A 3D acquisition system combination of structured-light scanning and shape from silhouette

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A robust and accurate three dimensional (3D) acquisition system is presented, which is a combination of structured-light scanning and shape from silhouette. Using common world coordinate system, two groups of point data can be integrated into the final complete 3D model without any integration and registration algorithm. The mathematics model of structured-light scanning is described in detail, and the shape from silhouette algorithm is introduced as well. The complete 3D model of a cup with a handle is obtained successfully by the proposed technique. At last the measurement on a ball bearing is performed, with the measurement precision better than 0.15 mm.

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Acquisition complete and accurate three dimensional (3D) data of the object is a longstanding and challenging problem in machine vision. However due to the complexity and diversity of the measured object's surface, as well as the limitation of various 3D acquisition algorithms, it is difficult to obtain the object surface point completely. Especially the regions have highly curved concavities and holes, at the same time these partial surface data are very important for reconstruction of completely 3D model. Some algorithms are proposed to repairing the incomplete partial surface data using the information of the surrounding surface point[1], which can merely acquire an approximate result. The most accurate approach is to measure the original surface data of the incomplete surface. Also a scheme is introduced to acquire 3D data by combining stereo image analysis and shape from silhouettes[2]. Then two groups of surface-point are integrated using volumetric integration technique to obtain the complete surface data of the object, but the registration error is difficult to be avoided in spite of the accurate integration algorithm.

This paper chiefly introduces a 3D acquisition system, which is capable of acquiring 3D data using structured-light scanning and shape from silhouette. Structured-light scanning is a high-accuracy and rapid 3D acquisition technique. However, because of occlusion of the light or line of sight, the surface points including holes and high-curvature edge are hard to be measured. Some technique discussed how to determine sensor's viewpoint to reduce the occlusion[3], which needed some contour information as pre-knowledge. Another widely applied high-accuracy 3D acquisition method, shape from silhouette, is difficult to acquire point data of concavities surface in respect that the parallel illumination-lights are often occluded by surrounding higher surface. On the contrary, surface data of holes and edge can be reconstructed successfully by shape of silhouette algorithm[4]. Two 3D acquisition algorithms are applied using a common world coordinate system. Consequently the final complete data can be obtained by integrating two groups of data together without any surface registration algorithm.

The mathematics model of proposed system is introduced. And we achieved the complete surface point of cup with a handle. The detailed surface point of the cup, especially handle part is reconstructed successfully. And the test on a ball bearing with standard diameter is performed to indicate the high measurement accuracy.

The structure of the 3D acquisition system is shown in Fig. 1. A structured-light sensor consists of charge coupled device (CCD) cameras and a laser. Here two CCD cameras are employed to avoid the view-occlusion. And through a cylindrical lens the laser projects a light-plane onto measured object to form a light-stripe. A backlight system is used to illuminate the scene for acuquiring silhouette of the object. In addition the motorized two-axis translation stages, including a translation stage and a rotary stage, enable the sensor to capture the objects' light-stripe images and the silhouette images from multiple viewpoints.

The sensor is mounted to make sure that light-plane is perpendicular to the moving direction of translation stage. World coordinate system o_w-$x_w y_w z_w$ is established to ensure that plane o_w-$x_w y_w$ coincides with the light-plane. Consequently axis $o_w z_w$ is parallel to the moving direction of translation stage. Through the perspective center of lens o_c, we define the camera coordinate

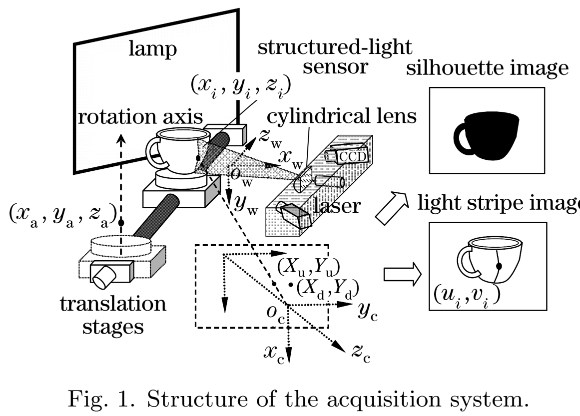


Fig. 1. Structure of the acquisition system.

