3D MODELING OF SMALL INDUSTRIAL PARTS BASED ON THE PROJECTOR-CAMERA SYSTEM

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ABSTRACT:

3D modeling of industrial parts is the key foundation and preceding step of 3D inspection and measurement of industrial parts. The common characteristic of industrial parts is that its surface is sleeky, homogeneous and lack of the texture. So the key difficulties in 3D modeling of industrial parts are the matching and the extraction of the suitable texture and the makeup of the 3D model. The paper proposes a flexible and practical method to three-dimensional model the small industrial parts based on the projector-camera system. The projector-camera system is composed of a slide projector, a digital camera, a control ground and a computer. After both calibrated respectively first, the projector-camera system is similar with the binocular vision system in the principle of 3D modeling. The 3D model of the target small industrial parts is acquired by connecting all neighbor space feature points and the real texture is rendered from relative images without the projected texture characteristic. The 3D modeling of small industrial parts is achieved finally. The method of 3D modeling is active and effective because the projected texture characteristic can be designed first on motivation. The 3D modeling method is non-touched so that it is remote and nondestructive. Because of little effect by the space factor or the time factor, the method of the small industrial parts 3D modeling is flexible and practical. The 3D modeling of small industrial parts proposed in the paper is confirmed to be correct and effective entirely by the results of the modeling experiments.

1. INTRODUCTION

1.1 3D Modeling

3D modeling is referred as a process of the recovery of three-dimensional model from the two-dimensional digital camera images. During the image formation process of the camera, explicit 3D information about the scene or objects in the scene is lost. Therefore, 3D model or depth information has to be inferred implicitly from the 2D intensity images. The key of the traditional method lies in the matching of the corresponding features in the images. When there is no feature or lack of feature in the objects, or when the features cannot be matched correctly at all, the main problems appear in the process of the 3D modelling.

The paper provides a method to resolve the problems above. It is an ordinary slide projector that can supply any feature what you want to the target object. These features are easy to be controlled and to be extracted out, which has paved the convenient path for the matching of them. According to the demand and real condition, the features can be changed or adjusted.

The paper explains clearly how to use the ordinary slide projector and how to apply it to the applications of the 3D modeling, too.

1.2 3D Modeling of Industrial Parts

3D modeling of object has become an important task and a current challenge of the digital close-range photogrammetry and computer vision. With the development of the photogrammetry and computer science, their theories and skills are applied to all kinds of the industry. 3D modeling of industrial parts is the key foundation and preceding step of 3D inspection and measurement of industrial parts. The common characteristic of industrial parts is that its surface is sleeky, homogeneous and lack of the texture. So the key difficulties in 3D modeling of industrial parts are the matching and the extraction of the suitable texture and the makeup of the 3D model. According to the above difficulties and troubles, the paper proposes a flexible and practical method to three-dimensional model the small industrial parts based on the projector-camera system.

The projector-camera system is composed of a slide projector, a digital camera, a control ground and a computer. The slide projector can project the texture characteristic onto the surface of the small industrial parts. Hence, The problem of lacking of texture of industrial parts is solved entirely. The projected texture characteristic is designed to be stable and clear so that it is easy to be matched correctly and rapidly. The digital camera can take images as the foundational data for 3D modeling. The control ground is a rotating platform with panel of the planar grid. The planar grid supplies the space coordinate system and the rotating platform is convenient to rotate the industrial parts for taking images from the different orientations. Because of the size of the planar grid, the target industrial parts are relatively small. The computer controls the slide projector to project, the digital camera to take images and the rotating platform to rotate by any angle, lets the other three equipments working together automatically and efficiently.

