Planar Structure Based Registration of Multiple Range Images

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Abstract

In this paper, we describe the method for aligning multiple range images given by a range finder. Especially we will use range images of inside and outside of buildings which contain many planar structures. In our method for registration of range images, we consider not only 3D positions of range data but normal vectors of planes in the scene in order to refine the ICP (Iterative Closest Point) algorithm. First, we extract planes of range images in order to calculate normal vectors of planes in the scene. Then, we estimate the motion parameters that are composed of a rotation matrix and a translation vector using our refined ICP algorithm. We present results that demonstrate our approach's ability to align range images more accurately and faster than the standard ICP algorithm.

1. Introduction

There is an increasing interest in modeling real objects in the areas of business, education, and entertainment. One popular way to create 3D models is 3D reconstruction from multiple range images. The 3D models are generally reconstructed by the two steps, which are registration and integration of range images from multiple viewpoints using a range finder. Especially, robust registration of multiple range images is an important problem in computer vision as we have no information on the positions of multiple range images.

There are generally two ways to register two 3D point sets. One method is feature-based method [3][8], and the other is ICP-based method [1][2]. The feature-based method can be used when the rough initial positions of each range image are unknown. However, the feature-based method only does rough registration and is not suitable for the applications that need precise registration. On the other hand, the ICP-based method can do precise registration if the rough initial positions of each range image are given. There are many applications for precise registration of two 3D point sets in computer vision. One area of these applications is the digital archiving projects [5][6]. As these digital archiving projects need the precise reconstructed 3D models, registration of range images has to be done precisely. When computing the registration of two 3D point sets, not only the point correspondences but also the motion parameters are computed. Therefore, registration algorithms can also be used for motion estimation [10].

As we describe above, the Iterative Closest Point (ICP) algorithm is undoubtedly the most popular algorithm for solving the robust registration problem. The ICP algorithm for registering two 3D point sets was introduced by Chen and Medioni [2] and Besl and McKay [1]. Basically, this algorithm iteratively performs two operations until convergence. The first operation is to find the closest point in one point set for each point in the other set. In the second operation, the motion parameters (a rotation matrix and a translation vector) between the two point sets are estimated using the corresponding point pairs. The ICP algorithm has been improved by many researchers. The Color ICP algorithm [4] uses not only the pure 3D information but also the color information in searching corresponding point pairs. The ICP algorithm using Invariant Features [7] uses Euclidean invariant features like curvature and moment invariants.

In this paper, we propose a new ICP based method using the normal vectors of the 3D points as well as the 3D position of every point. In the proposed method, we first eliminate the unnecessary 3D pointsets(the outliers) by extracting the planar strucures from the input range images. Then we use the normal vectors of the 3D point sets on the planar structures for searching the corresponding point pairs in the ICP algorithm. The normal vecotors are also used for estimating the motion parameters.

When we scan several range images, we acquire not only the objects themselves but also some outliers. For example if we scan buildings or rooms, we get the 3D point sets of not only the objective buildings but also the leaves of trees (See Figure 1). These kinds of outliers are supposed to have no corresponding point pairs so that the estimation of the motion parameters may not be done accurately. So when we estimate the motion parameters using ICP algo-

The 18th International Conference on Pattern Recognition (ICPR'06)
0-7695-2521-0/06 $20.00 © 2006 IEEE

Figure 1. An example of range image(Room): Many leaves taken through the window are also captured in the range image.

rithm, we have to eliminate these outliers which do not have corresponding point pairs in order to estimate the motion parameters accurately. We do this by extracting planes in the scene as a structure of buildings often consists of planes and these outliers (in our case, leaves of trees) are not supposed to form the planes. We use only 3D point sets of the buildings themselves so that we can estimate the motion parameters accurately. In addition to this, we will be able to reduce the computational time as we do not use the outliers in estimating the motion parameters. Also, we use the normal vectors of 3D point sets when we estimate the motion parameters using the ICP algorithm. Our ICP algorithm is different from the standard ICP algorithm in the sense that we consider not only the pure 3D information but also the normal vectors of 3D point sets. It greatly improves the accuracy of registration of the multiple range images when the scenes are mainly composed of planes like buildings or rooms.

2. Proposed method

Our registration method overview is described below. It mainly consists of three steps. The first step is to extract planes in the scene in order to eliminate the outliers (in our case, leaves of trees). Then the second step is to calculate the normal vectors of the planes so that we can use them in our ICP algorithm. The last step is to register multiple range images using modified ICP algorithm.

