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Towards 3D Model Reconstruction from Photometric Stereo

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Abstract

In this highly technological world, various methods have been developed for the purpose of recovering the shape of 3D objects from 2D images. In this paper, we introduce methods to combine a collection of range images, which is created by Photometric Stereo, into a single polygonal mesh completely describes an object. Experiments and analysis will be carried out to test the accuracy of our model reconstruction. Finally, results will be displayed.

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Towards 3D Model Reconstruction from Photometric Stereo

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Keywords: 3D Model Reconstruction, Range Images, Photometric Stereo

1 Introduction

Three-dimensional model reconstruction involves in two stages. Firstly, by acquiring 2-D digital images, the surface normal and depth of the points in the image can be computed. Secondly, the 3-D model can be recovered from the 2.5-D depth information from the images by registration and integration. The 3-D model recovery is the main subject of this paper.

This paper is organised as follows: Section 2 analysis the depth map generated by Photometric Stereo. Section 3 shows refinements of the elementary approach to the 3D model reconstruction and the analysis carried out by this approach. Section 4 addresses the issue of conclusion.

2 Depth Map Reconstruction

Photometric stereo [7] uses prior knowledge of the illumination geometry of the scene and the nature of surface reflection to obtain information about the surface normal and other characteristics of the surface. Multiple images of a surface are captured from a camera by illuminating the surface from different directions. The intensities in these images are used to mathematically invert the image formation process. The information on the gradient field has to be transformed into (relative) height or depth maps. The reconstruction accuracy depends not only on the method of generating surface normal, but also on the performance of the transformation from surface normal to height or depth maps.

2.1 Related work

The theory of Photometric Stereo for Lambertian surface was developed by Woodham [12]. Ray et al [9] conducted an error analysis of the Lambertian photometric stereo. Nayar et al [8] used distributed light sources for photometric stereo of surfaces whose reflection is a sum of specular and Lambertian components. Silver [10] showed how photometric stereo could be conducted with experimentally measured reflectance maps. Frankot [3] developed global optimisation techniques. Klette [6] conducted experimental evaluations on these integration techniques. These evaluations are invaluable to this thesis.

2.2 Analysis

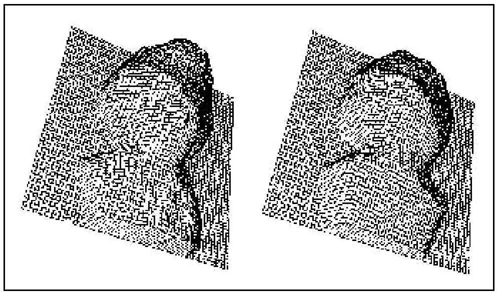

Figure 1: The 2.5-D plots of the front and back of the bust.

Figure 1 shows the 2.5D depth map of the plaster bust of Beethoven that was used by our experiment. An object of such complication was chosen for the purpose of identifying any situation in the reconstruction that might cause erroneous results. 81 images were captured from the Beethoven bust. Only 19 images which were captured under three different light source illuminations were used in the 3-D model reconstruction process. From the result of our experiment, we found that errors occurred at the boundary of the object. These situations can be eliminated in our model reconstruction to gain more accurate results. Figure 2 shows the input images and the cross-sections around the nose of the reconstructed depth map of the front and rotated bust. The dotted line shows the cross-section of the rotated bust. It shows that the left side of the nose was distorted in the rotated depth map. Moreover, it also shows the cross-sections around the shirt. Again, the depth values of the right bottom of the shirt were greatly increased.

The accuracy of orientation determination depends on the estimation of the light source direction and strength. It is sensitive to noise and measurement errors. Also, it depends on the complexity of the object. Errors occur at the boundary of the object where there are rapid changes of gradient information. Furthermore, error exists at the surface where discontinuities appear. Moreover, the computation of depth from surface normal is based on the assumption that the surface function is satisfied by the integrability condition. If there exist some locations of the surface where integration is not possible, then the computed depth values are not accurate.