Before the small industrial parts are 3D modeled, the slide projector and the digital camera must be calibrated in advance. Because the results of the calibration of the slide projector and the digital camera are the necessary and required parameters for the next 3D modeling of the small industrial parts. The planar grid is also functioned as the control ground for the calibrations of the digital camera and the slide projector. The digital camera takes images of the planar grid from the different orientations (at least two) as the data for calibrating the digital camera. The coordinates of the space points are the known data and the coordinates of the image points are extracted out accurately by using the image processing method. Using the correspondence of collinear equation and 2D direct linear transformation, the calibration of the digital camera is finished successfully. Then the slide projector projects a target grid slide onto the planar grid and the digital camera takes images again from the different orientations. The coordinates of the image points in the slide are calculated according to the first design and the coordinates of the space points is computed out by the parameters of the result of the calibration of the digital camera and the coordinates of the image points in the images taken by the digital camera. Using the same algorithm above, we can work out the intrinsic and extrinsic parameters of the slide projector. By this time, the slide projector is calibrated completely, too. After calibrated respectively first, the projector-camera system is similar with the binocular vision system in the principle of 3D modeling.

The positions of the slide projector and the digital camera are fixed. The target small industrial parts are put down on the center of the planar grid. The slide projector projects the designed texture characteristic onto the surface of the small industrial parts. The digital camera takes two images of the small industrial parts with the projected texture characteristic and without it at the same time. Then the digital camera takes two sequential images from the different orientations when the rotating platform rotates continually. For each space feature point projected on the surface of the target small industrial parts, there are two corresponding 2D points existing. One is an image point in one of the image sequences from the digital camera and another is a point in the slide from the projector. Using the image processing method, the image point can be extracted out accurately so that its 2D coordinates are gained. At the same time, the slide point is designed first so that its 2D coordinates are calculated by the known data. The 3D coordinates of the space feature point can be computed by the space forward intersection. Using the correspondence of the rotating angles of the rotating platform and whole adjustment, the 3D coordinates of all space points projected on the whole surface of the small industrial parts from the different orientations can be calculated out entirely and accurately. The precision of 3D coordinates of all projected space points is satisfied with the requirement of digital close-range photogrammetry and practical applications.

The 3D model of the target small industrial parts is acquired by connecting all neighbor space feature points and the real texture is rendered from relative images without the projected texture characteristic. The 3D modeling of small industrial parts is achieved entirely and finally. The method of 3D modeling is active and effective because the projected texture characteristic can be designed first on motivation. The 3D modeling method is non-touched so that it is remote and nondestructive. Because of little effect by the space factor or the time factor, the method of the small industrial parts 3D modeling is flexible and practical. The 3D modeling of small industrial parts proposed in the paper is confirmed to be correct and effective entirely by the results of the modeling experiments.

2. METHODOLOGY AND ALGORITHM

2.1 System Equipments

The projector-camera system is composed of a slide projector, a digital camera, a control ground and a computer. The computer controls the other three equipments working together automatically and efficiently. The control ground is a planar grid on a rotating platform. The planar grid is functioned as the calibration of the slide projector and the digital camera. After calibrated respectively in advance, the projector-camera system is similar with the binocular vision system on the principle of 3D reconstruction.

2.1.1 The Calibration of the Digital Camera: The digital camera needs to be calibrated in advance, because the late computation of the coordinates of the space feature requires the intrinsic and extrinsic parameters of the digital camera. Therefore, the calibration of the digital camera is an important preceding step.

Direct Linear Transformation (DLT) is a well-known method used in close-range photogrammetry because of it's no need for initial value of camera intrinsic and extrinsic parameters. The existed camera calibration techniques are studied thoroughly. The restricting condition among 2D-DLT parameters is worked out using the correspondence of collinear equation and 2D-DLT. The decomposition of initial values of camera intrinsic and extrinsic parameters using 2D-DLT is detailed. Planar-scene camera calibration algorithm with collinear equations is addressed. So the calibration of the digital camera is accomplished entirely and the intrinsic and extrinsic parameters of the digital camera are ready to be used in the future. (Zhang Zhengyou, 1998; Zuxun Zhang, and Yongjun Zhang, 2002.)

