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Keywords: shape recovery, photometric stereo, shape from contours.

1 Introduction

Photometric stereo and shape from contours are two shape recovery methods that obtain data that are complementary in nature. The photometric stereo method recovers dense surface orientations based on the surface irradiance values [4, 8]. However, the resultant gradient data need to be integrated to obtain surface depth values. Depth values obtained from various viewing directions must be registered and merged to recover the 3D model of the object. The shape from contours approach recovers a 3D model of the object according to object contours obtained from different viewing directions [5, 10]. Depending on the number of viewing direction, even though the recovered model may not be detailed, the model is able to act as a reference for the registration of depth values obtained by photometric stereo.

Photometric stereo with three light sources is used to obtain local surface orientations/gradients of the given object. The gradient data are calculated by an albedo independent analysis [5] where it is assumed that the object surface has approximative Lambertian reflectance. Gradient data is integrated by the Frankot-Chellappa algorithm to obtain surface depth data [3].

A recent survey on shape from shading algorithms [9] has again confirmed that the Frankot-Chellappa algorithm has generally better performance in integration of gradient data than other methods as already discussed in [4]. We
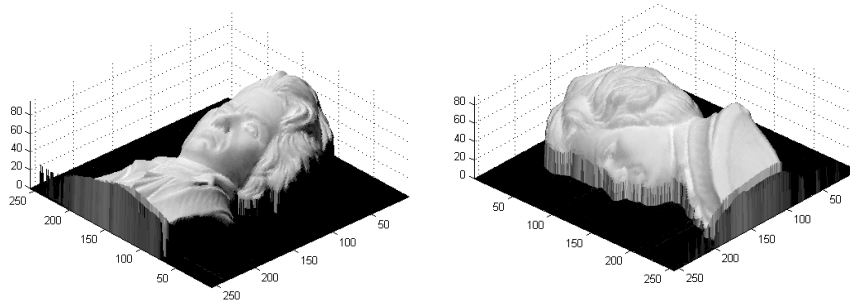
Figure 1: Examples of results obtained using photometric stereo.

use the Frankot-Chellappa algorithm for the integration of gradient data in our work.

The Frankot-Chellappa algorithm recovers integrable surfaces (surfaces with $Z_{xy} = Z_{yx}$) by integration using Fourier expansion. The gradient data is firstly transformed into the frequency domain, where the problem of finding the surface depth, Z, is equivalent to finding the expansion coefficients that minimize the error between the gradient obtained by photometric stereo and the gradient of the recovered surface Z. The surface Z is calculated via inverse Fourier transform of the expansion coefficients. An example of a recovered surface Z is shown in Fig. 1 (a plaster statue, see [5]).

The 3D shape of the object is directly indicated by the occluding contours in a 2D object image. The shape from contours method reconstructs a 3D model from such occluding contours of an object. Images of the object are acquired from different viewing directions. The 3D shape of the object is estimated by projection of contours from given viewing directions.

Volume carving is an intuitive way to construct a 3D model from occluding contours. It starts with a solid data block. Each projection of contours onto the data block serves to remove regions that are not contained within the object from the data block. Once the contours obtained from all viewing directions have been projected, the data block provides a rough estimate o the 3D shape of the object.

Surface based approaches are alternatives to volume carving. Locations of surface points are estimated by intersections of vectors projected from each viewing direction to the corresponding contour images. However, surface based approaches require the detection and handling of discontinuities in contour points, which significantly increases the complexity of the shape from contours method. Therefore, we use the volume carving approach in our work, since it is sufficient in providing a 3D model of the object for our purposes.

We assume the orthogonal projection model for the projection of contour points. An example of a resultant 3D contour model and one of its cross sectional slices are shown in Fig. 1.
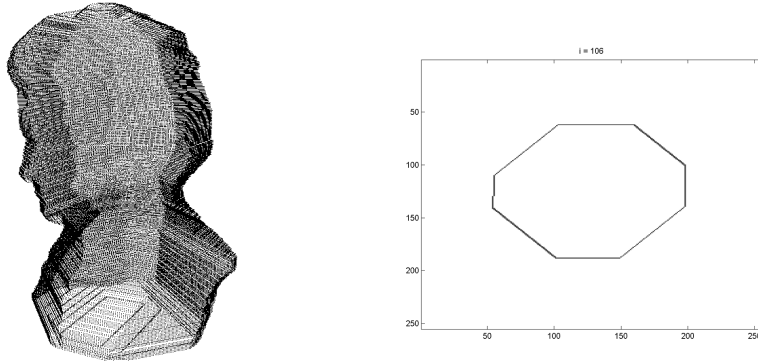
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Figure 2: Results obtained using shape from contours from (just) four viewing directions.