system o_c-$x_cy_cz_c$, and make axes o_cx_c and o_cy_c parallel respectively to row and column directions of the CCD pixel array. Axis o_cz_c coincides with optical axis of lens. On account of lens radial distortion, the corresponding image distorted coordinates of point $P_w(x_w, y_w, z_w)$ are actually $P_d(X_d, Y_d)$, while have a little offset from the undistorted coordinates point $P_u(X_u, Y_u)$. Let (u, v) be the point's pixel coordinates in computing image coordinate system. The relation between the world coordinate $P_w(x_w, y_w, z_w)$ and the pixel coordinate $p(u, v)$ is described as[5,6]

$$\begin{cases} X_d = s_x d_x(u - u_o) \\ Y_d = d_y(v - v_o) \\ X_u = X_d(1 + k(X_d^2 + Y_d^2)) \\ Y_u = Y_d(1 + k(X_d^2 + Y_d^2)) \\ f \cdot \frac{r_1x_w + r_2y_w + r_3z_w + t_x}{r_7x_w + r_8y_w + r_9z_w + t_z} = X_u \\ f \cdot \frac{r_4x_w + r_5y_w + r_6z_w + t_y}{r_7x_w + r_8y_w + r_9z_w + t_z} = Y_u \end{cases}, \quad (1)$$

where d_x and d_y are center-to-center distances between pixels in the row and column directions respectively, the CCD's specification is offered by manufactures. And u_o, v_o, s_x, f, k are camera parameters, which are determined by camera calibration[7,8], and denote some characteristics of the lens and CCD. Moreover, being the elements of transformation matrix from camera coordinate system to world coordinate system, r_1, r_4, r_7, r_2, r_5, r_8, r_3, r_6, r_9, t_x, t_y, t_z are called light-plane parameters and determined by the referred light-plane calibration[9].

In structured-light scanning measurement, camera acquires the light-stripe image. The pixel (u_i, v_i) of the point on light-stripe is extracted through image processing. Obviously z_w value of the light-stripe points is equal to 0. The world coordinates $(x_{wi}, y_{wi}, 0)$ are calculated from Eq. (1). Translation stages drive the object into stepping-translation and stepping-rotation to ensure that light-stripe covers most region of the objects' surface. And the data will be translation-transformed $\mathbf{T}$ and rotation-transformed $\mathbf{R}$ according to the position of the stage.

$$(x_i, y_i, z_i) = \mathbf{R}[\mathbf{T}[(x_{wi}, y_{wi}, 0), z_k], \theta, \mathbf{u}, P_a], \quad (2)$$

where z_k is the current translation position of stage and θ the rotation angle position. In addition, as the rotation axis parameters of the stage, $P_a(x_a, y_a, z_a)$ is one point on the axis, and $\mathbf{u}[r_1\ r_2\ r_3]$ is the direction vector in the world coordinate system, both of which are determined by rotation axis calibration. At last, the data of the each light stripe are registered into the 3D point-cloud data of the scanned object.

After the structured-light scanning, the laser is turned off whereas the backlight is turned on. The CCD captures multiple views of the object's silhouette image with the rotation stage. Due to the parallel light emitted from the backlight is occluded by the object volume, the object's silhouette in each view corresponds to a conic volume, as shown in Fig. 2. We suppose that a collection of points $P_i(x_i, y_i, z_i)$ distribute as cubic volume. The 3D spacing interval between points determined by the geometrical complexity is usually equal to the chosen resolution of structured-light scanning for the consistency of two groups of 3D point data. For one point $P_i(x_i, y_i, z_i)$, from the mathematics model of the structured-light sensor, X_u can be calculated and the following equation is derived,

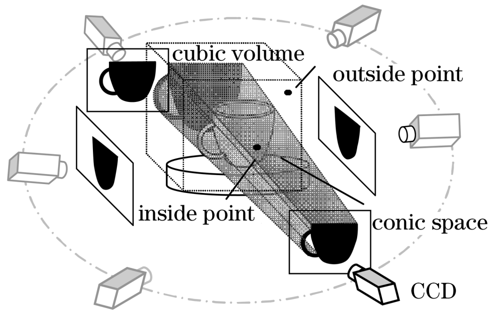


Fig. 2. Shape from silhouette.

$$k(1 + r^2)X_d^3 + X_d - X_u = 0 \quad (3)$$

with the scale factor $r = Y_d/X_d$. We use the ka'erdan equation to solve the cubic equation (3), and get the pixel coordinate (u_i, v_i) of this point (x_i, y_i, z_i),

$$\begin{cases} u_i = X_d/s_x\delta_x - u_o \\ v_i = Y_d/\delta_y - v_o \end{cases}. \quad (4)$$

After image segmentation on silhouette images, pixels are classed as black and white according to its gray value. If the corresponding pixel marked as white, point (x_i, y_i, z_i) is considered to lie outside of the cone space and removed from the point collection. On the contrary, if the pixel is marked as black, the corresponding point is inside the cone space and should be retained. This process is called space carving[10],

$$\text{gray}_i(u_i, v_i) = \begin{cases} \text{WHITE} & \text{removed} \\ \text{BLACK} & \text{retained} \end{cases}. \quad (5)$$

After space carving on each silhouette image of multiple views, the retained point which inside each silhouette conic space is considered as the point inside the object volume.