If the camera is not an ordinary one but a special digital measuring-camera, the calibration could be cancelled because the intrinsic parameters of the digital camera can be gotten as the known data. However, the extrinsic parameters of the digital camera are still required to calculated out first.

2.1.2 The Calibration of the Ordinary Projector: In this approach proposed in the paper, the slide projector makes the same function as a digital camera. So the ordinary slide projector also desires to be calibrated in advance. Its intrinsic and extrinsic parameters are also applied to the computation process.

The algorithm with 2D direct linear transformation (2D-DLT) and collinear equations is used to calibrate the projector. The algorithm is addressed systematically and entirely as following. First, the image coordinates of the projector are designed carefully and the space coordinates of the projector are computed by the image data and the intrinsic and extrinsic parameters of the digital camera. Then, the decomposition of initial values of the projector intrinsic and extrinsic parameters using the correspondence of 2D-DLT and collinear equation is deduced. Finally, the projector calibration parameters are worked out by the whole adjustment. By this time, the intrinsic and extrinsic parameters of the ordinary slide projector are ready to be used in the next program. (Jianqing Zhang, Jun Tao, Zuxun Zhang, 2003; Jun Tao, Jianqing Zhang, and Zuxun Zhang, 2004.)

2.2 Steps of the Method

First, the three positions of the digital camera, the slide projector and the rotating platform are adjusted suitably. Then the digital camera and the slide projector are focused respectively. So the texture feature projected is shown clearly on the surface of the industrial parts and the images of it taken are all in focus, too.

Second, the industrial part is put on the centre of the rotating platform. The slide projector projects a feature texture slide onto it with reference to the different condition, such as points, lines or grid. The digital camera takes the sequential images of it with the texture feature and without the texture feature at the same time.

Third, for each space feature point projected on the surface of the industrial parts, there are two corresponding 2D points existing. One is an image point in one of the image sequences and another is a point within the slide. Using the image processing method, the image points of each image can be extracted out completely and the 2D coordinates of them can be computed out correctly. At the same time, the slide projected is designed first so that the 2D coordinates of the points within the slide are gotten by the known data.

Fourth, how to get the homologous points from the slide and the image? Known the intrinsic and extrinsic parameters of the digital camera and the slide projector and the 2D coordinates of a point in the slide or the image, the 3D coordinates of the space points on the surface of the industrial parts can be worked out by the collinear equations when two 2D coordinates of the two corresponding 2D points are gotten already.

Fifth, The sequential images are taken from different directions of the solid of rotation. So there are the feature textures projected on the every aspect of the solid of rotation. Using the correspondence of whole adjustment and the inherent structure characteristic of the solid of rotation, the 3D coordinates of all space points projected on the whole surface of the solid of rotation can be computed out entirely.

Finally, The 3D model of this solid of rotation is acquired by connecting all neighbour space points and the real texture is rendered from relative images without the projected texture feature. By this time, the 3D reconstruction of the solid of rotation is achieved ultimately.

2.3 Algorithm

The collinear equations are: (Zuxun Zhang, and Jianqing Zhang, 2000; Zhizhuo Wang, 1990; Deren Li, 1992; Wenhao Feng, 2002.)

$$
\begin{aligned}
x - x_0 &= -f\frac{a_1(X-X_s)+b_1(Y-Y_s)+c_1(Z-Z_s)}{a_3(X-X_s)+b_3(Y-Y_s)+c_3(Z-Z_s)} \\
y - y_0 &= -f\frac{a_2(X-X_s)+b_2(Y-Y_s)+c_2(Z-Z_s)}{a_3(X-X_s)+b_3(Y-Y_s)+c_3(Z-Z_s)}
\end{aligned}
\qquad (1)
$$

where x_0, y_0, f = the intrinsic parameters of the projector

X_S, Y_S, Z_S = the coordinates of the projector centre

X, Y, Z = the space coordinates of points

x, y = the image coordinates of the relative points

$R = \{a_i, b_i, c_i, i = 1,2,3\}$ = the rotated matrix made up of rotated angles ϕ, ω, κ

To the planar grid, the coordinates Z = 0

There are four equations listed ordinarily according to a pair of homologous points. However, the space coordinates (X, Y, Z) can be calculated out only by three equations. Through the line matching based on the structure illumination, there exist three known equations shown in the Figure.1.

