3D Model Acquisition Based on Projections of Level Curves

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Abstract

A novel method for 3D model acquisition based on projections of level curves is presented. The idea is similar to surface from parallel contours. However, different from CT or laser range scanning for range data acquisition, our approach is implemented on a low-cost passive camera system. The object is placed in a container and the level curves are generated by raising the water level. The 3D surface is recovered by multiple 2D projections of parallel level curves with camera pose estimation. Furthermore, the complete 3D model is reconstructed by registration and integration of multi-view 3D shape acquisition. Experimental results are presented for real image sequences. The average error is less than 3 mm in the working range of about 1 meter from the camera.

1. Introduction

One of the essential problems in computer vision is to recover the 3D surface of an object from the observed images. Its application areas range from industrial inspection and object recognition to computer graphics. Commonly used techniques for 3D shape recovery include stereo vision or motion, shape from shading, shape from silhouettes, and photometric stereo, etc [6]. These methods require either multiple images captured from different viewpoints or controlled illumination conditions for image acquisition. There are also some other techniques such as depth from zooming/focus/defocus, which extract the depth information by comparing several images recorded by a single camera with different camera parameters. A motorized zoom lens is usually required to change the zoom or focus positions for these methods.

In addition to the conventional image-based methods, 3D model reconstruction can also be achieved by active approaches, such as laser range scanning, structured lighting, computed tomography (CT scan), and magnetic resonance imaging (MRI). These techniques usually process the object’s surface one cross-section at a time to obtain a 3D curve, and then merge the layered information into a 3D surface. Inspired by these shape recovery methods based on multiple planar scans, in this work we propose a 3D model acquisition system using the level curves associated with the object’s cross-sections. The idea is to use multiple 2D projections of parallel 3D curves to recover the level curves of the object. The 3D surface is then obtained by combining multiple 3D curves or contours.

In our prototype 3D model acquisition system, the object is placed in a water container mounted on a turntable. The images are captured by a static camera in front of the rotation stage. Different from most reconstruction methods with active projection on the object’s surface, the level curves are generated by increasing the water level in the container. For a given viewpoint, the visible surface of the object is recovered using projections of the parallel level curves and external parameters of the vision system. Furthermore, the complete 3D model is reconstructed by registration and integration of multi-view 3D shape acquisition.

Although 3D reconstruction from parallel slices of contours is a well developed technique, it usually requires expensive data acquisition equipment (such as CT or MRI). As for the structured lighting or laser range scanning systems, the reflectance property of the surface is one important issue to be solved, especially near the edges or abrupt depth changes of the object. The proposed 3D model acquisition method uses low-cost hardware setup, and it is insensitive to the environmental illumination change. This paper reports a preliminary of the feasibility of 3D surface reconstruction from projections of the object’s level curves.

2. Shape from Parallel 3D Curves

3D shape recovery of the proposed method is based on the integration of a set of 3D curves, with each of them lies...
To obtain the parameters $a, b, c, d$ of the plane equation (1) for each cross-section, the planar surface patch bounded by the cubic water container is used. It can be shown that the relative depths of four 3D points can be determined by their 2D projections if they form a parallelogram in the 3D space [4]. Thus, given the image points of the rectangular surface patch, the corresponding 3D points can be computed up to a scale factor. Now, suppose the four corner points are $P_i = (x_i, y_i, z_i)$, and the corresponding image points are $p_i = (\hat{x}_i, \hat{y}_i, f)$, where $i = 0, 1, 2, 3$, and $f$ is the focal length of the camera. Then we have $(x_i, y_i, z_i) = (\lambda_i x_i, \lambda_i y_i, \lambda_i f)$, where $\lambda_i$'s are the unknown scale factors. Since the relative depths of the corner points can be written as $\mu_i = \lambda_i / \lambda_0$, for $i = 1, 2, 3$, we have

$$
\begin{pmatrix}
\mu_1 \\
\mu_2 \\
\mu_3
\end{pmatrix} =
\begin{pmatrix}
x_1 & -x_2 & x_3 \\
y_1 & -y_2 & y_3 \\
1 & -1 & 1
\end{pmatrix}^{-1}
\begin{pmatrix}
x_0 \\
y_0 \\
1
\end{pmatrix}
$$

(4)

If the dimension of the surface patch is known, say, the width is $W$, then $W^2 = |P_0 - P_1|^2$, and we have

$$
\lambda_0 = \frac{W}{\sqrt{(x_0 - \mu_1 x_1)^2 + (y_0 - \mu_1 y_1)^2 + f^2(1 - \mu_1)^2}}
$$

That is, $\lambda_0$ can be calculated using $\mu_1$ given by Eq. (4), and then $\lambda_i$'s can be obtained by the relative depths, $\mu_i = \lambda_i / \lambda_0$, for $i = 1, 2, 3$. Consequently, the parameters $a, b, c, d$ used in Eq. (2) can be determined by the image of the water level corners and the dimension of the cubic container.

