3D Reconstruction Using Shape from Photometric Stereo and Contours

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Abstract

In this work, we further discuss an approach to 3D shape recovery by combining photometric stereo and shape from contours methods. Surfaces recovered by photometric stereo are aligned, adjusted and merged according to a preliminary 3D model obtained by shape from contours. Comparisons are conducted to evaluate the performances of different methods. It has been found that the proposed combination provides more accurate shape recovery than using either photometric stereo or shape from contours alone.

Keywords: 3D shape recovery, photometric stereo, shape from contours

1 Introduction

The photometric stereo method is the multi-image version of shape from shading [10]. Rather than using a single intensity image as in the conventional shape from shading, the photometric stereo method uses two or more intensity images of the object under different illumination conditions, thereby reduces the set of constraints required to recover the surface of the object and improves the accuracy of the result. The photometric stereo method is able to rapidly obtain dense local surface orientations from intensity images of the object illuminated by calibrated light sources [4, 5, 10, 11]. The surface orientation vectors are integrated, either globally or locally, to provide the depth values of the surface [2, 3, 4, 9]. However, independent of integration approaches, the surface depth values recovered by integration of the orientation vectors are scaled with respect to the depth values of the true surface.

The shape from contours method is an intuitive 3D shape recovery method that gives reliable 3D shape estimation from the occluding contours of the object [6]. The 3D model of the object can be calculated from the occluding contours of the object in images taken from various calibrated viewing directions, using method such as volume-carving [4, 7, 8]. Nevertheless, the method is unable to recover some concave regions on the surface and the accuracy of the recovered 3D model depends on the resolution of the viewing directions. Nevertheless, the shape from contours method has less restrictions on the illumination conditions, making it a more robust approach to obtain the preliminary 3D model of an object.

In this work, we further discuss a 3D shape recovery method to combine the depth information obtained by photometric stereo and shape from contours methods, which has been originally proposed in [1]. Our motivation is to design an alternative 3D shape recovery method that combines the advantages of photometric stereo and shape from contours to provide rapid, detailed and reliable 3D surface recovery.

The proposed shape from photometric stereo and contours method uses the 3D model obtained by shape from contours to align and adjust surfaces recovered by photometric stereo in different viewing directions. Neighbouring surface patches are then merged according to a weighting function associated with the reliability of the photometric stereo method to produce the final 3D model. Comparisons of experimental results have shown that the proposed approach has better performance than the photometric stereo or shape from contours method alone.

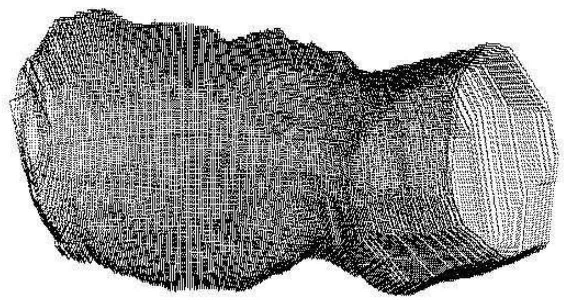
2 Shape from photometric stereo and contours

2.1 Input data

In this section we briefly describe how to apply photometric stereo and shape from contours methods (see [4] for details) for our purposes. The object is rotated in θ degree increments to provide views from different directions. At each viewing direction θ_{psm}, three light sources are used to provide input irradiance images for the albedo-independent photometric stereo method. Local surface orientation vectors are recovered by the photometric stereo method and globally integrated to obtain surface depth values. The algorithm in [9] generalises the method proposed in [2], which was formulated as an algorithm in [4], and this is also the integration approach used for this article.

Altogether, there are $360/\theta_{psm}$ partial surface reconstructions of the object. A 3D model of the object is constructed by acquiring the contour images of the object at θ_{sfc} degrees increment and applying the shape from contours method. Examples of input partial surfaces and 3D model are shown in Fig. 1. Experiments have been conducted using different combinations of θ_{psm} and θ_{sfc} to investigate the influence of the recovered partial surfaces and the preliminary 3D model on the final 3D model.

(a)



(b)

Figure 1: Examples of input data: (a) partial surface recovered by photometric stereo and (b) preliminary 3D model (*photo hull*) recovered by shape from contours.

Once the input partial surfaces and 3D model have been obtained, they are aligned according to the viewing directions in preparation for the following steps, where the input data will be adjusted and merged according to the proposed method.

2.2 Surface adjustment

The partial surfaces obtained by photometric stereo are adjusted with respect to corresponding regions on the 3D model obtained by shape from contours [1]. This process is necessary to account for the fact that surface values are obtained by the photometric stereo method through integration, which makes them somewhat scaled with respect to the true surface values. On the other hand, the 3D model obtains its shape directly from the contours of the object, hence it can serve as a reference for correcting the scaled surfaces.