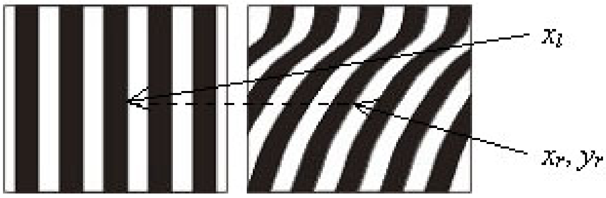


Figure 1. The line match based on the structure illumination

There is one point on the curve of the image taken by the digital camera, and its coordinates are x = x_r, y = y_r. from the formula (1), then:

$$
\begin{aligned}
&[a_3+f_r\frac{a_1}{(x_r-x_{r0})}]X+[b_3+f_r\frac{b_1}{(x_r-x_{r0})}]Y+[c_3+f_r\frac{c_1}{(x_r-x_{r0})}]Z= \\
&\quad [a_3+f_r\frac{a_1}{(x_r-x_{r0})}]X_{rs}+[b_3+f_r\frac{b_1}{(x_r-x_{r0})}]Y_{rs}+[c_3+f_r\frac{c_1}{(x_r-x_{r0})}]Z_{rs} \\
&[a_3+f_r\frac{a_2}{(y_r-y_{r0})}]X+[b_3+f_r\frac{b_2}{(y_r-y_{r0})}]Y+[c_3+f_r\frac{c_2}{(y_r-y_{r0})}]Z= \\
&\quad [a_3+f_r\frac{a_2}{(y_r-y_{r0})}]X_{rs}+[b_3+f_r\frac{b_2}{(y_r-y_{r0})}]Y_{rs}+[c_3+f_r\frac{c_2}{(y_r-y_{r0})}]Z_{rs}
\end{aligned}
\qquad (2)
$$

There is a corresponding line in the projected slide according to the point on the curve of the image taken by the digital camera and its equation is x = x_l. From the formula (1), then:

$$
\begin{aligned}
&[a_6+f_l\frac{a_4}{(x_l-x_{l0})}]X+[b_6+f_l\frac{b_4}{(x_l-x_{l0})}]Y+[c_6+f_l\frac{c_4}{(x_l-x_{l0})}]Z= \\
&\quad [a_6+f_l\frac{a_4}{(x_l-x_{l0})}]X_{ls}+[b_6+f_l\frac{b_4}{(x_l-x_{l0})}]Y_{ls}+[c_6+f_l\frac{c_4}{(x_l-x_{l0})}]Z_{ls}
\end{aligned}
\qquad (3)
$$

From the formula (2) and (3), then:

