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Measuring Three-Dimensional Shapes of a Human Face Using Photometric Stereo Method with Two Light Sources and Slit Patterns

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Abstract

In this paper, a new method for measuring 3D (three-dimensional) facial shapes is introduced. First, the normal vectors at the points on a face are computed by the photometric stereo method with two light sources. Next, multiple light stripes are projected onto the face with the slit pattern projector. The 3D coordinates of the points on the stripes are measured using the stereo vision algorithm. The normal vectors are then integrated within 2D finite intervals centered at the measured points on the stripes. The 3D curved segment within each finite interval is computed by the integration. Finally, all the curved segments are blended into the complete facial shape using a family of exponential functions. This method enables accurate 3D measurement of the complicated shapes of a human face in a short time.

1 Introduction

The human face is one of the most important parts of the human body, because it has great expressive ability which can provide clues to the personality and emotions of a person. Recently, automatic and noncontact facial analysis systems with video cameras and computers have been used in many applications. To analyze a human face correctly, the 3D shapes of the human face must be measured accurately. Therefore, the measuring time should be as short as possible to avoid errors due to changes in the shape of the face.

In most of the existing methods, such as the binocular stereo method [1], the 3D coordinates of objects are measured directly using multiple cameras. The 3D coordinates of points on the objects are determined using multiple images taken from different angles. In such methods, the greatest difficulty is encountered in the identification of corresponding points of the images. To measure the 3D facial shapes, the widely adopted methods of identification use characteristic regions such as the nose, mouth, eyes, and eyebrows or special markings on the face. These methods, however, can be used to measure only a small number of points on the face.

The slit pattern projecting method simplifies the identification problem. By projecting points or lines onto a face, we can compute the 3D coordinate values of the illuminated positions. To measure the entire face by the projecting method, the scanning method has been applied [2, 3, 4]. This method requires a long time to scan the entire face and the facial shape may change during scanning. Color-coded light stripes enable instantaneous measurement of the entire facial shape [5]. The accuracy of the measured data, however, is low because it is affected by the color of the skin.

Recently, several methods of measuring the normal vectors of objects based on photometric properties, such as the shape from shading method [6] and photometric stereo method [7, 8], have been proposed. These methods can provide a high density of 3D information about complicated object shapes in a short time. The methods, however, cannot be used to measure the 3D shapes of a human face accurately. This is because the accuracy of the measured data is affected by the various photometric properties of each face.

2 Method of Measurement

Figures 1,2, and 3 show the apparatus for the proposed 3D measurement and the 3D orthogonal coordinate system used for the measurement.

A video camera is set in front of a face. The origin of the coordinate system is the center of the camera lens. The x-axis is parallel to the axis of the abscissa of the camera image plane and the y-axis is parallel to the axis of the ordinate of the plane. Three light sources (S_1, S_2, S_3) are arranged on a straight line which is parallel to the y-axis. A slit is located in front of the light source S_3 and the stripes are projected onto the face through the slit.

With the apparatus, the proposed method takes four steps: (1) computation of normal vectors, (2) depth measurement by projecting stripes, (3) inte-

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gration of normal vectors inside finite intervals, and (4) blending of curved segments.