2.1. Extracting planes in the scene

When we scan the 3D objects by using a range finder, we get only the 3D positions and colors of the points on the object surface. For extracting planar structures from the input range images, we firstly classify the 3D points into three types by using the method proposed by Vandapel et al. [9]. We do this by calculating the distribution of the 3D point sets. The distribution is calculated by the decom-

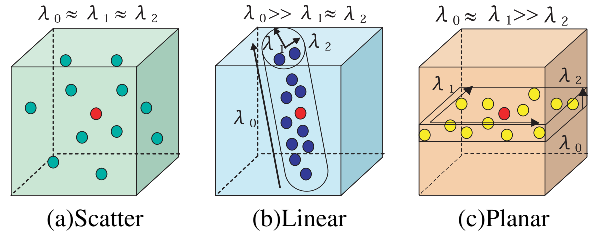


Figure 2. Classification of 3D points

position into principal components of the covariance matrix of the 3D points computed in a local neighborhood. The symmetric covariance matrix for a set of N 3D points $\{\boldsymbol{X}_i\} = \{(x_i, y_i, z_i)\}$ with $\bar{\boldsymbol{X}} = \frac{1}{N}\Sigma\boldsymbol{X}_i$ is defined in equation 1.

$$\frac{1}{N}\Sigma\left(\boldsymbol{X}_i - \bar{\boldsymbol{X}}\right)\left(\boldsymbol{X}_i - \bar{\boldsymbol{X}}\right)^{\top} \tag{1}$$

The covariance matrix is decomposed into three eigenvectors. Then we classify the 3D point sets into three types by the distribution (See Figure 2). After the classification, we extract the "planar" points and eliminate the "scatter" points as these kinds of "scatter" points (in our case, leaves of trees) will be the outliers that are supposed to have no corresponding point pairs.

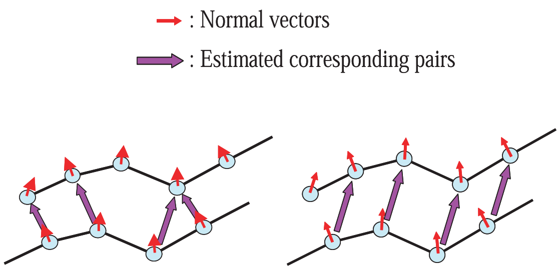
2.2. Estimation of the normal vectors of the planar points

After we extract the "planar" 3D points and eliminate the "scatter" 3D points, we estimate the normal vectors of the planar 3D points using the least square method. We consider a local neighborhood and estimate the plane that may fit all the 3D points included in a local neighborhood and then calculate the normal vectors of the planar 3D points.

2.3. Our ICP algorithm

As we described in the Section 1, the ICP algorithm is an effective registration technique when the rough initial position between two 3D point sets are known. We estimate the initial position by giving some corresponding point pairs manually.

The outline of the ICP algorithm is shown below. At all the vertices of one 3D point set, we search for the nearest point by the Euclidean distance out of the vertices of the other 3D point set which exist in a nearby area. If a corresponding point exists in a nearby area, the distance to the point will be computed. It carries out to all the data points of range data, and total of the distance between all the acquired corresponding points is computed. Then the motion parameters (a rotation matrix and a translation vector) are

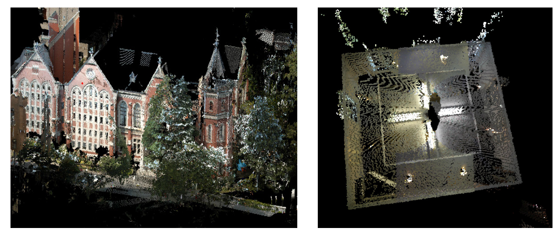


(a)Standard ICP algorithm (b)Our ICP algorithm

Figure 3. A comparison of the standard ICP algorithm and our ICP algorithm

(a)Input range image (b)Output range image

Figure 4. A result of extracting planes (Room)



(a)Library:12 range images (b)Room:2 range images (from upper viewpoint)

Figure 5. A result of registration by using proposed method

optimized so that the sum of distance can be minimized. If the optimal motion parameters are determined, we will search for other corresponding points again, and the same processing will be repeated until convergence of the motion parameters. If we can obtain good estimation of corresponding pairs, the ICP algorithm converges to an exact registration. Therefore, the accuracy of registration depends on how well we can search the corresponding pairs. However, it is not easy to get such good estimation of corresponding pairs. Many researchers do the work for better registration but it does not still provide sufficient accuracy.