A vertical profile extracted from each partial surface is compared with the profile extracted from the 3D model in the same viewing direction and the difference between two profiles is approximated by a linear function. The linear function is then weighted and applied to the partial surface to adjust surface depth values towards those on the 3D model. Figure 2 shows an example of the vertical profiles. In Fig. 2, the solid light gray line represents the profile extracted from the preliminary 3D model, the solid dark gray line represents the profile extracted from the corresponding partial surface obtained by photometric stereo, and the dashed black line is the profile extracted from the adjusted surface.

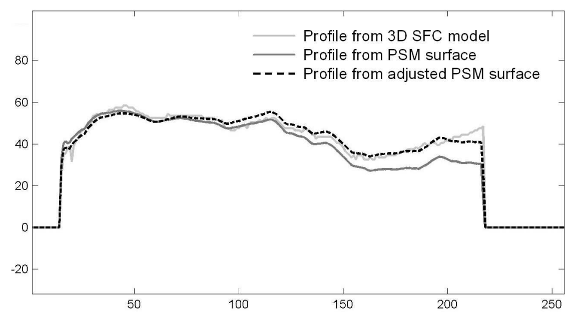


Figure 2: A vertical cross-section showing profiles extracted from the 3D model, the corresponding partial surface and the adjusted partial surface.

When all partial surfaces have been aligned and adjusted, the next step is to merge these surface with respect to the reliability of depth values on each surface.

2.3 Merging of surfaces

In the merging step, depth values on overlapping partial surfaces are merged according to weighting functions to produce a 3D model of the object. The weighting functions are based on the characteristics of the photometric stereo method when recovering a given surface. Generally, surface orientations recovered by photometric stereo becomes less accurate as they approach 90 degrees with respect to the viewing direction, since those are regions where shadows begin to occur. Hence depth values towards the edges of a given partial surface are less reliable than values towards the center of the surface.

Suppose $S_{\theta,j}$ represents the j^{th} horizontal cross-section of partial surface obtained from viewing direction θ. Given two overlapping profiles $S_{\theta1,j}$ and $S_{\theta2,j}$, let $\phi_{\theta1,j}$ denote the angle of the overlapping region and ϕ_i denote the angle from the start of the overlapping region for each point i (where i is the index for points) within the overlapping region. The weighting function for each point i within the overlapping region is

$$w_{\theta1,j}(i) = 1 - \phi_i/\phi_{\theta1,j} \ , \qquad (1)$$

and the merged profile is

$$S_j(i) = w_{\theta1,j}(i) * S_{\theta1,j}(i) + (1 - w_{\theta1,j}(i)) * S_{\theta2,j}(i). \quad (2)$$

Figure 3 shows two overlapping profiles and the resultant merged profile. It can be seen that the merged profile has a smooth transition from one profile into the next, and it retains the details provided by both profiles.

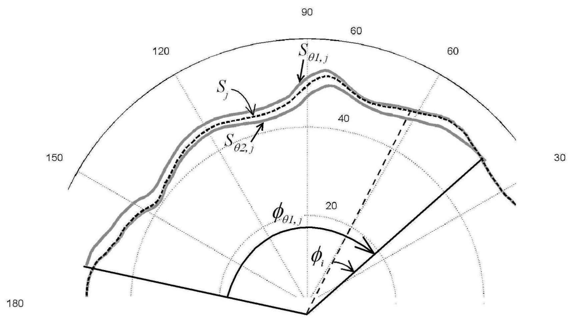


Figure 3: Overlapping profiles and the resultant merged profile

The merging process is repeated for all horizontal profiles for all viewing directions to obtain a 3D model from the partial surfaces.

3 Results

We show results obtained by fusion of partial surfaces and the preliminary 3D model, and evaluate the reconstruction accuracy of each method. Figure 4 shows a partial surface of the original 3D model *Beethoven*, Fig. 5 shows the errors calculated for corresponding surfaces reconstructed using photometric stereo (first), shape from contours (second), photometric stereo surface adjusted using the preliminary 3D model (third), and the surface reconstructed by merging the adjusted surface according to the weighting function (fourth). The intensity of the error images represent the error magnitude, and the mean percentage error is given at the bottom of each image.

Figure 4: The original surface depth image for *Beethoven*.

It can be seen from Fig. 5 that the surfaces reconstructed by the fusion of photometric stereo and shape from contours are more accurate than surface obtained by the other methods. Reconstructions and comparisons for other models also been performed with similar results as shown in Fig. 5. Figures 6(a) and 6(b) show the error plots for two of the models used in this work and Table 1 shows the overall errors for all four reconstructed 3D models. For the examples, we used $\theta_{psm} = 30°$ and $\theta_{sfc} = 30°$.

