Obtaining 3D Shape of Specular Surface Using Five Degrees of Freedom Camera System

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Abstract : In this paper, a new method of obtaining specular surface shape by using five degrees of freedom camera system is described. The normal vectors of the surface are extracted by achieving the coincident condition between the camera axis and the surface normal vector. This method uses a five degrees of freedom (5DOF) camera to fulfill this task. From the normal vector data, the shape of the surface is reconstructed. The result shows that the methodology improves the 3-D shape of object measurement with good accuracy.

1. Introduction.

Specular surface has become interesting object since it is used widely especially in glass and metal industries. Beside that, many industrial materials are made of metal and have strong specularity and little diffuse reflection. Moreover, many practical tasks in robot vision and inspection require interpretation of images of specular or shiny surfaces.[3][4].

Several methods of obtaining the shape of a surface have been proposed such as multiple view, slit ray projection, moiré method, shape from shading and some of them are widely used in practical applications. This paper depicts a new method of obtaining the shape of specular surface by extracting all the surface normal vectors based on the reflection theorem and image processing. A 5 degrees of freedom camera is used to obtain the normal vector by scanning the location of coincidence between the incident and reflected rays. A LED(Light Emitting Diode) is put on the camera axis to give an incident ray to the surface. The camera axis intersects the image center is assumed, hence, the coincidence condition is reached when the reflected images coincide with the image center. The location of the lens center and the direction of the camera axis on the coincident condition is recorded as the normal of the surface. From the normal vector data, the shape of the surface is reconstructed patch by patch. This reconstruction gives a limitation in application, that is used only to a smooth curve of object with no hole.

2. Principle.

2.1 Extracting the Normal vector.

From the characteristics of the specular surface which reflects the incident ray in the same angle, the normal at the point on a surface can be found if the incident and reflected angles are 0° or the incident ray coincides with reflected ray. Since the brightness depends on viewing direction, the position of directed and reflected ray must be arranged in the position of the camera as a viewer. The camera must be a mobiling camera that can move in 5 DOF to achieve the coincident condition of incident and reflected ray.

The condition in which the incident ray coincides with the reflected ray can be achieved if the light source in the same location with the viewer. If a camera is used as a viewer, the light source must be made on the camera position.

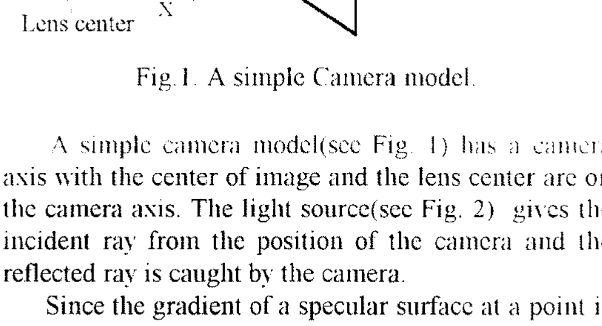

Fig.1. A simple Camera model.

A simple camera model(see Fig. 1) has a camera axis with the center of image and the lens center are on the camera axis. The light source(see Fig. 2) gives the incident ray from the position of the camera and the reflected ray is caught by the camera.

Since the gradient of a specular surface at a point is not directly perpendicular to the incident ray, the camera must be panned, tilted and moved in three coordinate axes to satisfy the coincident condition. Figure 1 shows the formation of an image of a single point, denoted by A, which has the coordinates (X, Y, Z). The coordinates of A in the image are $A'(x_A, z_A)$.

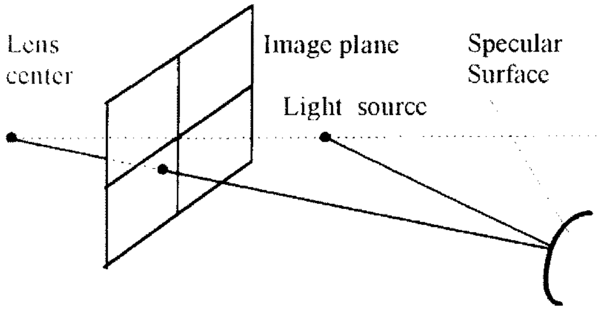

Fig. 2. Light source and Viewer

where

$$x_A = f\frac{X}{Y} \; ; \quad z_A = f\frac{Z}{Y} \; ; \qquad (1).$$

Y is called the depth of A, which measured from the lens to the object. The distance from the lens to the image plane is denoted by f, the focal length. In the image coordinate system, A'(x_A, z_A) becomes A'(u,v), after converting x and z by scale factor α to u and β to v as follows

$$u = U_o + x_A\alpha \text{ (pixels)}; \; v = V_o - z_A\beta \; ; \qquad (2).$$

where α, β in pixel/mm.