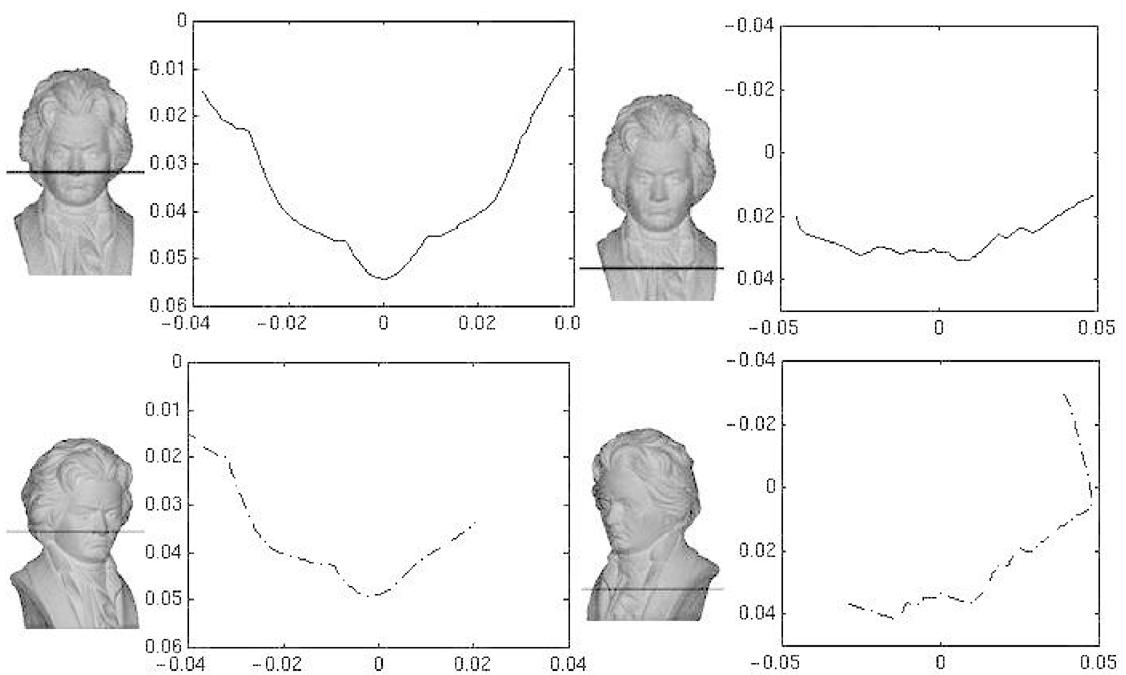

Figure 2: The input images and cross-sections around the nose and shirt of the bust.

3 Model Reconstruction

The whole 3-D object can be reconstructed by using registration and integration. In registration, each depth map has its own local 3-D coordinate system, so all coordinate systems must be related to each other through a coordinate transformation. Integration will remove all repeated or redundant information.

3.1 Related work

Faugeras [2] proposed the use of quaternions for least squares registration of corresponding 3-D point sets. Kamgar-Parsi et al [5] described a method for the registration of multiple overlapping range images without distinctive features extraction. Besl [1] developed a theory called iterate closest-point algorithm to perform registration. Turk [11] modified the Besl algorithm by using certain constraints and performed a directed search in transformation space and iterated to a series of local minimum of registration error.

3.2 Surface Registration

Registration of 3-D shapes is based on the iterative closest point (ICP) algorithm. It requires a procedure to find the closest point on a geometric entity to a given model. The ICP algorithm always converges monotonically to the nearest local minimum of a mean-square distance metric and experience shows that the rate of convergence is rapid during the first few iterations. Therefore, given an adequate set of initial rotations and translations for a particular class of objects with a certain level of shape complexity, one can globally minimise the mean-square distance metric over all six degrees of freedom by testing each initial registration. There were a few constraints suggested by [11] to improve speed of the algorithm. However the algorithm and the input depth maps need to have some additional modifications so that it is suitable for registration of our range images generated by PSM.

A distance threshold is used in the basic iterated closest point method to avoid matching any vertex which are not found in the other surface. Second, the vertices, which are on the edge, are ignored to count as corresponding points in the matching procedures. Third, we can search all vertices within an uniform subdivision of space instead of searching all points in the mesh. [11]

The additional modification is we can specify the mesh level x_1 to start on registration and the mesh level x_2 to stop. The algorithm can calculate the error between the previous and current registration. If the error is below a threshold, then the alignment will continue to the next mesh level which is more detailed in surface. Next, results from surface reconstruction are accurate if the smoothness constraint is satisfied. The accuracy from PSM is not very high at the border of the depth maps. Therefore, only the middle part of each depth map will be used to register surfaces. The accuracy of the results of registration also depends on the initial position of range images. Since the angle of rotation of taking the images is known, the depth map can be rotated by the same angle. After that all depth maps can be transformed so that they are very close together but only approximately aligned.

3.3 Integration

Integration is the process of creating a single surface representation from the sample points from two or more range images. The task of integration is divided into two parts. The first part is creating a mesh that reflects the topology of the object; the second is refining the vertex positions of the mesh by averaging the geometric detail that is present in all scans.