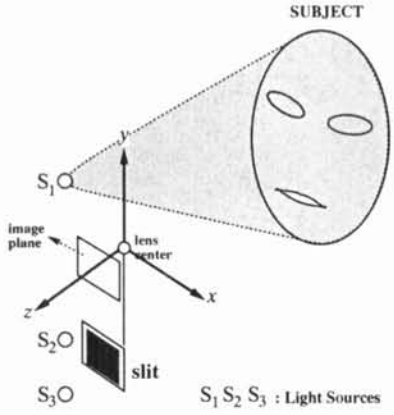


Figure 1: A face is illuminated by S_1

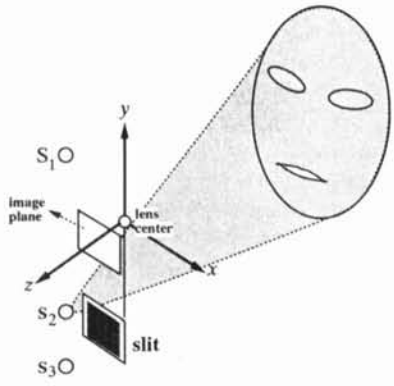


Figure 2: A face is illuminated by S2

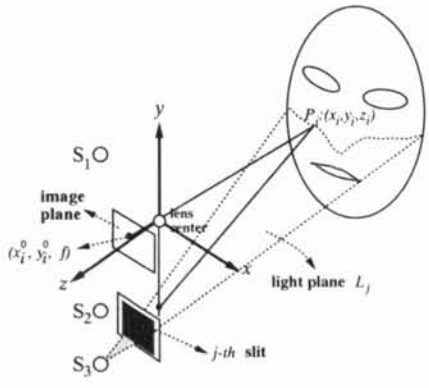


Figure 3: A face is illuminated by S3

2.1 Computation of Normal Vectors

The normal vectors at the points on the face are computed by the photometric stereo method.

In the conventional photometric stereo method, three light sources are used. To measure the vectors rapidly, only two light sources S1 and S2 are used and they are switched at high speed (Figures 1, 2). Two images of the face, one illuminated by each light source, are obtained using a video camera. From the two images, one of the components of each normal vector on the face is determined by solving Lambertian reflectance map. This method can provide a high density of information about the facial shape in a short time.

First, the normal vector $\mathbf{N}(x, y)$ at the point (x,y,z) on the face is described as

$$\mathbf{N}(x, y) = (N_x(x.y), N_y(x, y), 1). \tag{1}$$

Two vectors $\mathbf{S_1}$ and $\mathbf{S_2}$ which point in the direction from (x,y,z) to the light sources S_1 and S_2 respectively are described as

$$\mathbf{S}_1 = (0, S_{1_y}, 1), \mathbf{S}_2 = (0, S_{2_y}, 1). \tag{2}$$

Assuming Lambertian reflectance map, the following two equations are given:

$$L_{S_1} = I_{S_1} R \frac{S_{1_y} N_y + 1}{\sqrt{S_{1_y}^2 + 1}\sqrt{N_x^2 + N_y^2 + 1}}, \tag{3}$$

$$L_{S_2} = I_{S_2} R \frac{S_{2_y} N_y + 1}{\sqrt{S_{2_y}^2 + 1}\sqrt{N_x^2 + N_y^2 + 1}}, \tag{4}$$

where I_{S_k} is the intensity of incident illumination from S_k, L_{S_k} is the intensity of radiance by S_k (k = 1,2), and R is the reflectance factor. The intensity L_{S_k} is obtained from the pixel values of the two images taken by the video camera.

From these equations, $N_y(x, y)$ is derived as follows:

$$N_y(x, y) = \frac{1 - \alpha}{S_{2_y}\alpha - S_{1_y}}, \tag{5}$$

where

$$\alpha = \frac{L_{S_1} I_{S_2} \sqrt{S_{1_y}^2 + 1}}{L_{S_2} I_{S_1} \sqrt{S_{2_y}^2 + 1}}.$$

2.2 Depth Measurement by Projecting Stripes

To obtain the boundary condition of integration, the proposed method uses the light projection method; i.e., multiple light stripes are projected onto the face using the slit pattern projector (the light source S3 and the slit (Figure 3)) [9, 10]. The algorithm for the measurement is as follows:

1. Multiple light stripes are projected onto the face from a direction.
2. An image is taken by a video camera from another direction.
3. Bright regions are extracted from the image by thresholding.
4. The 3D coordinate values of the points on the extracted bright regions are computed by the stereo vision algorithm.