Figures 6(a) and 6(b) show that the merged 3D models have generally lower errors than either the surfaces obtained by photometric stereo, shape from contours, or the photometric stereo partial surfaces adjusted by the preliminary 3D models obtained by shape from contours. It can be seen from the graphs that the error plots of the merged models approximately follows the error plots of the preliminary 3D model. We also experimented with different values of θ_{psm} and θ_{sfc}. For example, using $\theta_{psm} = 90°$, $\theta_{sfc} = 30°$, $\theta_{psm} = 90°$ and $\theta_{sfc} = 90°$, as well as other combinations of θ_{psm} and θ_{sfc}. It has been found that if the preliminary 3D model is accurate (e.g., mean error is less than 10%), then the merged model will have improved accuracy. On the other hand, if the preliminary 3D model is not so accurate, then it degrades the effects of the surface adjustment process, resulting in a less accurate 3D model.

The effectiveness of the adjustment and merging functions can be seen from the comparisons. Errors in the partial surfaces are dramatically reduced once the surfaces are adjusted. The merging process also reduced the errors further by discarding the less reliable regions on the partial surface and placing higher weight on the more reliable and detailed regions.

Table 1 summarises the errors for models recovered by each of the three shape recovery methods used in this work, it can be seen that the 3D models recovered by the proposed method have lower overall error than models obtained using other approaches.

Table 1: Error for reconstructed models.

(%)	**PSM**	**SFC**	**Adjusted**	**Merged**
Beethoven	12.49	4.88	4.92	3.93
Monk	16.21	4.96	5.54	3.83
Mozart	13.17	5.68	5.34	4.06
Penguin	13.35	6.48	5.95	4.39

4 Conclusion

We have refined an alternative method for 3D shape recovery by combining data provided by photometric stereo and shape from contours. Partial surfaces obtained by photometric stereo in multiple viewing directions are aligned and adjusted with respect to a preliminary 3D model recovered by shape from contours. The surfaces are then merged with respect to a weight function to produce a 3D model. The 3D model recovered by the proposed method has the advantages from both the photometric stereo and shape from contours methods. The adjusting function adjusts the partial surfaces towards the shape of the preliminary 3D model, and the weighting function merges the partial surfaces together. Both functions have been selected such that while conforming to the shape of the object, it also retains the details on the surface of the object. Experiments and comparisons have been performed using different objects. Overall, the proposed 3D shape recovery approach by combining photometric stereo and shape from contours can effectively obtain 3D models with higher accuracy than that of using either method alone. Future work may include experiments by merging with surface patches rather than the horizontal profiles, and reconstructing models with different reflectance and geometric properties.

References

[1] C.-Y. Chen, R. Klette and C.-F. Chen, ”Improved fusion of photometric stereo and shape from contours”, in *Proc. Image Vision Computing New Zealand*, pp. 103–108, (2001).

[2] R. Frankot, R. Chellappa, ”A method for enforcing integrability in shape from shading algorithms”, *IEEE Trans. Pattern Analysis Machine Intelligence*, **10**, pp. 439–451, (1988).

[3] R. Klette, K.Schlüns, ”Height data from gradient fields”, in *Proc. SPIE*, **2908**, pp. 204–215, (1996).

[4] R. Klette, K. Schlüns, A. Koschan, *Computer Vision: Three-dimensional Data from Images*, Springer, Singapore (1998).

[5] R. Klette, R. Kozera and K. Schlüns, Reflectance-based shape recovery, in *Handbook of Computer Vision and Applications*, eds. B. Jahne, H. Haubecker, and P. Geiblerk, **2**, Academic Press, pp. 531–590, (1999).

[6] J. J. Koenderink, *Solid Shape*, Cambridge, MA, MIT Press (1990).

[7] K. N. Kutulakos and S. M. Seitz, ”A theory of shape by space carving”, in *Proc. 7th Int. Conf. Computer Vision*, pp. 307–314, (1999).

[8] S. Tokai, T. Wada, T. Matsuyama, ”Real time 3D shape reconstruction using PC cluster system”, in *Proc. 3rd Int. Workshop Cooperative Distributed Vision*, pp. 171–187, (1999).

[9] T. Wei and R. Klette, ”Depth recovery from noisy gradient vector fields using regularization”, in *Proc. 10th Int. Conf. Computer Analysis of Images and Patterns*, pp. 116–123, (2003).

[10] R. J. Woodham, ”Photometric method for determining surface orientation from multiple images”, in *Optical Engineering*, **19**, pp. 139–144, (1980).