To get the normal vector, the image of point A must be moved to the center of image plane (U_o, V_o). The camera must be panned and tilted as much as :

$$\theta = \tan^{-1}((U_o - u)/F) \; ; \quad \phi = \tan^{-1}((V_o - v)/F) \; ; \; (3)$$

where F = $f\alpha$ (pixels).

θ is the pan angle, and ϕ is the tilt angle.

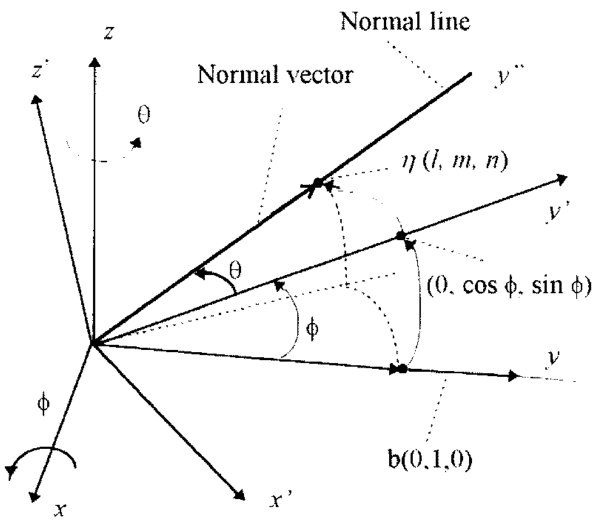

Fig. 3. Pan and tilt Angle.

We can express the normal line of a point on the specular surface as follows.

$$\frac{y - y_C}{m} = \frac{x - x_C}{l} = \frac{z - z_C}{n} \qquad (4).$$

x_c, y_c, z_c are the coordinates of a point on the normal line and l, m, n are the direction number of the normal line.

We can derive that $l = m \tan\theta$ (5).

$n = m \tan\theta / \cos\phi$

2.2 Shape Reconstruction.

Reconstruction of the shape begins with the assumption that the shape is smooth, otherwise we can not determine the shape of object from the surface normal vectors. Since there are infinite number of surfaces have the same normal vectors, the shape of object can not directly be reconstructed from the extracted normal vectors. This problem is solved by knowing at least one point coordinates of on the surface as a starting point to lead the reconstruction. Cubic polynomial function of a surface shape is used here and expressed as follows :

$$y = \alpha_0 + \alpha_1 x + \alpha_2 x^2 + \alpha_3 x^3 + \alpha_4 z + \alpha_5 xz +$$

$$\alpha_6 x^2 z + \alpha_7 z^2 + \alpha_8 xz^2 + \alpha_9 z^3 \qquad (6).$$

The partial derivatives of this surface function is related to the components of surface normals, that are :

$$\frac{\partial y}{\partial x} = p; \; \frac{\partial y}{\partial z} = q \;\; \text{where } p = -\frac{l}{m} \; ; q = -\frac{n}{m} \quad (7).$$

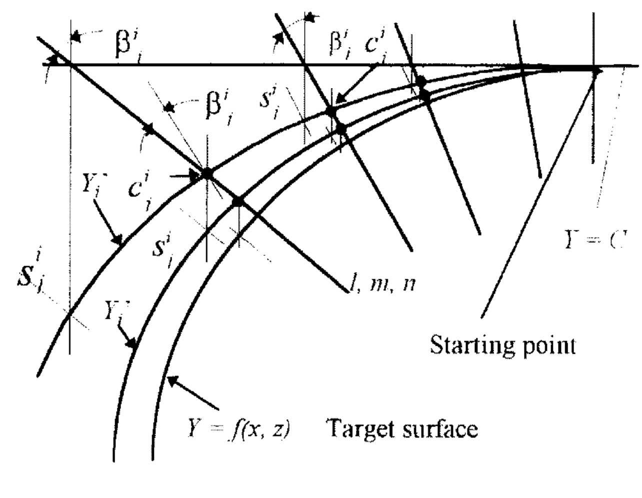

Fig. 4. Reconstruction of the Shape.

