Proc. of 1st KSV Conference
KAIST, Daejeon, KOREA, Nov. 8, 2002

영상 기반 3차원 형상 추출 및 가시화

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Determination and Visualization of Three-Dimensional Shape Based on Images

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Abstract

We propose an image based three-dimensional shape determination system. The shape, and thus the three-dimensional coordinate information of the 3-D object, is determined solely from captured images of the 3-D object from a prescribed set of viewpoints. The approach is based on the shape from silhouette (SFS) technique and the efficacy of the SFS method is tested using a sample data set. This system may be used to visualize the 3-D object efficiently, or to quickly generate initial CAD data for reverse engineering purposes. The proposed system potentially may be used in three dimensional design applications such as 3-D animation and 3-D games.

Key Words : Shape from Silhouette, Triangulation, Cloud of Points, Shape Reconstruction.

1. Introduction

Recent advances in computer and related technologies have enabled ordinary users to experience virtual three-dimensional space just with a conventional desktop computer. What used to be only available to professionals is now reaching the general public. For instance, three-dimensional design software tools such as 3DMAX and Pro-E have developed to provide incredible levels of sophistication. Parallel to these software development efforts, 3-D shape detection and content generation systems have also been keeping pace to satisfy modern user's appetite for 3-D content.

The three-dimensional shape detection systems can be categorized broadly into two groups. The first is based on laser-scanning and the second is based on captured images.

The laser-based technique consists of a laser that illuminates a known pattern (such as a grid) on the surface of the object and an optical camera that detects the reflected pattern. The acquired images from the optical camera called the "range images"[1,2,3,4,5] are analyzed to determine the 3-D shape of the object. This technique has been used successfully in the "Digital Michelangelo Project"[6] and many similar commercial systems are now available in the market.

The image-based technique is still in the development stage, showing much promise. This technique determines the 3-D shape solely based on captured images of the object from a prescribe set of viewpoints. Currently, there are various research groups working towards improving this technique for their own special needs[21]. In this paper, for our eventual goal of efficient visualization of 3-D objects, we present our own design of an image-based 3-D shape determination system. The 3-D shape is "carved" based on the silhouette data determined from captured images, namely the shape from silhouette (SFS) technique. This technique is followed by a new iterative triangulation algorithm to generate the final mesh model of the 3-D object.

2. Image Acquisition System

The proposed 3-D shape determination and visualization system captures images of 3-D objects from all possible view angles (viewpoints)[17]. Thus, the camera must rotate around the object on the surface enclosing it and must point towards the object for capturing images. Fig. 1 shows our image acquisition system, which captures images of 3-D objects from all possible viewpoints.

The object is placed on the turntable and is imaged by the camera on the carriage. The carriage, powered by a stepper-motor equipped with an encoder for position feedback, moves along the vertical C-arm by means of a timing belt (difficult to see in the photo) attached to it. The turntable is powered by a second independent stepper-motor, also is equipped with an encoder for

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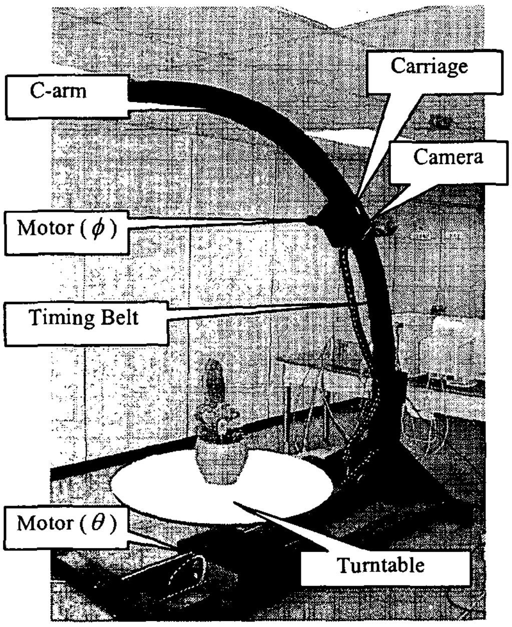


Fig. 1. The 3-D content generation system for capturing images of objects from all possible view angles. See text.

position feedback. Thus, the camera is able to capture images of the 3-D object at all possible view angles on the upper hemisphere.

Two motors controlling θ (turntable) and ϕ (camera carriage) are pre-programmed from the operator console (PC) to run in a prescribed manner. The shutters are released at the predetermined position of (θ, ϕ) upon consulting feedback values of the two encoders on both motors. As the expected, the actual view angles (θ, ϕ) will differ, and the system records the encoder readings of all image capture positions and tags each captured images with the actual θ and ϕ values.