3.4 Analysis

A set of 2.5-D depth maps of the Beethoven bust was used, which were generated by PSM from chapter 2, to test our approach in 3-D model reconstruction. Since the object was complicated and there existed some errors in the depth maps, we had to consider several steps before reconstructing it. Next, the results of our experiments will be discussed step by step and errors that were found will be explained.

The accuracy of our 3-D model reconstruction depends on the following factors. (1) the initial position of the range images, (2) the size of the range images, (3) the mesh level of the range images, (4) the number of the range images used in the registration process, (5) the accuracy of the depth maps generated by PSM and (6) the orientation of registration. Experiments were carried out to analyse the effects of these factors. Errors in our reconstruction process can be reduced to the minimum by controlling the effects of these factors. Therefore, it is very important to know how these factors change the results of 3-D model reconstruction.

Firstly, we must move one image to the other so that they are approximately aligned before the registration process begins. Otherwise, the results are invalid. Secondly, if the difference between range images increases, the accuracy of alignment will decreases. If the border of depth maps is excluded, the accuracy of the results will increase and the time for registration will decrease. Thirdly, the higher the mesh level, the lower the number of vertices in the range image and the less details of the surface of the object. The average distance between the corresponding points decreased as the mesh level decreased. It showed that the range images were aligned more closely together. However, the time spent on registration from mesh level 2 to level 1 was very large. Next, the number of depth maps determines the time spent on registration and integration and the accuracy of our result. Too many depth maps will delay our reconstruction process, but too few depth maps will create holes and scars in our object. In addition, the accuracy of the depth maps generated by PSM directly affects the accuracy of 3-D model reconstruction. Each image will be checked to see whether there exist some discontinuities in the surface. If these do exist, these surfaces should not be used in experiments.

Finally, the constrained ICP algorithm registers only two meshes at a time. Therefore, we have to design the direction of registration. All images were labelled by the angles that the images were captured at in anti-clockwise direction. There are many ways to register all depth maps. (1) “Single-direction”, (2) “Double-direction”, (3) “Double-direction-two-pieces” and (4) “Triple-tree-direction”.

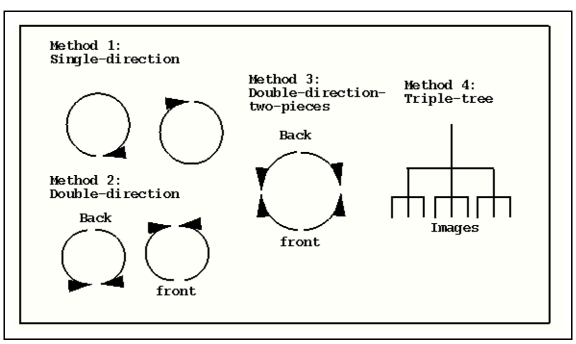

Figure 3: The four methods in orientation of registration.

There are four options in “single-direction”. Alignment starts from the front(brack) of the Beethoven bust in clockwise or anti-clockwise direction. There are two options in “double-direction”. It starts from the front(back) of the bust and aligning images, which was captured below 180°, in clockwise direction. The remaining images are aligned in anti-clockwise direction. In“double-direction-two-pieces”, it starts from the front of the bust and aligning images to the front of the bust, which were captured below 90°, in clockwise direction. The images that were captured between 270° to 360° are aligned in anti-clockwise direction to the front. The images that were captured between 91° to 180° are aligned in clockwise direction to the back of the bust. The remaining images are aligned in anti-clockwise direction to the back. All range images are divided in an interval of three. The middle image is chosen as an anchor image. The other two images are aligned to the middle one. These three images are merged into one image. The step is continued until we have only one image left. Figure 3 shows these methods of registration.

Different methods will have different accuracy and timing of registration. Experiments were carried out to find out a suitable method to reconstruct our model in lowest errors and the time spent on registration is reasonable. From the results of our experiement which are shown in Figure 4, we found that different orientation of registration will result in different accuracy of the reconstructed 3-D model and the time for registration. “Single-direction” was not suitable for registration since it accumulated large errors at the final image of the bust. The accumulated errors in “Double-direction” were reduced. “Double-direction-two-pieces” joined the range images of the front (back) of the bust with minimum errors. However, it was difficult to join these final meshes. “Triple-tree-direction” was very time-consuming, but errors did not accumulate into the last mesh. Correctness in surface reconstruction depends on the fulfilment of the assumption of PSM. Obviously, if errors exist in a depth map, the neighbour depth maps will be different. Therefore, the registration of these depth maps is incorrect. Since our object is not a simple object, the optimal local distance depends greatly on the initial position of the range images. If the range images are not close to each other, this approach will fail to find the best rotation matrix and translation vector to align these range images.

