed for coordinate values of the vertexes of each triangle.

First, the mesh which expresses a target object shape is generated (step1). Then, the mesh calculated by step1 is modified using original range data (step2). The coordinate value of each vertex of a mesh is changed in consideration of the surrounding vertex coordinate values (step3). Each step will be explained in detail below.

In step1, the surface shape of the target object is formed from voxel space from which the object occupancy space is determined. Each voxel in the voxel space has a flag which indicates whether it is object occupancy space. A mesh is generated by checking the flags of the eight neighbor voxels of each voxel. Figure 6 shows all the possible patterns of the flags in the eight neighbor voxels which indicates object occupancy space and the triangles generated from each flag pattern. The patterns obtained by rotating a pattern around the x, y, or z axis are considered the same pattern. In Figure 6, ● indicates a voxel which is object occupancy space, ○ indicates a voxel which is not object occupancy space. By determining triangles in advance generated from one of twenty-three flag patterns, a mesh can be created efficiently from only the flag check of neighbor voxels for each voxel. The triangle generation from the eight neighbor voxels is based on the following reasons:

- Triangles are generated only when the total number of the neighbor voxels which are object occupancy space is three or more.
- The triangles to be generated form a closed polyhedron; the pattern (f), (g), (h), (i), and (k) form the polyhedron of volume 0.
- The direction of the normal vector of each triangle is taken to be the heading outside from the interior of a polyhedron; in the cases of pattern (f), (g), (h), (g), (i), and (k), the same three vertexes are used to generate two triangles, and the normal vectors of the two triangles point in the opposite direction from each other.
- Vertex coordinate of each triangle is considered as the center of gravity of the corresponding

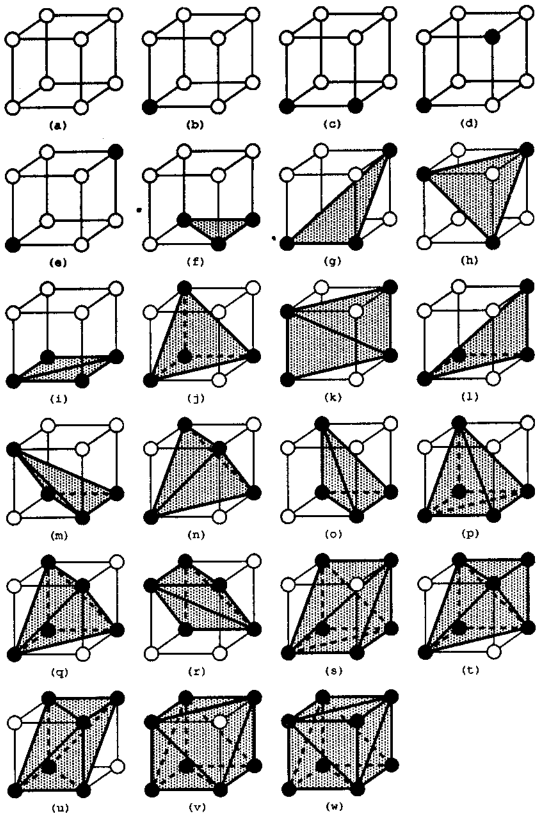

Figure 6: The generated triangular mesh pattern

voxel, which is in object occupancy space.

At this time, the mesh which reflects the 3D shape of the target object is generated according to the generation pattern shown in Figure 6. But when two of the pattern (j), (ℓ), (m), (o), (p), (q), (r), (s), (t), (u), (v), (w) are adjacent, the triangles generated on the boundary of the two patterns are inside of the object. Therefore, our mesh generation method method generate such triangles.

In step2, the mesh obtained by step1 is modified using original range data because each vertex of the mesh is the center of gravity of the corresponding voxel. First, all the points in range data corresponding to a voxel in object occupancy space are extracted. Then, a mean coordinate value of the points associated with each voxel is calculated and assigned to the voxel. At last, each vertex of the mesh is substituted for the mean coordinate value assigned to the voxel associated with the vertex. When there is no corresponding range data, a location of the vertex is still a center-of-gravity position of a corresponding voxel.