3. System Setup and Implementation

The proposed 3D model acquisition system is shown in Figure 2(a). The cubic container used to place the object is specifically designed so that the water level can increase smoothly with the equally spaced holes on the bottom (see Figure 2(b)). It is placed on a PC controlled turntable for multi-view 3D shape recovery with a single camera. For a given viewpoint, the problem of determining the plane equation of the water level for 3D reconstruction is equivalent to the problem of camera pose estimation. A self-calibration method using the water level curves is described in the previous section. As for the complete 3D model acquisition, it is also mandatory to find the rotation axis of the turntable for multi-view 3D registration and integration. To avoid additional calibration for the rotation axis estimation, the unit vector and location of the turntable are obtained as follows.

It is clear that the perspective projection of a circle is an ellipse in the image. Thus, Canny edge detection is first applied on the image with only the turntable [3], followed by a least square fitting algorithm to detect the elliptical shape.
in the edge image [5]. The relative orientation between the camera and the turntable is then estimated by an SVD-based pose ellipse algorithm [9]. Since the unit vector of the rotation axis is in the 3D space, its location can be represented by the turntable center. Thus, the scale factor associated with the perspective projection of the circle is derived from the physical size of the turntable. It is then used to recover the 3D coordinates of the turntable center.

In the implementation, the parallel planes for obtaining the cross-sections of the object are acquired by increasing the water level in the container. The coplanar 3D curves are then generated and recorded by a camera. To obtain the corresponding 2D curve of an object’s cross-section, a quadrilateral image region within the water surface (which is bounded by the container) is extracted and used for edge detection. Since the object might contain edge features other than its boundaries, robust cross-section detection is achieved by transforming the quadrilateral region to the HSI color space for region segmentation and boundary extraction. The cross-section curve is then identified by scanning the resulting edge image horizontally from the left and searching for the “smooth” edge segment with a predefined orientation change range for two neighboring pixels in the curve (typically from $-45^\circ$ to $45^\circ$).

As shown in the previous section, for each water level the corresponding plane equation can be derived from the image points of the water surface. To obtain the corner points of the surface patch, edge detection and Hough transform are applied to identify the line features in the image. The vertical lines which represent the edges of the container are removed from the image. The intersections of the remaining straight lines are selected as candidate corners and further checked with the water region segmentation. Only the four points near the boundary of the water surface region are selected for plane parameters computation. Figure 3(a) shows the results of a recorded image with coplanar corner detection and the extracted 2D curve.

3.1. Multi-View 3D Model Acquisition

To obtain the complete 3D model of the object, multiple 3D shapes are acquired by rotating the turntable with a fixed angle, and then registered and integrated into a common coordinate system [8]. For the multi-view range data registration, a modified ICP (Iterative Closest Point) approach is used [2]. The initial registration required for the ICP algorithm is given by the rotation axis estimated using the turntable image and pose from ellipse. Alternatively, the multi-view transformation can also be obtained by the 3D corner points registration of the cubic container without the turntable axis estimation. However, the results are generally not satisfactory in the experiments mainly due to the imprecise corner detection on the thick edges of the container. The registered multiple range data sets are finally integrated into a complete 3D model using the power crust algorithm [1].

4. Experimental Results

The proposed shape from parallel 3D curves approach has been tested on several real objects. White colored water is used in order to avoid the object’s reflection on the surface. For single viewpoint acquisition, the water level is raised continuously during the image captures. But for the multi-view complete 3D model reconstruction, the water level remains static during the rotation of the turntable (every $90^\circ$ with four image captures). To make sure the 2D curves distinguishable between the images, only the images with water level difference greater than 10 pixels are used. In the experimental setup, it corresponds to about 5 mm in the real scene. Two experimental results are shown in Figure 3(b). The left figure shows a bottle object from a single
viewpoint and the right figure shows the complete 3D model of a wooden block object.

To analyze the accuracy of the proposed method, a cylindrical object with known dimension is used for error analysis. Figures 4(a) and 4(b) show the results when the camera’s viewpoint is perpendicular and with a tilt angle to the turntable axis, respectively. The left figures show the real surface points (in black) and the recovered 3D curves (in blue). The average errors in each slice (in mm) for both cases are illustrated in the right figures. It can be seen that the error roughly increases with the water level. The reason could be the inaccurate depth computation due to the foreshortening of the surface patch, especially for the second case.

5. Conclusions and Future Work

This paper has described a 3D model acquisition system based on projections of level curves, and demonstrated some results from a prototype implementation. The idea is similar to CT or laser range scanning, but our approach can be implemented on a low-cost passive camera system. The system parameters can be obtained by self-calibration without additional experimental setup. Since the 3D coordinates are computed directly from the corresponding image points, dense depth map can only be achieved by adopting high resolution 2D curves. Currently the average error of the system is less than 3 mm in the working range of about 1 meter from the camera. In the future work, lens distortion of the camera will be taken into account to improve the 3D reconstruction accuracy.

References