Therefore, we try to search corresponding point pairs more accurately than the conventional methods in the following two points. 1) If we have many outliers (in our case, leaves of trees) which are supposed to have no corresponding points, the estimation of the motion parameters will end in a failure. Therefore, we only use the planar 3D points which are considered to be included in the buildings and have the corresponding pairs. 2) In addition, we search for the nearest point by not only the 3D information, that is the Euclidean distance, but also the normal vectors of the planar 3D points so that we can align two 3D point sets more accurately than the standard ICP algorithm. In the standard ICP algorithm, the criterion defined in equation 2 between two points (p_1, p_2) is used for finding corresponding points. In our ICP algorithm, however, we search the closest point by using the criterion defined in equation 3, in which the terms of the normal vectors $\boldsymbol{n} = [a, b, c]^\top$ weighted by $\alpha_1, \alpha_2, \alpha_3$ are added in equation 3. By doing this, we can make an estimate of the motion parameters successfully.

$$d(p_1, p_2) = (X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2 \quad (2)$$

$$\begin{aligned} d(p_1, p_2) = {} & (X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2 \\ & + \alpha_1(a_1 - a_2)^2 + \alpha_2(b_1 - b_2)^2 + \alpha_3(c_1 - c_2)^2 \quad (3) \end{aligned}$$

By adding the normal vector terms, we can avoid inconsistent correspondences between planar structures, as shown in Figure 3. The incorrect corresponding points are estimated by using the standard ICP algorithm but we can find the correct corresponding points by considering not only the 3D information but also the normal vectors of the planar 3D points.

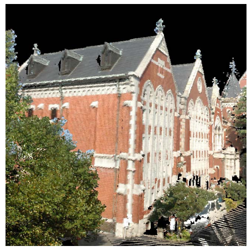
3. Experimental results

We perform the experiments with the range finder, LMS-Z360i by Riegl. We scanned the building of the Old-Library of Mita Campus of Keio University, which is registered as important cultural properties of Japan. We took 12 range images of Library and 2 range images of a room and then we register them by using our ICP algorithm.

First, we show the result of extracting planes in the scene. Then we demonstrate the result of our registration method and compare it with the result of the standard ICP algorithm. The result of extracting planes is shown in Figure 4. The outliers (leaves seen from the window) are eliminated so that the estimation of the motion parameters will be done well. On the other hand, the planar 3D points (like the walls or the ceiling) are extracted accurately. In this experiment, we set the size of the local neighborhood as $0.2 \times 0.2 \times 0.2 m^3$. Each input range image has $60,000$ – $100,000$ 3D points and the output range image has $10,000$ – $50,000$ 3D points after the elimination of the outliers.

The merged range data by the registration of 12 range images (Library) and 2 range images (Room) are shown in

(a)Standard ICP algorithm



(b)Our ICP algorithm

Figure 6. A comparison of registration

Table 1. A comparison of registration error

	Standard ICP	Our ICP
Library (12 range images)	14.1cm	8.5cm
Room (2 range images)	8.2cm	6.0cm

Figure 5. All the range images can be successfully merged for generating complete 3D model of the objective buildings. Figure 6 shows comparisons between the standard ICP algorithm and our ICP algorithm. As shown in Figure 6, the standard ICP algorithm failed to register two 3D point sets at the walls and the pillar of the library because there are many outliers that could be the cause of incorrect estimation of the motion parameters. On the other hand, our method can register them successfully as we estimate the motion parameters accurately by using our refined ICP algorithm. Also the registration error is calculated in order to compare our ICP algorithm with the standard ICP algorithm (See Table 1). The registration error between one point sets $\boldsymbol{a}$ and $\boldsymbol{b}$ is given by

$$e = \sqrt{\frac{1}{N}\sum_{(i,j)} ||\boldsymbol{b}_j - \boldsymbol{R}\boldsymbol{a}_i - \boldsymbol{t}||^2} \tag{4}$$

where $\boldsymbol{R}$ and $\boldsymbol{t}$ are the rotation matrix and the translation vector respectively, and N is the number of corresponding point pairs. Compared to the standard ICP algorithm, our method can reduce the registration error.

We also do the experiment to measure the computational time on Pentium 4, 3.0GHz CPU, 2.0GB RAM machine. The result clearly shows that our method is faster than the standard ICP algorithm (See Table 2). This is because we eliminate the outliers (leaves of trees) and search corresponding pairs by the planar 3D points. Therefore, our method is effective in the computational time.

4. Conclusion

We proposed a refined ICP method for registration of multiple range images. We improve the accuracy of registration by both eliminating the outliers and using the normal vectors of the planar 3D point sets in the ICP algorithm. We also show that our method is faster than the standard ICP algorithm as we search the corresponding pairs by using no outliers but the planar 3D points. We demonstrate some experiments that show our method is effective to the objects that mainly consist of the planes like buildings.

Table 2. A comparison of computational time

	Standard ICP	Our ICP
Library	111.4sec	22.1sec
Room	110.5sec	49.9sec

Acknowledgements

This research is based upon the project supported by Research Institute for Digital Media and Content, Keio University. We thank all the people involved in this project.

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0-7695-2521-0/06 $20.00 © 2006 IEEE