Step3 smoothes the mesh data created by step2. A mesh obtained in step2 is based on the measured data (range data). Even if a target object surface is smooth, the mesh may have an uneven shape under the influence of the error in the range data at the time of observation. Then, in order to improve appearance, a simple local smoothing process is performed.

At this time, a generated mesh is composed of triangles and vertexes. A triangle has three indices identifying the vertex, and a normal vector. A vertex holds 3D coordinate value and a normal vector. To each vertex, brightness value will be assigned as described in the next section.

4 Brightness Information

To achieve a final object model, brightness value should be associated to each vertex on the generated mesh. The vertex corresponding to range data can be easily associated with brightness value because that value is already given in the range data. However, the following problems occur when establishing the correspondence of the brightness value.

problem 1 Brightness values from multi-view correspond to one vertex on the mesh.

problem 2 The vertex not corresponding to range data exists.

problem 3 Brightness value on the same position might be different according to every orientation of observation.

For problem 1, from multi-view observations, we select brightness value with the largest angle (smallest angle in terms of directions) between the normal vector of a vertex and the projection vector of brightness value. For problem 2, by applying the same local smoothing process used for the vertexes on the mesh, brightness values are also interpolated. Problem 3 comes from the specular reflection on the object surface and the lighting condition at the time of observation. Thereby, an unnatural brightness change may occur because of the different orientation of the observations. Then, when the surrounding vertexes of a vertex under consideration are associated with the brightness values observed from different orientations, a discontinuous brightness change can be reduced by the local smoothing process stated above.

5 Experiment

We experimented using the system described above. All of the algorithms were coded in C and computed on a Silicon Graphics 4D/420VGX. The range finder used in the system is a product of Serbo-Robot Inc. The depth resolution of the range finder is less than 0.015mm at a distance of 10cm and 1.5mm at a distance of 100cm. We made an experiment using an object as shown in Figure 7. We performed observations from eight directions ($\Delta\theta$=45°), and the number of sampling points of range data to each orientation was taken as 201 × 512. Figure 8 and Figure 9 show range data obtained from these observations. Figure 8 depicts the surface points of all the range data, and Figure

9 shows a close-up of surface points around left arm. The total number of surface points became 102,466 points. Many noises are observed as shown in Figure 8 and Figure 9. Figure 10 shows the voxels supported from seven or more observations. This threshold was obtained from several experiments. The size of a voxel and the total number of voxel were set as 0.6mm, 256 × 256 × 256 respectively. Also, Figure 11 and Figure 12 show a cross-section of the X-Z plane in voxel space. The noise in Figure 8 and Figure 9 is successfully removed in Figure 10. A mesh generated using the adjacent relationships from this voxel is shown in Figure 13. A mesh on which the smoothing process was applied is shown in Figure 14. A final mesh in which brightness values were associated with each vertex is shown in Figure 15 and Figure 16. The uneven surface on the mesh in Figure 13 became smooth as shown in Figure 14. The mesh generated finally is made up of 50,464 polygons and 100,950 vertexes. Execution time of all observations was about an hour, and computation time required to generate the final mesh from the measured data was around an hour. We also executed the experiments for two more objects; a monster doll as an example of more complicated shape and a cup as an example with a lustrous surface. Figure 17, Figure 18, and Figure 19 show experimental results for the monster doll, and Figure 20, Figure 21, and Figure 22 show experimental results for the cup. The measured noise for each object was successfully removed as shown in these figures.

6 Conclusion

We presented a system which automatically models an object. Our system can remove the noise at the measurement without adhoc threshold, by using only range data supported from almost all the observations. Experimental results for real objects showed that our system is robust to noise. Also, our mesh generation method can efficiently reconstructs 3D shape from adjacent relationships between voxels. Moreover, a fine object model can be obtained by associating each vertex of the mesh with the brightness value. However, the surface color may become blurred when the texture on the object is fine, or when the generated polygon size is large. The problem of the fineness of the texture remains to be solved in future works.