3. Extraction of 3-D Shape

3.1 Segmentation

Before the 3-D shape can be determined, individually captured images must be segmented. That is, the object must be separated from its background. This segmentation is a difficult process at best in a general setting. However, if the image is captured with monotone background (which can be controlled when imaging the object), the object can be segmented with a relative ease through a simple thresholding and the connectivity test. Thus, all objects have been imaged with a monotone (usually white to avoid glares) background.

3.2 Shape from Silhouette

Martin and Aggawal[7] presents a three-dimensional shape determination technique using orthogonally projected silhouettes. Others have followed refining this

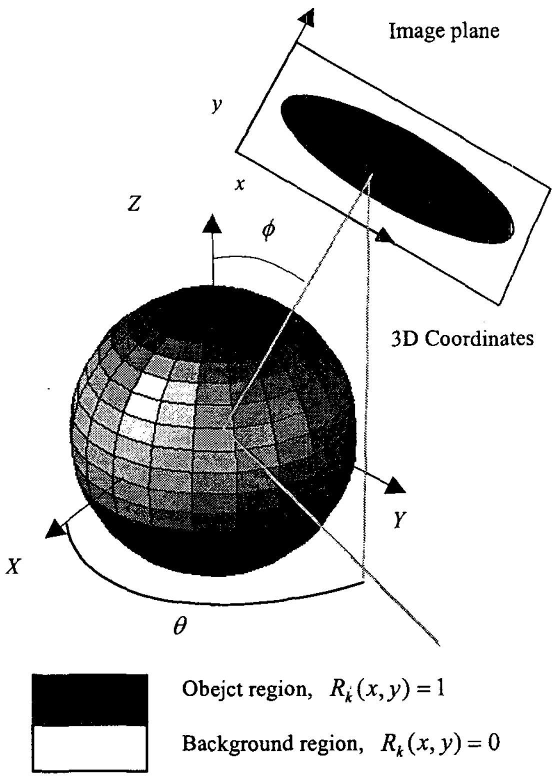


Fig. 2. Coordinates set for orthogonal projection.

shape from silhouette strategy technique to date[14,15,16].

Our proposed technique similarly delineates the boundary of the 3-D object and uses the SFS algorithm as follows. Figure 2 defines the coordinate system used in the following description. On the image plane $[x, y]^T$, let $R_k(x, y) = 1$ denote the object and $R_k(x, y) = 0$ denote background regions, respectively. Here, the index k represents the image number and (ϕ_k, θ_k), $k = 0,1,K,N-1$, denote corresponding view angles, where N is the total number of acquired images. The aforementioned segmentation step determines $R_k(\text{o,o})$. Based on this segmented object data, the binary volumetric data $V(X, Y, Z)$ is generated. The volume data $V(X, Y, Z)$ is set to "1", if that voxel represents the object, or a "0", if background. The following is a pseudo code of the algorithm:

For ($k = 0,1,K,N-1$)

  For (all $[X, Y, Z]^T$)

    $[x, y]^T = M(\phi_k, \theta_k)\,[X, Y, Z]^T$

    If ($R_k(x, y) = 1$) $V(X, Y, Z) = 1$

    Else $V(X, Y, Z) = 0$

In the above, $M(\phi_k, \theta_k)$ is the transformation matrix that takes the 3-D point $[X, Y, Z]^T$ to the 2-D image

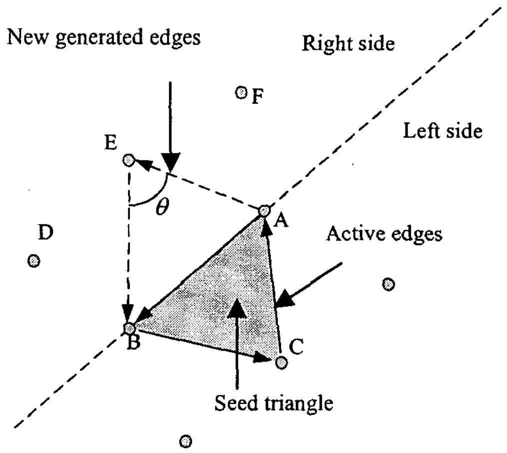


Fig. 3. Seed triangle and polygon growth.

point $[x, y]^T$ according to the view angle (ϕ_k, θ_k) defined as follows.

$$M(\phi_k, \theta_k) = \begin{bmatrix} \cos\theta_k & -\sin\theta_k \cos\phi_k & -\sin\theta_k \sin\phi_k \\ 0 & \sin\phi_k & -\cos\phi_k \end{bmatrix}$$