Generally, more viewing directions may improve the accuracy of the 3D model recovered by shape from contours. Nevertheless, one of the underlying problems with shape from contours is that surface points that are occluded from viewing directions by other regions on the object surface cannot be recovered from contours alone.

This paper proposes a method for 3D shape recovery by the fusion of depth data obtained from photometric stereo and shape from contours: photometric stereo is used to recover the depth values of the object from a number of viewing directions. The recovered surfaces are registered based on the 3D model obtained with shape from contours. Registered surfaces are merged to produce the final 3D model. Details of procedures involved in the proposed method are discussed in the following sections.

2   Registration

The accuracy of the final 3D model depends highly on the correct registration of partial surfaces obtained by photometric stereo for the different viewing directions. However, registration of surfaces can be a complicated problem, since there is no information on how the height values in surfaces recovered from different viewing directions relate to each other. The surfaces recovered by photometric stereo are height values with respect to an arbitrary background. Therefore, if only surfaces obtained by photometric stereo are given, we would require registration approaches, such as the iterative closest point (ICP) algorithm to match surfaces obtained from different viewing directions [1, 2, 6, 7].

With the proposed approach, the registration problem is simplified by having the 3D model obtained by shape from contours as a guide for registering surface obtained from different viewing directions.

The registration between two surfaces is defined as a rigid 3D transformation
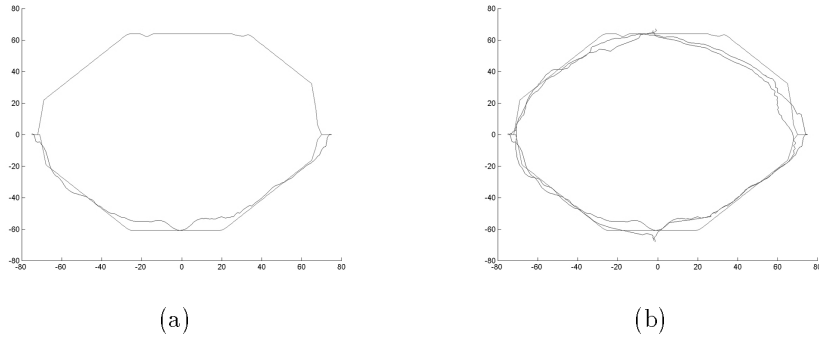
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(a)   (b)

Figure 3: (a) shows a single registered profile and (b) shows registered profiles from viewing directions of 0, $\pi/2$, π and $3\pi/2$

which can be represented by

$$\mathbf{T}(S_\theta) = \mathbf{R}S_\theta + \mathbf{t} \, , \tag{1}$$

where S_θ is the partial surface provided in the photometric stereo depth data from viewing direction θ, $\mathbf{R}$ is the 3D rotation matrix and $\mathbf{t}$ is the 3D translation vector. Let M_θ be the set of all surface points of the 3D object reconstructed via shape from contours and visible from the viewing direction θ. The transformed surface $\mathbf{T}(S_\theta)$ should match this object surface, i.e. it would be $\mathbf{T}(S_\theta) \subseteq M_\theta$. However, note that both sets are erroneous approximations of the unknown object surface.

We will look at the problem on a slice by slice basis. The Z-axis is assumed to coincide with the optical axis of the camera [5], and we consider slices defined by fixed Y-values. Let $\mathbf{m} = (m_x, m_y, m_z)$ be a single point on M_θ. Each *partial SFC profile* $M_{\theta,y}$ is a cross section of the surface reconstructed from shape from contours, defined by

$$M_{\theta,y} = \{\mathbf{m} \in M_\theta : m_y = y\} . \tag{2}$$

where θ is the direction of the line of sight. A (complete) *SFC profile* M_y is defined to be the union of all partial SFC profiles $M_{\theta,y}$, for all available angles θ in $0°$ and $360°$.