References

[Sakaguchi90] Y. Sakaguchi, K. Kato, K. Sato, S. Inokuchi, "Generation of 3-D Models Based on Image Fusion of Range Data," MVA'90, pp.147-150, (1990)

[Sakaguchi91] Y. Sakaguchi, K. Kato, K. Sato, S. Inokuchi, "Acquisition of Entire Surface Data Based on Fusion of Range Data," IEICE TRANSACTIONS, Vol.E74, No.10, pp.3417–3422 (1991)

[Suenaga90] Y. Suenaga, Y. Watanabe, "A method for the Synchronized Acquisition of Cylindrical Range and Color Data," MVA'90, pp.137-141, (1990)

[Nishino89] H. Nishino, K. Akiyama, Y. Kobayashi, "Acquisition of 3-Dimensional Object Shape Using Slit-Ray Projection and Reconstruction of Surface Model," IEICE TRANSACTIONS, Vol.J72-D-II, No.11, pp.1778-1787, (1989) (In Japanese)

[Turk94] G. Turk, M. Levoy, "Zippered Polygon Meshes from Range Images," Computer Graphics Proceedings, Annual Conference Series (SIGGRAPH'94), pp.311–318, (1994)

[Hoppe92] H. Hoppe, T. DeRose, T. Duchamp, J. McDonald, W. Stuetzle, "Surface Reconstruction from Unorganized Points," Computer Graphics, Vol.26, No.2 (SIGGRAPH'92), pp.71–78, (1992)

[Lorensen87] W.E. Lorensen, H.E. Cline, "Marching Cubes:A High Resolution 3D Surface Construction Algorithm," Computer Graphics, Vol.21, No.4 (SIGGRAPH'87), pp.163–169, (1987) [Suzuki93] K. Suzuki, T. Wada, M. Bro-Nielsen, "Automatic Objet Modeling Based on Multi-viewing Sensing Images," ACCV'93, pp.244–247, (1993)

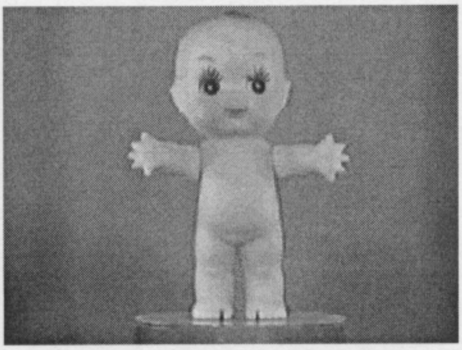

Figure 7: An observed object

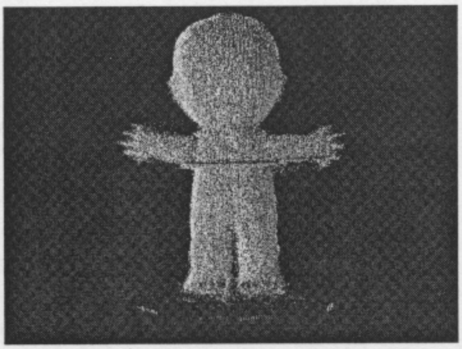

Figure 8: All range data from eight observations

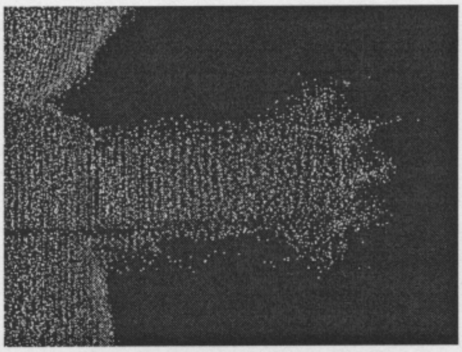

Figure 9: A part of range data from eight observations (close-up of left arm and left hand)