$$
\begin{cases}
X=\dfrac{\begin{vmatrix}
[a_3+f_r\frac{a_1}{(x_r-x_{r0})}]X_{rs}+[b_3+f_r\frac{b_1}{(x_r-x_{r0})}]Y_{rs}+[c_3+f_r\frac{c_1}{(x_r-x_{r0})}]Z_{rs} & [b_3+f_r\frac{b_1}{(x_r-x_{r0})}] & [c_3+f_r\frac{c_1}{(x_r-x_{r0})}] \\
[a_3+f_r\frac{a_2}{(y_r-y_{r0})}]X_{rs}+[b_3+f_r\frac{b_2}{(y_r-y_{r0})}]Y_{rs}+[c_3+f_r\frac{c_2}{(y_r-y_{r0})}]Z_{rs} & [b_3+f_r\frac{b_2}{(y_r-y_{r0})}] & [c_3+f_r\frac{c_2}{(y_r-y_{r0})}] \\
[a_6+f_l\frac{a_4}{(x_l-x_{l0})}]X_{ls}+[b_6+f_l\frac{b_4}{(x_l-x_{l0})}]Y_{ls}+[c_6+f_l\frac{c_4}{(x_l-x_{l0})}]Z_{ls} & [b_6+f_l\frac{b_4}{(x_l-x_{l0})}] & [c_6+f_l\frac{c_4}{(x_l-x_{l0})}]
\end{vmatrix}}{\Delta} \\[2ex]
Y=\dfrac{\begin{vmatrix}
[a_3+f_r\frac{a_1}{(x_r-x_{r0})}] & [a_3+f_r\frac{a_1}{(x_r-x_{r0})}]X_{rs}+[b_3+f_r\frac{b_1}{(x_r-x_{r0})}]Y_{rs}+[c_3+f_r\frac{c_1}{(x_r-x_{r0})}]Z_{rs} & [c_3+f_r\frac{c_1}{(x_r-x_{r0})}] \\
[a_3+f_r\frac{a_2}{(y_r-y_{r0})}] & [a_3+f_r\frac{a_2}{(y_r-y_{r0})}]X_{rs}+[b_3+f_r\frac{b_2}{(y_r-y_{r0})}]Y_{rs}+[c_3+f_r\frac{c_2}{(y_r-y_{r0})}]Z_{rs} & [c_3+f_r\frac{c_2}{(y_r-y_{r0})}] \\
[a_6+f_l\frac{a_4}{(x_l-x_{l0})}] & [a_6+f_l\frac{a_4}{(x_l-x_{l0})}]X_{ls}+[b_6+f_l\frac{b_4}{(x_l-x_{l0})}]Y_{ls}+[c_6+f_l\frac{c_4}{(x_l-x_{l0})}]Z_{ls} & [c_6+f_l\frac{c_4}{(x_l-x_{l0})}]
\end{vmatrix}}{\Delta} \\[2ex]
Z=\dfrac{\begin{vmatrix}
[a_3+f_r\frac{a_1}{(x_r-x_{r0})}] & [b_3+f_r\frac{b_1}{(x_r-x_{r0})}] & [a_3+f_r\frac{a_1}{(x_r-x_{r0})}]X_{rs}+[b_3+f_r\frac{b_1}{(x_r-x_{r0})}]Y_{rs}+[c_3+f_r\frac{c_1}{(x_r-x_{r0})}]Z_{rs} \\
[a_3+f_r\frac{a_2}{(y_r-y_{r0})}] & [b_3+f_r\frac{b_2}{(y_r-y_{r0})}] & [a_3+f_r\frac{a_2}{(y_r-y_{r0})}]X_{rs}+[b_3+f_r\frac{b_2}{(y_r-y_{r0})}]Y_{rs}+[c_3+f_r\frac{c_2}{(y_r-y_{r0})}]Z_{rs} \\
[a_6+f_l\frac{a_4}{(x_l-x_{l0})}] & [b_6+f_l\frac{b_4}{(x_l-x_{l0})}] & [a_6+f_l\frac{a_4}{(x_l-x_{l0})}]X_{ls}+[b_6+f_l\frac{b_4}{(x_l-x_{l0})}]Y_{ls}+[c_6+f_l\frac{c_4}{(x_l-x_{l0})}]Z_{ls}
\end{vmatrix}}{\Delta}
\end{cases}
$$

where

$$
\Delta=\begin{vmatrix}
[a_3+f_r\frac{a_1}{(x_r-x_{r0})}] & [b_3+f_r\frac{b_1}{(x_r-x_{r0})}] & [c_3+f_r\frac{c_1}{(x_r-x_{r0})}] \\
[a_3+f_r\frac{a_2}{(y_r-y_{r0})}] & [b_3+f_r\frac{b_2}{(y_r-y_{r0})}] & [c_3+f_r\frac{c_2}{(y_r-y_{r0})}] \\
[a_6+f_l\frac{a_4}{(x_l-x_{l0})}] & [b_6+f_l\frac{b_4}{(x_l-x_{l0})}] & [c_6+f_l\frac{c_4}{(x_l-x_{l0})}]
\end{vmatrix}
$$

At present, the space coordinates (X, Y, Z) have been calculated out already.

