AUTOMATIC CORRESPONDENCE AND GLOBAL REGISTRATION OF RANGE IMAGES FOR 3D MODELING

Ajmal S. Mian, Mohammed Bennamoun and Robyn A. Owens
School of Computer Science and Software Engineering
The University of Western Australia
35 Stirling Highway, Crawley, WA 6009, Australia
{ajmal, bennamou, robyn}@csse.uwa.edu.au

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ABSTRACT

A free-form object must be acquired from multiple viewpoints to make its complete 3D model. These views are then registered by establishing correspondence between them. Pair wise registration of the views may result in a 3D model with large seams due to the accumulation of registration errors. Global registration is therefore performed to register the views simultaneously, distributing the registration errors evenly over the 3D model. In this paper we present an automatic 3D modeling approach using our automatic correspondence algorithm combined with global registration. Our algorithm takes an ordered set of views of an object, automatically finds pair wise correspondences between the views and finally, registers the views with global registration. To show the accuracy of our technique, we perform a comparative analysis of the pairwise registration, resulting from our automatic correspondence technique alone, and the resultant global registration.

1 INTRODUCTION

A single view of a free-form object is generally not sufficient to form its complete 3D model due to self occlusions. Multiple views must be acquired to cover the entire surface of the object. Correspondences are then established between these views and based on these correspondences, a rigid transformation is derived to register the views in a common coordinate basis. There are two approaches to registration. One is to register the views locally performing pair wise registration. In this approach the registration error may accumulate, resulting in a significant misalignment between views that are not consecutive in the pair wise correspondence sequence. The second approach takes the correspondences and registers the views simultaneously distributing the registration error evenly over the entire 3D model.

Various techniques have been proposed for the identification of correspondences between two views of an object. Examples include matching oriented points (Johnson and Hebert, 1997), geometric histogram matching (Ashbrook et al., 1998), RANSAC-based DARCES (Chen et al., 1991), SAI matching (Higuchi et al., 1994), Roth's technique (Roth, 1999), 3-tuple matching (Chua and Jarvis, 1996), bitangent curve matching (Wyngaerd et al., 1999), Iterative Closest Point (ICP) (Besl and McKay, 1992), Chen and Medioni's algorithm (Chen and Medioni, 1991) and the Rangarajan *et al.* algorithm (Rangarajan et al., 1999). However, these techniques are based on various unrealistic assumptions and are not fully automatic. Moreover, these techniques have been used for pairwise correspondence and registration only. To the best of our knowledge none of these techniques has been used in conjunction with a global registration algorithm. On the other hand, multiview global registration techniques such as the Williams and Bennamoun's technique (Williams and Bennamoun, 2001) and Benjemma and Schmitt's technique (Benjemma and Schmitt, 1997) assume that correspondences have already been identified or the views are approximately registered. In this paper, we present an automatic 3D modeling approach using our automatic pairwise correspondence algorithm combined with global registration. Our algorithm takes an ordered set of views of an object and makes its complete 3D model. The algorithm proceeds as follows. First, pairwise correspondences are identified using our automatic correspondence algorithm. Second, the views are registered locally (pair wise) and correspondences are identified between all the views based on the nearest neighbours. Finally, these correspondences are fed to a global registration technique (Williams and Bennamoun, 2001) which registers the views globally. To estimate the accuracy of our technique we perform a comparative analysis of the registration resulting from our pairwise correspondence technique only and the resultant global registration.

The rest of this paper is organized as follows. Section 2 gives a brief description of our tensor-based automatic correspondence algorithm. Section 3 explains the details of our 3D modeling procedure. In Section 4 we report our 3D modeling results. Section 5 contains an analysis of the 3D models resulting from our technique. Finally, in Section 6 we present our conclusions.