Let $P_i = (x_i, y_i, z_i)$ $(i = 1, 2, 3, \cdots)$ be the points contained in the intersection of the face and the light plane L_j, where L_j is defined as the plane containing the j-th slit and the light source. The coordinate values (x_i, y_i, z_i) of P_i is computed from the following equations :

$$(l_{j_x}, 1.0, l_{j_z}) \cdot (x_i, y_i, z_i) = -d_j, \quad (6)$$

$$x_i = \frac{x_i^0}{f} \cdot z_i, \quad (7)$$

$$y_i = \frac{y_i^0}{f} \cdot z_i, \quad (8)$$

where f is the focal length of the camera, (x_i^0, y_i^0) is the coordinates of the intersection point of the image plane and the line passing through both the lens center and P_i, and $(l_{j_x}, 1.0, l_{j_z}) \cdot (x, y, z) = -d_j$ is the equation of the plane L_j.

2.3 Integration of Normal Vectors inside Finite Intervals

The surface normals $\mathbf{N}(x, y)$ computed by the photometric stereo method are integrated in each local domain D_i to reconstruct the 3D curved segment. The domain D_i is a 2D finite interval centered at a point (x_i, y_i) on the xy-plane where the coordinate values (x_i, y_i, z_i) of P_i is computed by the projecting stripes on the face. The interval is parallel to the y-axis and the length of the interval is L_i. To compute z coordinates at the point (x_i, y) in the domain D_i, that is $Z_i(x_i, y)$, the following equation is used:

$$Z_i(x, y) = \begin{cases} Z_i(x_i, y_i) - \int_{y_i}^{y} N_y(x_i, Y)dY & (x = x_i), \\ 0 & (x \neq x_i). \end{cases} \quad (9)$$

2.4 Blending of Curved Segments

The integration domains are overlapped in several regions. Computed curved segments in the overlapped regions of the domains are blended using infinitely differentiable functions.

In each domain D_i, the blending function h_i is given as follows [11]:

$$h_i(x, y) = \begin{cases} a\left(\frac{L_i - |y - y_i|}{L_i}\right) & (|y - y_i| < L_i \text{ and } x = x_i) \\ 0 & (otherwise) \end{cases},$$

where

$$a(t) = \begin{cases} 0 & (t \leq 0) \\ \frac{b(t)}{b(t) + b(1-t)} & (0 < t < 1) \\ 1 & (1 \leq t) \end{cases}$$

and

$$b(t) = \begin{cases} 0 & (t \leq 0) \\ e^{-\frac{1}{t}} & (0 < t) \end{cases}.$$

Figure 4 shows the shape of the function $h_i(x, y)$. Clearly, the function $h_i(x, y)$ is infinitely differentiable. Now, the surface $Z(x, y)$ is computed as follows:

$$Z(x, y) = \frac{\sum_i h_i(x, y) \cdot Z_i(x, y)}{\sum_i h_i(x, y)}, \quad (10)$$

where $Z_i(x, y)$ is the z coordinates of the curved segment at (x, y) computed in the domain D_i (Figure 5).

The error of the surface $Z(x, y)$ is smaller than the maximum of the errors of the curved segments $Z_i(x, y)$ $(i = 1, 2, 3, \cdots)$. This property is proved as follows:

$$\begin{aligned} |Z(x, y) - Z_t(x, y)| &= \left| \frac{\sum_i h_i(x, y) Z_i(x, y)}{\sum_i h_i(x, y)} - Z_t(x, y) \right| \\ &= \frac{\sum_i h_i(x, y) |Z_i(x, y) - Z_t(x, y)|}{\sum_i h_i(x, y)} \\ &\leq \frac{\sum_i h_i(x, y) \max_i |Z_i(x, y) - Z_t(x, y)|}{\sum_i h_i(x, y)} \\ &= \max_i |Z_i(x, y) - Z_t(x, y)|, \end{aligned}$$

where $Z_t(x, y)$ is the true z value at (x, y) of the facial shape.