3. DATA AND EXPERIMANTAL RESULTS

3.1 Design Data

The size of the rotating platform is 60cm×60cm. A planar grid is fixed upon it, which supplies the controlling points and the coordinates system. There are 18×18=324 controlling points in the planar grid. The interval of these points is the same and is 30mm. Each point has its own serial number which is exclusive. By using the coordinates of these points, the digital camera and the slide projector can be calibrated correctly and the extrinsic parameters of both are also calculated out entirely.

The size of the feature slide designed is 1024 pixels×768 pixels. The texture feature is designed as stripe which is better to show the surface of the industrial parts. The stripe is between white and black and is 7 pixels or 5pixels or 3 pixels in width respectively.

3.2 Image Sequences

When the positions of the camera and the projector are adjusted well and fixed relatively, both need to be focused respectively. The distance from the digital camera to the rotating platform is about 0.8 meters and the distance from the slide projector to the rotating platform is about 1.5 meters.

The target industrial part is common and ordinary shown in the Figure 2.

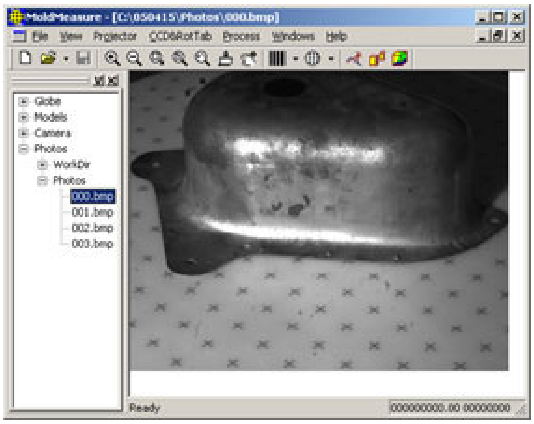
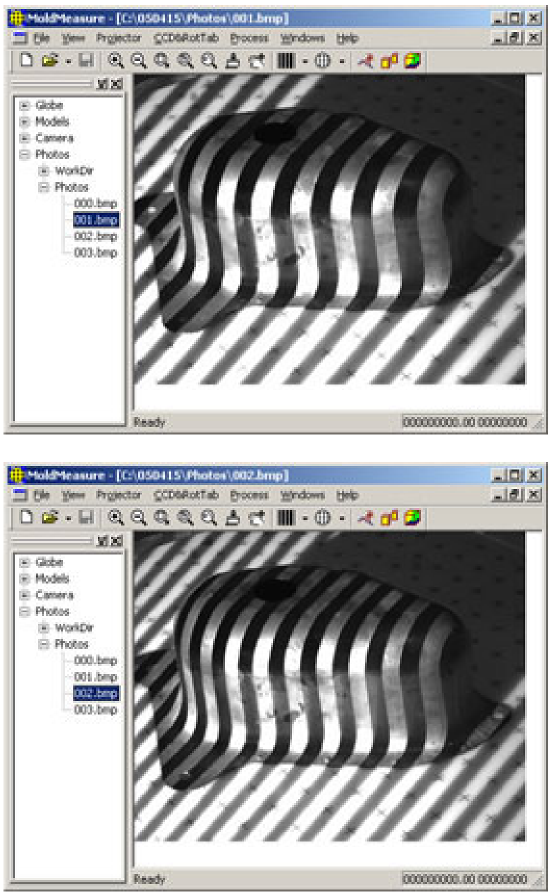


Figure 2. The target industrial parts

Then the industrial part is put on the centre of the rotating platform. The slide projector projects the stripe in the slide onto the surface of the industrial parts. Then the camera is used to take sequential images of the industrial parts with the slide projector illuminating when the stripe width changes continually. In the experiment the camera takes images from 3 stripe widths and there are 3 images in total as the image data shown in the Figure 3. The size of each image is 1300pixels×1030pixels.