2 AUTOMATIC CORRESPONDENCE

In this section, we shall briefly describe our automatic correspondence algorithm. For details of the algorithm the reader is referred to (Mian et al., 2004). Our correspondence algorithm converts the views into a tensor-based representation. The representation algorithm proceeds as follows. First, the 2.5D views (in the form of a cloud of points) are converted into triangular meshes and normals are calculated for each vertex and triangular facet. Next, all possible pairs of points that are four mesh resolutions apart are selected from each mesh. Each point pair, along with its normals, is used to define a 3D basis centered at the middle of the line joining them. The average of the two normals defines the z-axis, the cross-product to the normals define the x-axis and the cross-product of the z-axis with x-axis defines the y-axis. This coordinate basis is used to define a $10 \times 10 \times 10$ grid centered at the origin of the coordinate basis. The bin size of the grid is selected as a multiple of the mesh resolution (one mesh resolution in our case). The area of the triangular facets and their average weighted normals crossing each bin of the grid is calculated (using Sutherland Hodgman's algorithm) and stored in a 4th order tensor.

To find correspondence between say view 1 and view 2, a tensor is selected at random from view 1 and matched with all the tensors of view 2. For efficiency, two tensors are only matched if their overlap ratio $R_O = \frac{\sum I_{12}}{\sum U_{12}}$ is greater than 0.6, where $\sum I_{12}$ is the amount of intersection of the occupied bins and $\sum U_{12}$ is the amount of union of the occupied bins of the two views. Matching proceeds as follows. The correlation coefficient of the two tensors is calculated in their region of overlap. If the correlation coefficient is higher than a threshold t_c (which is set dynamically), one of the two points used to define the view 2 tensor is transformed to the coordinates of view 1 using the transformation given by Eqn. 1 and Eqn. 2.

$$\mathbf{R} = \mathbf{B_2^T B_1} \quad (1)$$

$$\mathbf{t} = \mathbf{O_1} - \mathbf{O_2 R} \quad (2)$$

Here $\mathbf{R}$ and $\mathbf{t}$ are the rotation matrix and translation vector respectively. $\mathbf{B_1}$ and $\mathbf{B_2}$ are the matrices of the coordinate basis of view 1 and view 2 tensors respectively. $\mathbf{O_1}$ and $\mathbf{O_2}$ are the vectors of origins of the view1 and view 2 tensors respectively.

If the distance between the transformed point and its corresponding point (of the view 1 tensor) is less than d_{t1} (set to one fourth of the mesh resolution), the entire view 2 is transformed using Eqn. 1 and Eqn. 2. Finally, all sets of points of view 1 and view 2 that are within a distance d_{t2} (set equal to the mesh resolution) are converted into correspondences. If this list of correspondences is greater than half the total number of points of view 1 or view 2, the transformation is accepted and refined with the ICP (Besl and McKay, 1992) algorithm.

3 GLOBAL REGISTRATION FOR 3D MODELING

Our 3D modeling approach takes an ordered set of views of an object and finds correspondences between the overlapping views according to the algorithm described in Section 2. The overlap information is either extracted from the order of the views or it is provided explicitly (see Fig. 3).

Figure 1: First row contains three 2.5D views of the bunny. The second row contains the complete 3D model viewed from different angles.

The transformations accompanied with the above correspondences are applied to each view and all the views are pairwise registered in the coordinate basis of a reference view (view 1 in our case). After all the views are pairwise registered, correspondences are established between all sets of overlapping views on the basis of nearest neighbour that are within a distance d_{t2}. Views that have correspondences less than a threshold (one tenth the number of points of either view) are considered as non overlapping views and their correspondences are rejected. The remaining set of correspondences is fed to a global registration algorithm (Williams and Bennamoun, 2001) which registers all the views globally.

4 RESULTS

We present two results from our experiments in this paper. The first data set is of a bunny and the second data set is of a robot. Ten views of the bunny and eleven views of the robot were taken to make their complete 3D models. Fig. 1 shows three of the ten 2.5D views of the bunny and its complete 3D model viewed from three different angles. Similarly Fig. 2 shows three out of the eleven 2.5D views of the robot and its complete 3D model viewed from three different angles. Once all the views are registered in a common coordinate basis, it is easy to integrate them and reconstruct a single smooth and seamless surface. We have intentionally presented the raw results of our experiments without performing integration and reconstruction so that the accuracy of our algorithm can be appreciated. Note that the extra parts on the surface of the models (e.g. with