An object profile will be calculated based on those depth data obtained by photometric stereo which are on the y-plane parallel to the $\mathbf{XZ}$ plane, given as *partial PSM profiles*

$$S_{\theta,y} = \{\mathbf{s} \in S_\theta : s_y = y\}, \tag{3}$$

where $\mathbf{s} = (s_x, s_y, s_z)$ is a single point on S_θ and θ goes through the finite set of used viewing orientations. We define a translation along the line of sight to align $S_{\theta,y}$ and $M_{\theta,y}$, using the maximum distance

$$d_{\theta,y} = \max\{|M_{\theta,y} - S_{\theta,y}|\} . \tag{4}$$

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between corresponding points (same XY-coordinates) in each partial profile.

A given partial PSM profile $S_{\theta,y}$ is shifted by $d_{\theta,y}$ along the line of sight. Afterwards, a rotation $\mathbf{R}$ is applied to $S_{\theta,y}$ with respect to the known angle θ and a fixed rotation axis to transform $S_{\theta,y}$ into a position in 3D space where it will be used for the subsequent merging process.

The convex polygon M_y in the cross sectional slice of the shape from contours model acts as the outer boundary for surfaces obtained by photometric stereo, such that the 'centre part' of the partial PSM profile $S_{\theta,y}$ is enclosed within the SFC profile M_y as shown in Fig. 2.

3   Merging

Once the surfaces have been registered, they need to be merged, such that the resultant surface forms a surface that represents the 3D shape of the object.

After the registration process, it can be expected, see Fig. 2, that there is an overlapping region between consecutive pairs of registered profiles. Since each profile recovered by photometric stereo may cover up to 180 degrees of view, the size of the overlapping regions increases with the number of viewing directions.

We have found that rather than using the usual Cartesian coordinate system, the polar coordinate system is more suitable for performing the merging process. The conversion into a polar coordinate systems is only possible after the registration process, from which we can obtain the distance between the center of rotation and each point on the profile. After the conversion, each surface point, $\mathbf{s}$ is given by a pair of (σ, r) values in the polar coordinate system, which has its origin in the center of rotation. The value of σ represents the angle between the point on the profile and a reference starting direction. The value of r represents the absolute distance between the point and the center of rotation. An increment of σ by θ is the equivalent to applying $\mathbf{R}$ in the Cartesian coordinate system.

An inherent problem in fusing the overlapping region of the two profiles is caused by the given discrete data. Since for many points in $S_{\theta 1,y}$, there are no points in $S_{\theta 2,y}$ at the corresponding σ value, and vice versa. Therefore, interpolation in the overlapping region is necessary, such that for any given σ value, there are two values for r, respectively obtained from the interpolated profiles of $S_{\theta 1,y}$ and $S_{\theta 2,y}$.

To estimate the r value for a given σ value on profile $S_{\theta 1,y}$, we first locate two points $\mathbf{s}_1 = (\sigma_1, r_1)$ and $\mathbf{s}_2 = (\sigma_1, r_1)$ in $S_{\theta 1,y}$, where $\sigma_1 < \sigma < \sigma_2$. A linear interpolation function is used to interpolate the r values between s_1 and s_2. The interpolated value of r is given as

$$r'_1 = r_1 + (a * (r_2 - r_1)), \tag{5}$$

where $a = (\sigma - \sigma_1)/(\sigma_2 - \sigma_1)$. This (simple) linear interpolation supports efficient implementations.