4. Three Dimensional Shape Reconstruction

4.1 Cloud of Points

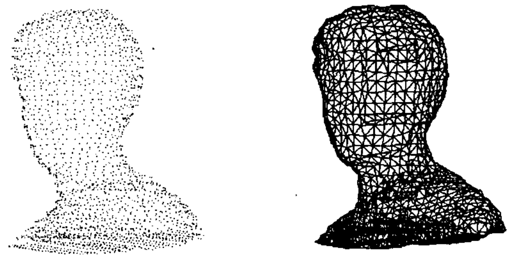
The binary volumetric data $V(X,Y,Z)$ actually represents the 3-D object where "1" and "0" indicates object and background regions, respectively. The data is used to determine the *cloud of points* on the boundary of the object, which can then be used to generate the 3-D mesh of the object. For this purpose, we simply divided the volume into $M \times M \times M$ sub-blocks and selected the point on the surface that is closest to the center of the $M \times M \times M$ cube. The selected points become the cloud of points to be used in the following triangulation algorithm.

4.2 Triangulation

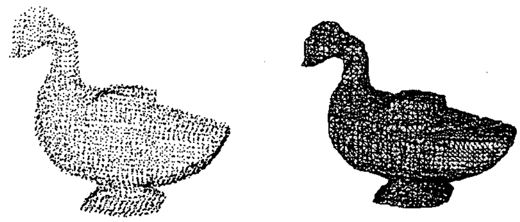
There exists many algorithms to perform the task of triangulation from cloud of points. The most popularly used Delaunay-Vornoi triangulation algorithm[19] guarantees optimum polygon state. However, its complexity of order N^4 for triangles in 3-D is costly. In addition, it is known to generate superfluous triangles in concave regions, and thus the process referred to as *crust algorithm*[20] is needed. Other approaches include *marching cubes*[18], *ball pivot algorithm* (BPA) [9], and a method using linear interpolation between polygon slices [8] also have been proposed.

Our proposed triangulation is a modified version of fast algorithms proposed by Hoppe[10] and Oblonšek[11] based on *k*-neighbor[12] points sets and their approximate tangent planes. All points in the *k*-neighbor point set are projected to their approximate tangent plane. The triangulation procedure is executed in this tangent plane and the extracted triangle is back-projected to the three-dimensional space before storage. However, the algorithm does not guarantee optimum state of triangles and a clean-up procedure such as the "swap edge" algorithm must be used for the generation of optimum state of triangles. Our approach is a modification of this *k*-neighbor and its approximate tangent plane triangulation algorithm.

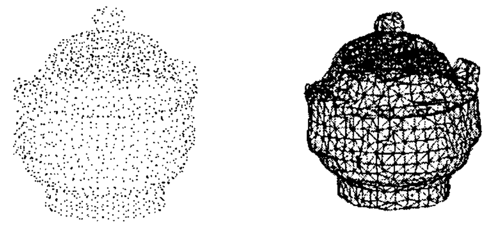
Our proposed triangulation begins with determination of a seed triangle. The highest point (in *Z*) is first detected for this purpose. The plane that contains this highest point and orthogonal to the *Z*-axis is used to detect the remaining two points to complete the seed triangle. If there are over three points without tilting, then we are done, as two closest points are selected. The plane is tilted with respect to the *Z*-axis until two remaining points are found to complete the seed triangle. Of the two normal vectors for the seed triangle the one



(a)



(b)



(c)

Fig. 4. Examples of 3D shape modeling results. (a) Shape of a male with 4179 triangles. (b) Traditional art "Gaya duck-shape pottery" with 7121 triangles. (c) Traditional art "Baekjahyangro" with 2677 triangles.

that forms the smaller angle with the Z-axis is chosen.

The algorithm starts with three active edges, based on the seed triangle. Figure 3 summarizes our triangulation algorithm. The algorithm searches for the next triangle for each active edge (three in the beginning, AB, BC, and CA in Fig. 3). For instance, for the edge AB, all points in the k-neighbor of the point A and B are projected to the approximate tangent plane. Based on the direction of the normal vector, the tangent plane is divided into LEFT and RIGHT half-planes. All points on the RIGHT half-plane are tested and the point that forms the largest θ with no other points in the new triangle is selected as the vertex of the new triangle. Then, AB becomes inactive and zero, one or two new active edges are formed (in this case, two new active edges). When it comes time that zero new active edge is formed, the algorithm stops.

5. Results and Conclusions

Figure 4 shows the results for (a) a human head, (b) a sculpture of a duck and (c) an antique pottery. All were scanned with the system shown in Figure 1. These objects are available on the Internet for 3-D viewing [13].

The triangles, which describe the shape of object, can be imported into 3-D tools such as 3DMAX and Pro-E for further manipulation for PC game or CAD applications. We are currently progressing towards extracting the texture information from captured images for each triangle.

Acknowledgement

This research was supported in part by a grant "A development of 3-D modeling and making contents based on real-life imagery" from the Ministry of Culture and Tourism

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