From the data of normal vectors, we have the value of l, m, n and the value of x, y, z. By inputting these values to the derivation of eq. (6) due to x and z, using at least five points, we have the value of α_1 to α_9. α_0 is obtained by inputting all values to eq. (1) using a known point (called the starting point). Then the value of p and q can be calculated. By minimizing the difference between the value of p and q by the value of measured l, m, n, in the sense of least mean square in some iteration, the reconstruction will lead the shape to the nearest shape of the object surface. (see Fig. 4).

3. Experiment.

3.1 Preparation.

In order to obtain surface normal vectors, we use five degrees of freedom mobiling camera system. The camera is equipped with a LED which is attached on the camera axis and acts as the light source. Five degrees of freedom camera system is shown in Fig. 5. This system consists of a mobile camera, a movement control equipment, an image processor and a personal computer. The camera is attached on two rotary tables which are mounted on one of three linear stages in such a way that the camera can be moved along X,Y, and Z axes and also can be panned and tilted by computer control. The ray from the LED is reflected by the specular surface and caught by the camera. The image of the reflected ray is analyzed by an image processor and a computer.

A. Parallelization of Y Axis and the Camera Axis.

When the system is started, we don't know whether the camera axis is parallel or not to the Y axis since the zero value of the rotary table is not set to a certain coordinate. A procedure using a plane with a spot mark is performed to make the Y and camera axis parallel by moving the camera along the camera axis.

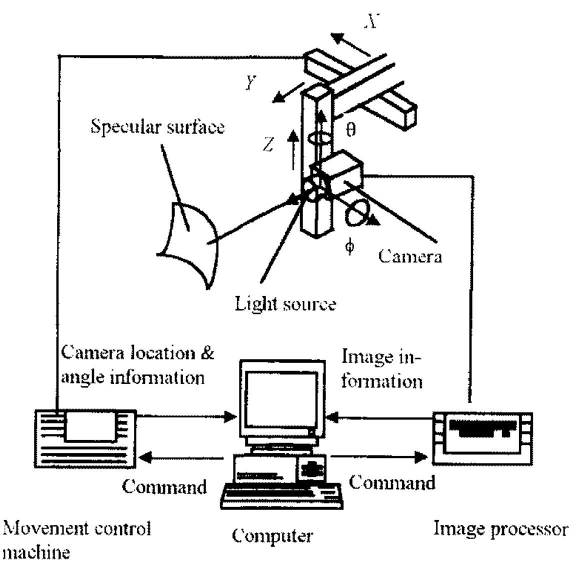

Fig. 5. Five Degrees of Freedom Camera System.

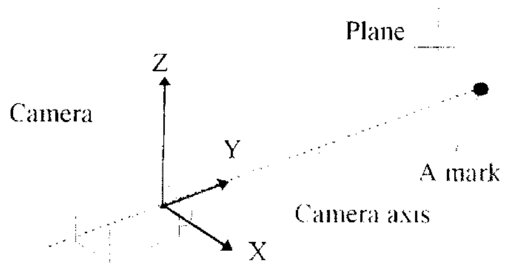

Fig. 6. Parallelization of the Y and the Camera Axis.

B. Camera Scanning Path.

As shown in Fig. 7, camera is moved in x and z axis from the starting point, however it must be panned and tilted if the object has a curved surface. The distance between camera and object will change and the camera will not catch the reflected image if the path in Y-Z plane is not arranged. Therefore, after first movement, the distance of the camera to the object is calculated and the calculated distance is used for the next movement (see Fig. 8).

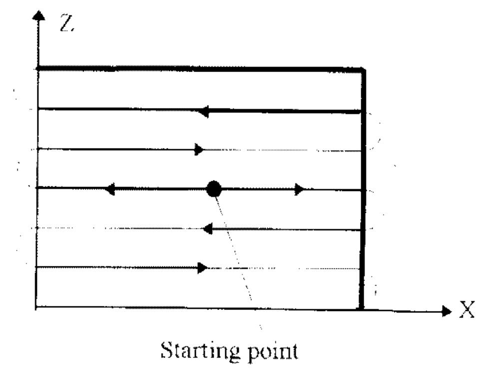

Fig. 7. Camera scanning Path in X-Z Plane.