The interpolation for r values is performed for all σ values in the overlapping region of the two given profiles to obtain the interpolated profiles $S'_{\theta 1,y}$ and
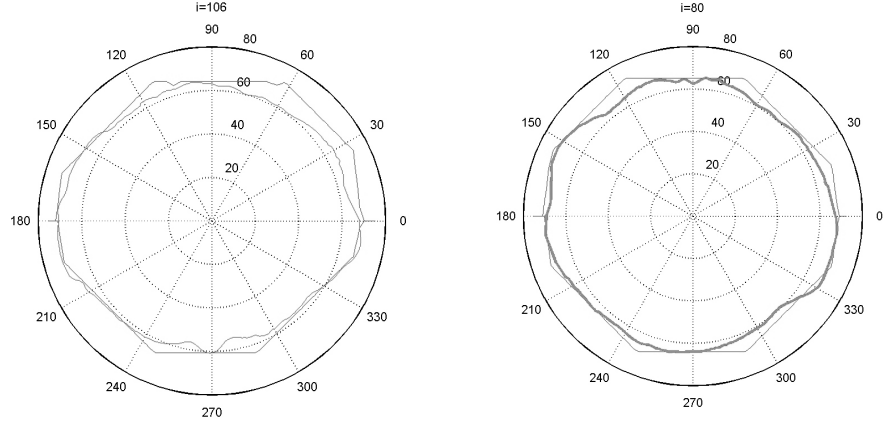
Figure 4: (a) shows merged profiles for $i = 106$ and (b) shows merged profiles for $i = 80$

$S'_{\theta 2,y}$. The interpolated profiles have a new set of σ values which is equal to the unification of σ values in $S_{\theta 1,y}$ and $S_{\theta 2,y}$ in the overlapping region.

The interpolated profiles $S'_{\theta 1,y}$ and $S'_{\theta 2,y}$ are fused using a linear weighting function. One reason for using this function is its ability to provide a smooth transition between two profiles. The other reason lies in its ability to approximate the confidence in the accuracy of the obtained profiles. That is, points close to the edge of profiles would have smaller weighting factors than points near the center of the profile, since edge points are more likely to be erroneous. By applying a linear weighting function to the overlapping region, the r value of a point in a profile obtained from the fusion of $S'_{\theta 1,y}$ and $S'_{\theta 2,y}$ is given by

$$r_{12,j} = (1 - j/N) * r'_{1,j} + (j/N) * r'_{2,j} , \qquad (6)$$

for $0 \leq j < N$, where N denotes the number of points and j represents the index of the point in the overlapping region, $r'_{1,j}$ and $r'_{2,j}$ respectively denotes corresponding r values from profiles $S'_{\theta 1,y}$ and $S'_{\theta 2,y}$, and $r_{12,j}$ represents the jth r value obtained by the fusion of $r'_{1,j}$ and $r'_{2,j}$.

Figure 3(a) shows the profile obtained by the fusion of the overlapping profiles in Fig. 2(b). From Figure 3(a), we can see that the resultant profile has a smooth transition from one profile to the other, as well as retaining the details provided by the original profiles.

The final 3D model is obtained by performing the process of fusion for all profiles at each slice. During the fusion of r values, we can also using the same approach to fuse the corresponding image irradiance values from the texture images, and obtain a fused texture image for mapping onto the final 3D model.

4 Discussion and Conclusion

The accuracy of depth data recovered by photometric stereo is dependent on the angle between the surface's local orientation and the viewing direction. Larger angles lead to more erroneous results. Therefore, data near the edge of the visible object surface is generally less accurate compared with data elsewhere, since the surface orientations near the edge are almost perpendicular to the viewing direction. In our work, we consider this aspect by using a linear weighting function that places less weight on the data close to the edge of the surface. This avoids an introduction of large errors into the final result. Some aspects for future work may include:

- non-rigid transformations for alignment of profiles,

- alternative methods for the interpolation of profiles, and

- different weighting functions for the fusion of profiles.

In this work we have proposed an approach to reconstruct 3D models through registration and fusion of data acquired by the photometric stereo method and shape from contours. Experiments have been performed on real data obtained in the laboratories, as well as synthetic data obtained by a simulation of photometric stereo and shape from contours. Results from experiments have shown that the method is able to provide promising results.

The advantage of a fusion between photometric stereo and shape from contours is that the method may utilize just one image acquisition system: three light sources for photometric stereo, one camera and one turntable. The data required for shape from contours are already inherently included in the images acquired for photometric stereo. Furthermore, the proposed method not only recovers dense 3D coordinates on the surface of the object, it is also capable of recovering the surface reflectance characteristics of the object. This feature can be extremely useful for rendering of 3D models since models rendered with known surface reflectance properties will appear more realistic than if an artificial reflectance model (such as the Lambertian, or the specular reflectance models) is applied.

The proposed method has a wide range of potential applications: virtual museums, simulation, marketing and other applications where the acquisition of a 3D model is required.

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