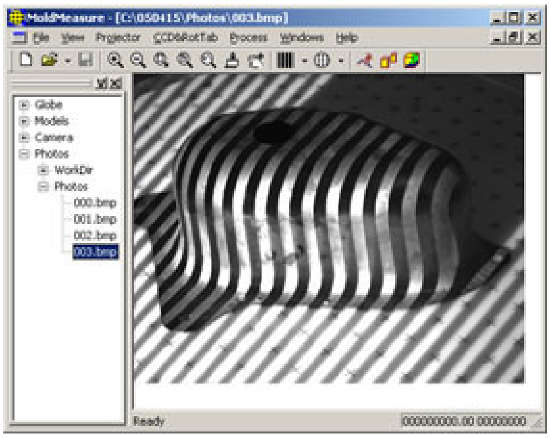


Figure 3. The sequential images with the feature

3.3 Experimental Results

According to the method above, all points projected on the surface of the industrial parts can be computed out entirely and are shown in the Figure 4.

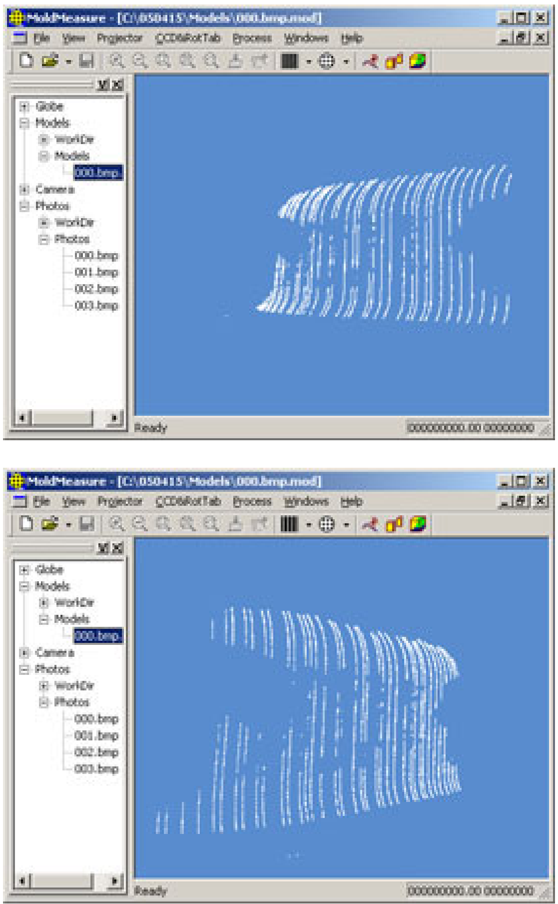
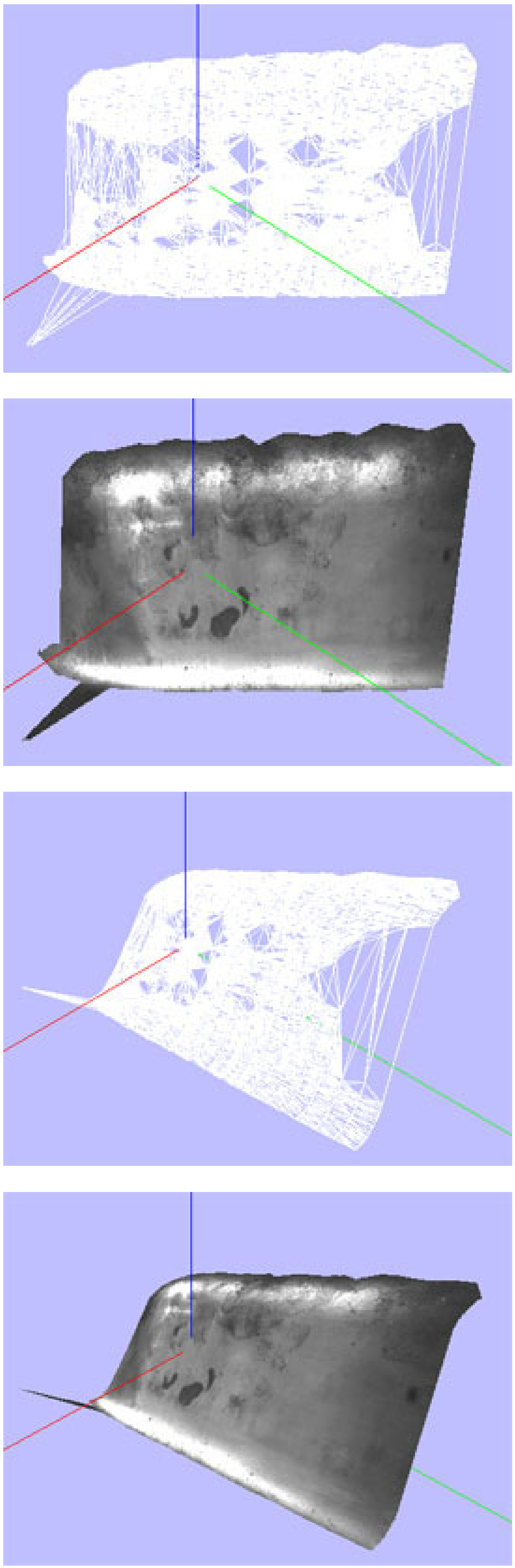