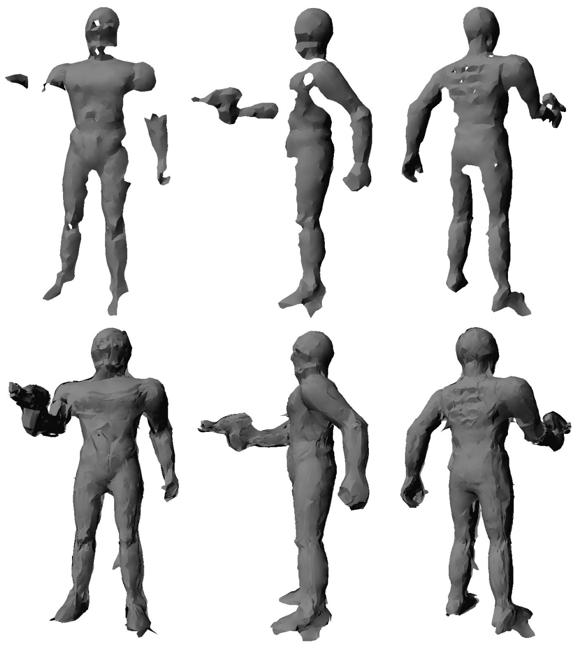

Figure 2: First row contains three 2.5D views of the robot. The second row contains the complete 3D model viewed from different angles.

the right foot of the robot and left hand of the bunny) were already present in the individual views (due to the presence of noise in the acquisition phase), and are not due to error in our technique. Such parts would be removed during the reconstruction phase.

5 ANALYSIS

Qualitative analysis of the resultant 3D models was performed by visual inspection of the registered surfaces. The features on the registered 3D models were compared with the features visible in their pictures (taken from the viewing angles). Silhouettes of the 3D models were compared with its picture taken from a similar pose to find errors in geometry. Our qualitative analysis show that the 3D models resulting from our technique are very accurate. We could only observe small seams, present between some parts of the surfaces, whose magnitude was within the mesh resolution. These small seams are present due to noise and variations in the surface sampling during the acquisition phase and are unavoidable. The integration and reconstruction phases of the 3D modeling removes these seams by approximating the data by a single smooth surface.

For quantitative analysis, the ground truth data must be available. In our case, since the ground truth was not available, we took a different approach to perform quantitative analysis. We have compared the transformations resulting from the pairwise registration with the transformations resulting from the global registration. Since global registration distributes the error present in pairwise correspondences evenly over all the views of the 3D model, the difference between the pairwise and global transformations should give us an estimate of the error that was present in the pairwise correspondence/registration.

The comparison was performed as follows. View 1 of the objects was taken as a reference in each case. The rotation matrices of each view n resulting from pairwise registration $\mathbf{R_{pn}}$ and global registration $\mathbf{R_{gn}}$ were calculated. Next the amount of rotational difference θ_n present in the two rotation matrices was calculated according to Eqn. 3 and Eqn. 4.

$$\begin{aligned} \mathbf{R_{dn}} &= \mathbf{R_{pn}}\mathbf{R_{gn}^{-1}} && (3)\\ \theta_n &= cos^{-1}\left(\frac{trace(\mathbf{R_{dn}})-1}{2}\right)\times\frac{180}{\pi} && (4) \end{aligned}$$

In Eqn. 3, $\mathbf{R_{dn}}$ is a rotation matrix representing the difference between $\mathbf{R_{pn}}$ and $\mathbf{R_{gn}}$. Eqn. 4 is derived from Rodrigue's formula. θ_n represents the amount of rotation error (about a single axis) present in the rotation matrices of pairwise registration and global registration. The difference t_n between the translation vectors of each view n resulting from pairwise registration $\mathbf{t_{pn}}$ and global registration $\mathbf{t_{gn}}$ is calculated according to Eqn. 5.

$$t_n = \frac{||\mathbf{t_{pn}} - \mathbf{t_{gn}}||}{mesh\ resolution} \qquad (5)$$

In Eqn. 5, the difference between the translation vectors is normalized with respect to the mesh resolution in order to make it scale-independent. In our experiments the mesh resolution of the bunny was twice the mesh resolution of the robot.