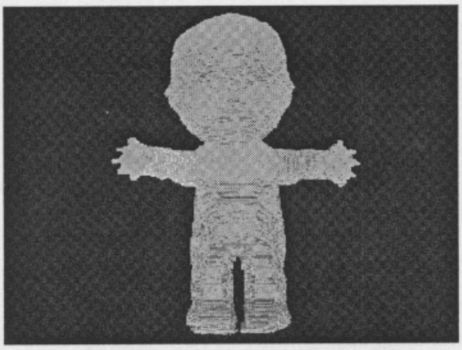

Figure 10: Voxels in object occupancy space

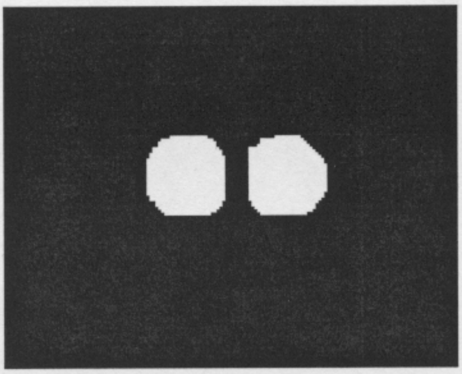

Figure 11: A cross-section in voxel space (51th X-Z plane, top view)

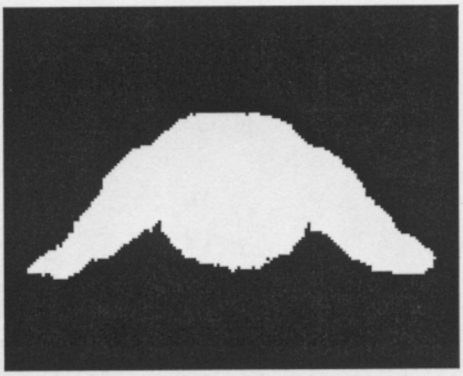

Figure 12: A cross-section in voxel space (129th X-Z plane, top view)

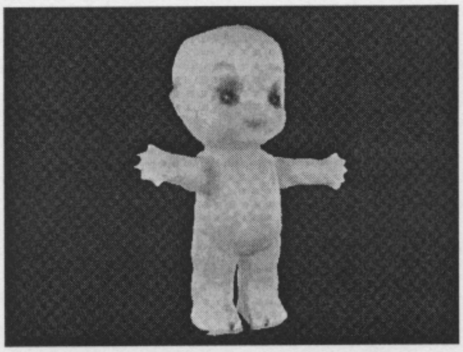

Figure 15: A mesh associated with brightness values after performing smoothing process (front view)

Figure 13: A mesh before performing smoothing process (before step3 of mesh generation)

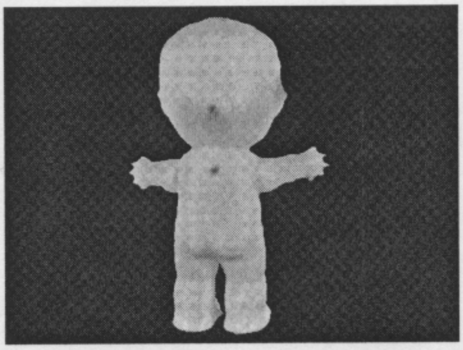

Figure 16: A mesh associated with brightness values after performing smoothing process (back view)