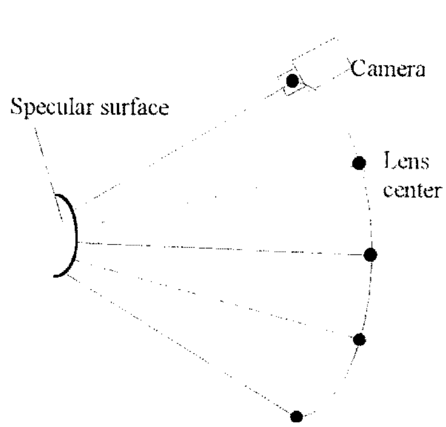

Fig. 8. Camera scanning Path for a Ball in Y-Z Plane.

C. Obtaining the Starting Point.

The starting point is obtained by putting a spot on the object and measured the distance between the lens center and the spot mark by triangulation.

3.2 Experimental Result.

We present here the result of two types of specular surface object that are : a flat surface, a ball shape surface. These two objects are used since they have a simple surface function and can easily be checked.

For the flat surface, we used a flat mirror. This flat mirror is assumed to be ideal in flatness. 100 point data (10 x 10) of the normal vector (*x, y, z, l, m, n*) were scanned on the surface. The starting point was obtained by method of triangulation. The experimental result is shown in Fig. 9. Even though we didn't have the contact measurement data of the flat surface as comparison and just assumed the flat as an ideal surface, the maximum error of reconstructed result comparing with the ideal data was only 12 μm.

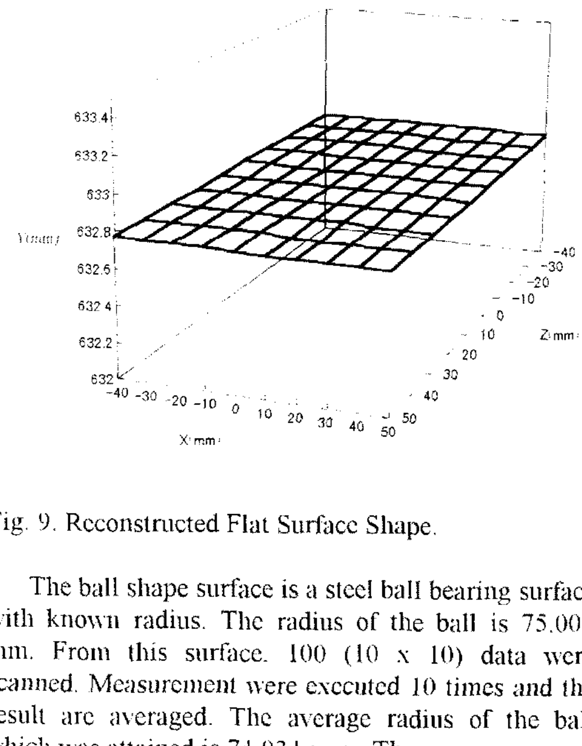

Fig. 9. Reconstructed Flat Surface Shape.

The ball shape surface is a steel ball bearing surface with known radius. The radius of the ball is 75.000 mm. From this surface, 100 (10 x 10) data were scanned. Measurement were executed 10 times and the result are averaged. The average radius of the ball which was attained is 74.934 mm. The average error of the radius was 0.066 mm. Reconstructed shape of the ball is shown in Fig. 10.

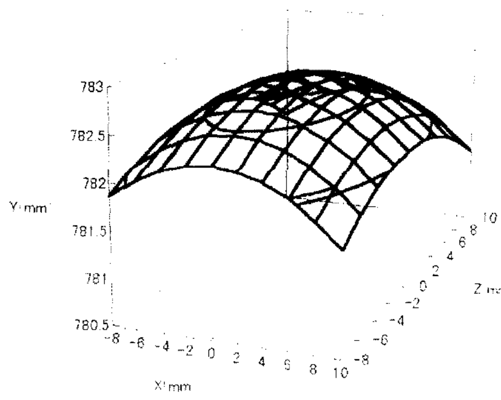

Fig. 10. Reconstructed Ball Shape Surface.

Present result have a good accuracy (below 150 μm), but more research and development is needed to achieve the better result. Both hardware and software equipment have their own source of error, however, the hardware development need other precision technology to make precise machine.

4. Conclusion.

The new method of reconstruction of the shape of specular surface has been developed. This method uses normal vector to reconstruct the shape of the surface leading by a starting point of the surface. The normal vector is obtained by scanning the location and direction of the point on the surface by making the coincident condition of the incident ray on and reflected ray from the surface.

5. References.

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