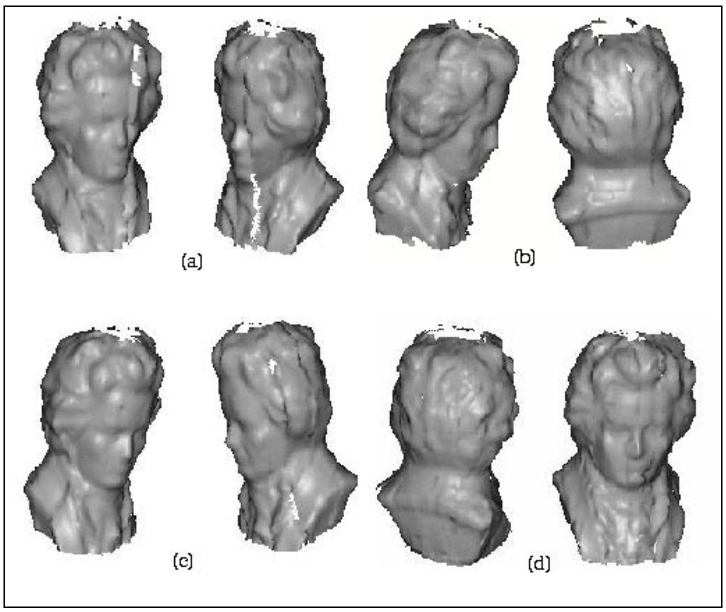

Figure 4: Comparision of reconstructed models by different methods. (a) single-direction, (b) double-direction, (c) double-direction-two-pieces, (d) triple-tree direction.

Errors existed in the shoulders of the Beethoven bust. Some depth values of the shoulders were different between each pair of range images. Therefore, the shoulder of the reconstructed model could not be joined very smoothly. These errors were reduced by removing the bottom part. Hence, we computed the new rotation matrix and translation vector more accurately. The high value of the errors in the registration of the back of the bust was due to the incorrect initial position of the range images. Errors can be reduced to the minimum by adjusting the range images and performing registration again. The results of the new reconstructed model were improved. Figure 5 shows the result of the 3D model reconstruction.

4 Conclusion

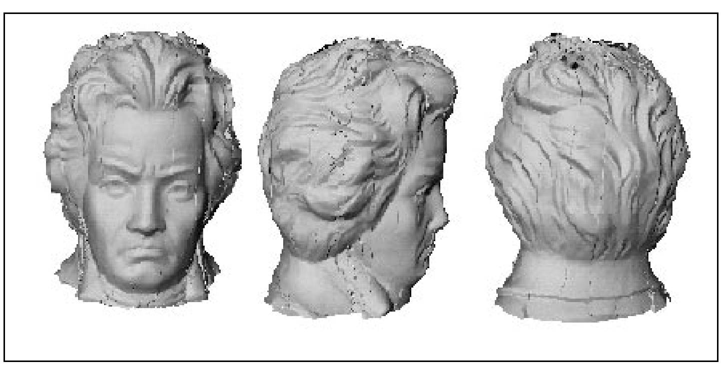

Figure 5: The 3D model of the bust.

The reconstruction of surface normal orientation from photometric stereo could be considered a reasonable quality. Given a set of images, three light source illumination, geometry of imaging system, the 2.5D depth maps can be calculated from this information. It is a fast and reliable method. The reconstruction process is restricted only by the time involved in the use of three different light source illuminations. However, problems arise when range images are used to register and integrate into the 3D model. These difficulties arise largely from the necessity of finding corresponding points in multiply images. We must start to register surfaces with some information on the initial position of the surfaces in the object. The algorithm then iterates to find the best fit for these surfaces. Errors in our model reconstruction arose from depth maps reconstruction and alignment of range images. Holes appeared in the results of the model reconstruction because discontinuities existed in our surfaces or the edges were not perfectly joined. Smoothing or simplifying of our model can improve its appearance.

Future Work This work may be extended to the investigation of strategies to improve surface gradient around discontinuity surface. Also, it may be possible to extend the algorithm to allow some kind of deformation of the model shapes in registration process and to improve the accuracy of registration. Another problem is how an algorithm might automatically determine the next best view to capture more of an object's surface. Finally, there is also opportunity for further computational speedup.

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