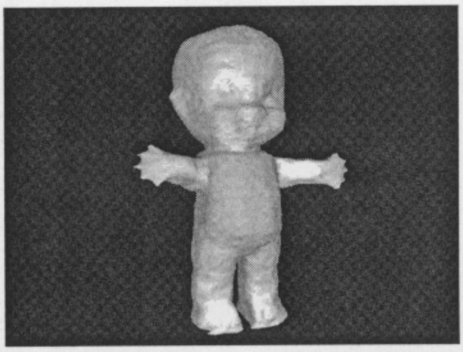

Figure 14: A mesh after performing smoothing process

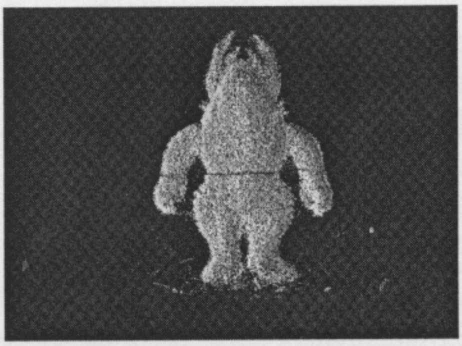

Figure 17: Range data from eight observations (for the monster doll)

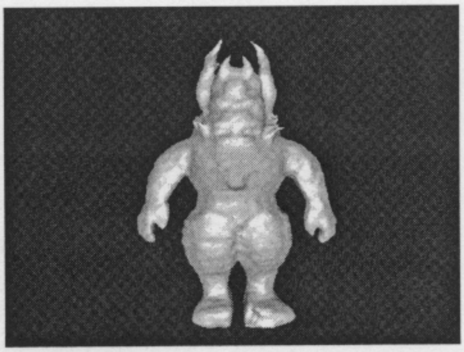

Figure 18: A mesh after performing smoothing process (for the monster doll)

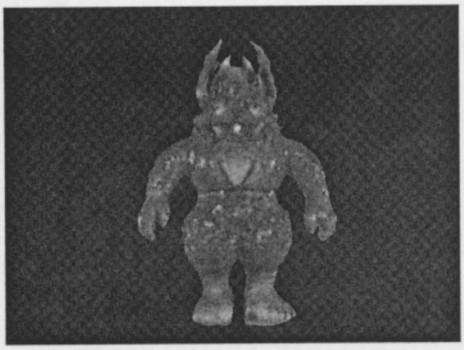

Figure 19: A mesh associated with brightness values after performing smoothing process (for the monster doll)

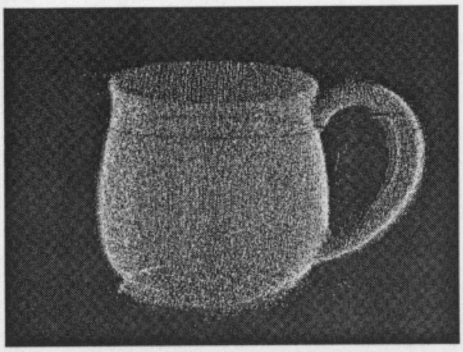

Figure 20: Range data from eight observations (for the cup)

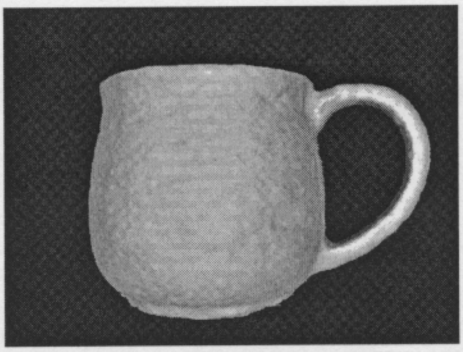

Figure 21: A mesh after performing smoothing process (for the cup)

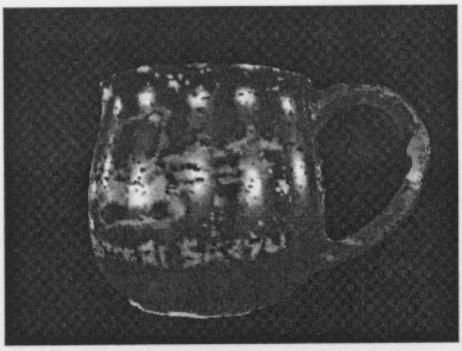

Figure 22: A mesh associated with brightness values after performing smoothing process (for the cup)