Figure 4. The point cloud of the industrial parts

The whole model of the industrial parts is added on the real texture of it. The view of the final model is shown in the Figure 5.



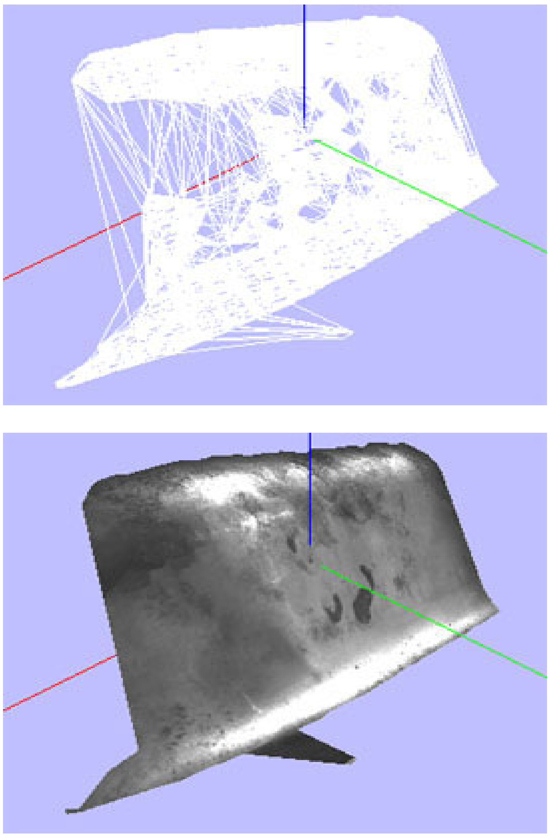


Figure 5. The model of the industrial parts

4. CONCLUSIONS

4.1 Achievements of the Paper

The approach proposed in the paper is confirmed to be proper and applicable from the results of the experimental data. This approach only requires a digital camera, an ordinary slide projector and a rotating platform. These equipments are easy to be ready for the applications.

The paper also deduces the detail algorithm of this approach which is understandable and relatively simple. Using the algorithm provided, the correct model results can be gotten from the image data. To sum up, the approach with this algorithm is effective and effectual.

According to the size of the industrial parts, the distance of the slide projector from the rotating platform and the density of the feature in the slide can be changed and adjusted, so that this approach is suitable for many kinds of applications. Moreover, it is hardly affected by the space factor or time factor. The approach provided by the paper is flexible and practical.

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