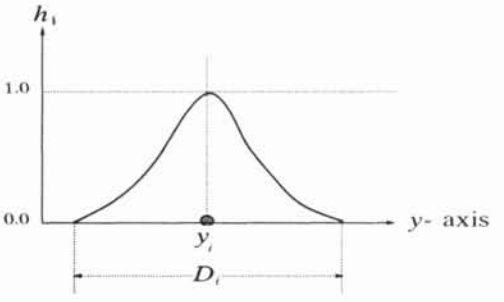


Figure 4: $h_i(x, y)$

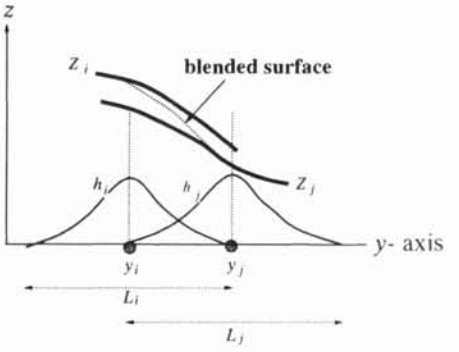
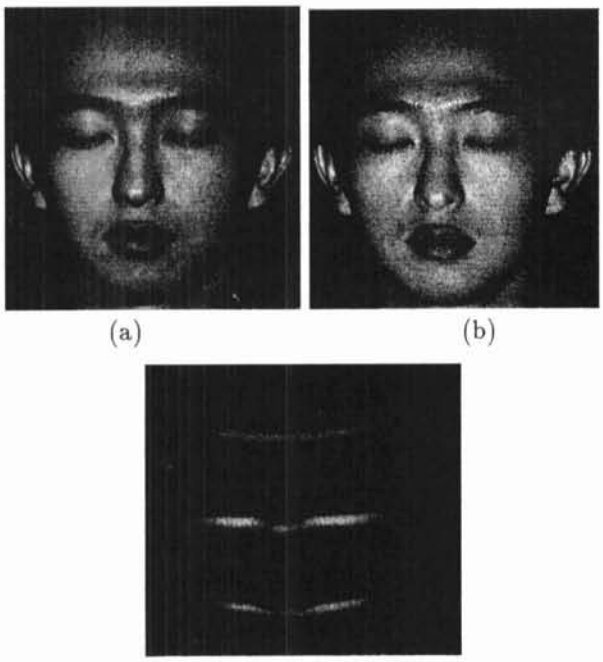


Figure 5: Surface blending

3 Experiments

Figure 6 shows three images of a subject illuminated by the light sources S1, S2, and S3 (slit pattern projector). The three light sources are switched in turn at the rate of 10 times per second. The gray scale images of the subject are taken 10 frames per second using the video camera. Therefore, 3D facial shapes in 10 scenes per second can be measured. The size of these images is 640 x 480 pixels. Figure 7 shows the 3D facial shape which is measured in one scene. The accuracy of the measured data is better than 2.0%.



(a) (b)

(c)

Figure 6: (a)A face is illuminated by S1, (b)A face is illuminated by S2, (c)A face is illuminated by S3

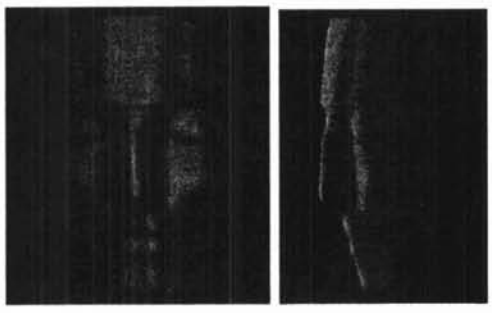


Figure 7: 3D facial shape

4 Conclusions

This paper has introduced a new method for measuring 3D shapes of a human face. This method uses two light sources and a slit pattern projector. The face is illuminated by them in turn. The 3D facial shapes in 10 scenes per second can be measured. Even if the human face moves and deforms, the detailed 3D facial shapes at a particular instant can be measured accurately. The 3D deformations of the facial shapes are obtained from the time-sequence of the measured 3D facial shapes. The proposed method can be applied to the analysis of the subtle changes in the human facial expressions.

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