[11] R. Zhang, P. S. Tsai, J. E. Cryer and M. Shah, ”Shape-from-shading: a survey”, *IEEE Trans. Pattern Analysis and Machine Intelligence*, **21**, pp. 690–706, (1999).

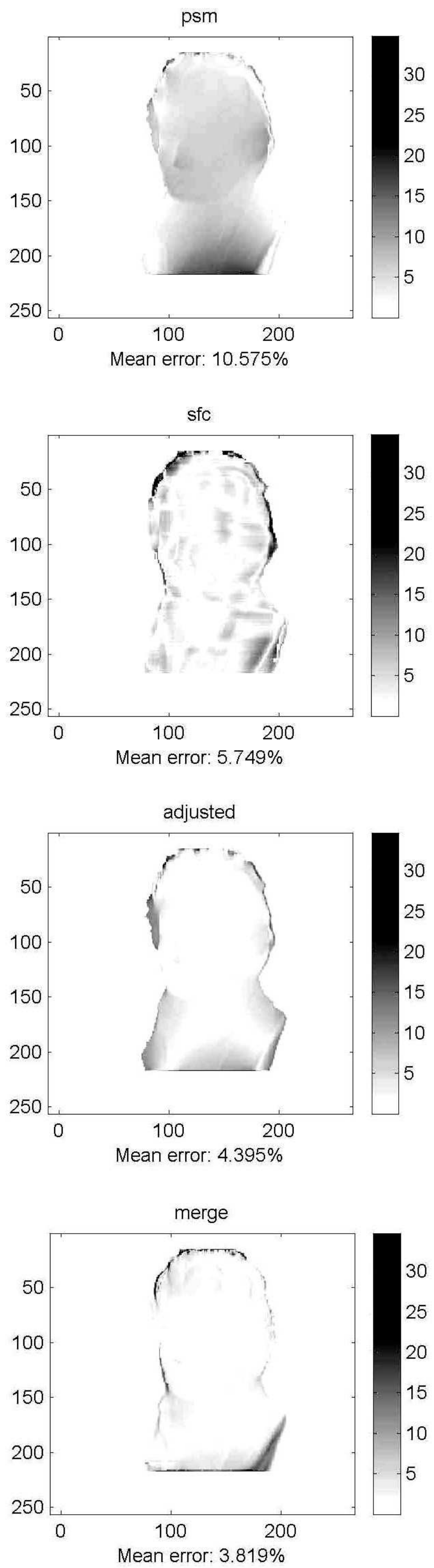
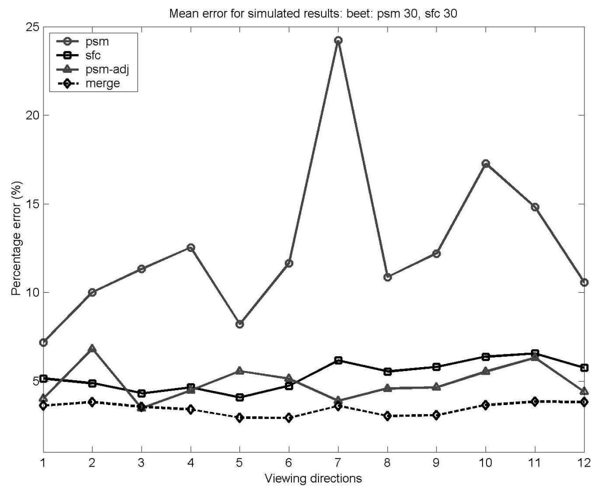
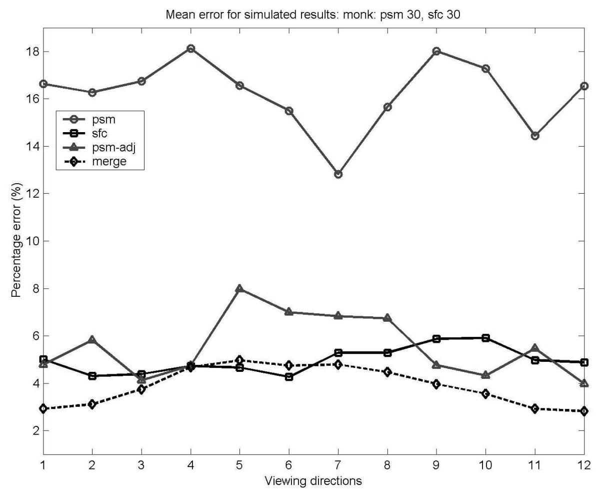


Figure 5: Comparison of errors in surfaces reconstructed by different methods for *Beethoven*.



(a)



(b)

Figure 6: Error plots for reconstructed (a) *Beethoven* and (b) *Monk*.