Fig. 4(a) shows the θ_n and Fig. 4(b) shows the t_n for all the views of the bunny. Similarly Fig. 5 shows the θ_n and t_n for all the views of the robot. θ_n and t_n for view 1 of the bunny and the robot are zero because view 1 is taken as the reference view. In the case of the bunny (Fig. 4), view 4 has the maximum difference in rotation (1.2^o) and translation (0.9 mesh resolution). This is because view 4 is at one end of the pairwise correspondence chain (see Fig. 3(a)). The overlap information used by the pairwise correspondence and registration algorithm is shown by the graph of Fig. 3. Each node represents a view and an arc represents an overlap. The dotted arcs represent overlaps that were not used by the pairwise registration (since pairwise registration requires a spanning tree graph). Note that our technique considers all possible overlaps for the global registration and not just the ones given in Fig. 3. The overall difference between the rotation and translation resulting from our pairwise registration and global registration is very small (see Fig. 4 and Fig. 5). In the case of the bunny, the average θ_n is equal to 0.34^o and the average t_n is equal to 0.24 mesh resolutions. In the case of the robot, the average θ_n is equal to 0.30^o and the average t_n is equal to 0.20 mesh resolutions. In other words since there was very small error in the pairwise registration, the global registration algorithm had to distribute a very small amount of error. Since the pairwise registration was derived from the pairwise correspondence, the corollary is that the correspondence algorithm is accurate. Had the correspondences

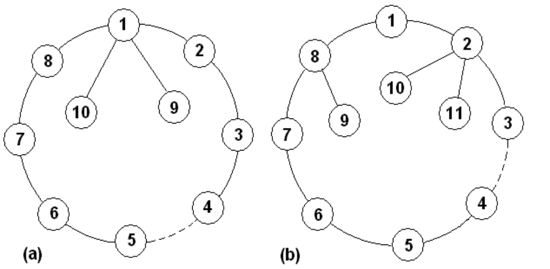

Figure 3: Graphs showing the limited overlap information of the views of the bunny (a) and the robot (b), used by pairwise correspondence and registration.

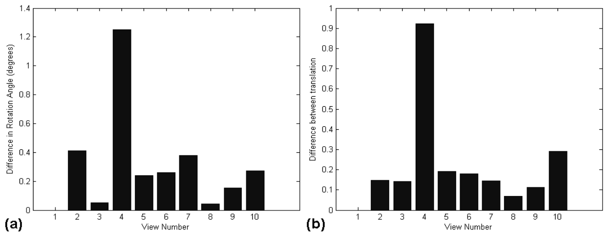

Figure 4: The difference in rotation angles (a) and normalized translation (b) of the views of the bunny derived with pair wise and global registration.

been inaccurate the errors in the resulting pairwise registration would have been large. A very large error would have accumulated between views that are far apart in the graph of Fig. 3 and hence global registration would have had to distribute these large errors resulting in much greater differences between the pairwise and global registrations.

6 CONCLUSION

We have presented an automatic 3D modeling technique using our automatic correspondence algorithm combined with global registration. Our technique is fully automatic and only assumes the prior information of the ordering of the views which is generally available from the sequence of acquisition. We have also presented qualitative and quantitative analysis of our technique. Qualitative analysis was performed by visual inspection of the registered 3D models. The quantitative analysis was performed by comparing the results of pair wise registration with the global registration results. In future work, we plan to extend our technique to be able to construct a 3D model from an unordered set of views.

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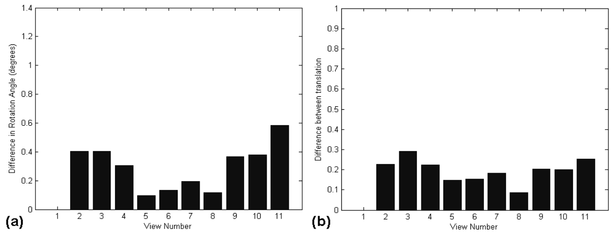

Figure 5: The difference in rotation angles (a) and normalized translation (b) of the views of the robot derived with pair wise and global registration.

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