We suppose that a cube-collection composes the cubic volume, and each cube partitions the volume into sub-cubic. There are altogether 26 neighbor-cubes for each cube. The cube is seemed to be inside the object's volume when at least one of the 26 neighborhood cubes encloses point data. According to the rules, the point inside the cube, which is seemed as the inner points of the measured object, should be removed. On the contrary the surface point should be retained. The final retained points are indeed the surface points of the object.

The light-stripe image and silhouetted image are acquired using the common camera. Namely the point-cloud is acquired through structured-light scanning and surface data from silhouette using a common world coordinate system, which means we can integrate two parts of point data directly to obtain complete final 3D model.

The cup with a handle is measured using the proposed 3D acquisition system, as shown in Fig. 3. First the structured-light scanning on cup is performed and the point-cloud data (*sl* data) are acquired, as shown in Fig. 4(a). Obviously the shape detail of the handle which is really a hollow shape has not been scanned. Figure 4(b) shows the surface point data acquired through shape from silhouette (*sfs* data). Most of surface data of

Table 1. Calculated Result of the Ball Bearing Surface Data

Acquisition Method	Diameter (mm)	Calculated Ball Center
Structured-Light Scanning Data	50.020	(47.639,0.421,90.689)
Shape from Silhouette Data	50.138	(47.649,0.431,90.692)

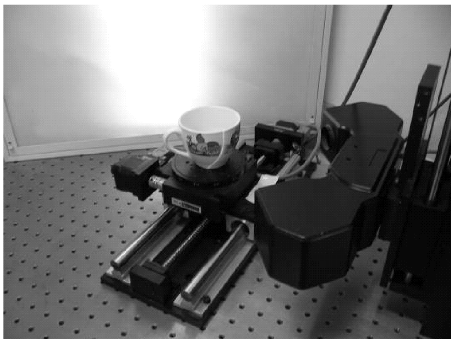
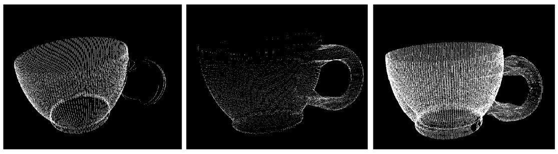


Fig. 3. 3D acquisition system.



(a) (b) (c)

Fig. 4. The measured point-cloud of a cup.

the handle are acquired accurately except the connection area between the cup and the handle, which is in fact a concave surface, but expressed as a flat surface. We use the manual polygon selection method to select the handle partial point from the *sfs* data. Then the selection-partial data and *sl* data are integrated into the final complete cup's 3D point data, with all the shape detail laid out clearly, as shown in Fig. 4(c).

The resulted 3D data are acquired through integrating two groups of 3D point data together without any integration or registration algorithm. Therefore a high measurement consistency and measurement precision of two 3D acquisition approach is required to ensure the accuracy of the final data. In order to test the consistency between two measurements, a ball bearing, 50 ± 0.001 mm diameters, was measured through structured-light rotation scanning and the shape from silhouette. We solved out the coordinates of the ball center P_s and diameter D_s using the *sl* data and *sfs* data respectively, as shown in Fig. 5. The calculated result is listed in Table 1. The difference between two groups of data is less than 0.15 mm, i.e., the consistency of two groups of data is better than 0.15 mm. And both two approaches have the measurement accuracy better than 0.15 mm. The test result indicates that the measurement accuracy of the proposed system is reliable and robust.

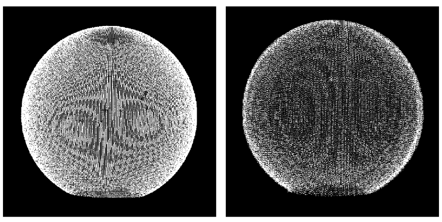


Fig. 5. The measured point-cloud of a ball.

In summary, a novel 3D acquisition system, which is capable of acquiring point-cloud data with structured-light scanning and surface point data with shape from silhouette, is presented. Two groups of data share a common world coordinate system, and can be integrated into the final complete data accurately. The system overcomes the shortcoming of two applied 3D acquisition algorithms. And the integrity of final 3D data is improved effectively. Also a test on a ball-bearing indicates that 3D measurement accuracy is reliable. The proposed scheme of incorporating two kinds of algorithm into one system is extraordinary available to solve the incompleteness problem of 3D acquisition. The future work will focus on how to utilize the contour information from *sfs* data to determine sensor's views for structured-light scanning, aiming at improving the efficiency and quality of scanning.

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