Reconstruction of complete 3D object model from multi-view range images.

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ABSTRACT

In this paper, we designed and implemented a method which can register and integrate range images obtained from different view points for building complete 3D object models. This method contains three major parts: (1) registration of range images and estimation of the parameters of rigid-body transformations, (2) integration of redundant surface patches and generation of triangulated mesh surface models, and (3) reduction of triangular mesh and texture mapping. We developed the RANSAC-based DARCES technique to estimate the parameters of the rigid-body transformations between two partially-overlapping range images without requiring initial estimates. Then, we used a circular-ICP procedure to reduce the global registration error. We also used the consensus surface algorithm combined with the marching cube method to generate triangular meshes. Finally, by texture blending and mapping, we can then reconstruct a virtual 3D model containing both geometrical and texture information.

Keywords: *3D Computer Vision, Range Images, 3D Model Reconstruction, 3D Registration, Range Data Integration.*

1. INTRODUCTION

Reconstruction of complete 3D object model from multi-view range images has important applications in VR (virtual reality) and CAD (computer aided design). In this paper, we developed a systematic approach to register and integrate multiple range images obtained from different viewing directions for 3D object-model building. To achieve this purpose, typically three consecutive tasks are implemented: (1) registering the 3D data contained in all of the range images w. r. t. a common coordinate system, (2) integrating the 3D data contained in the range images and generating a triangular mesh, and (3) mapping and blending textures onto the reconstructed geometric model.

In the first stage, we used the RANSAC-based DARCES (data-aligned rigidity-constrained exhaustive search) method which we proposed recently for the registration of partially overlapping range images [5]. Given a sequence of range images of an object, namely, I_1 I_2, ...,I_n, grabbed from different views. The RANSAC-based DARCES method is used to register each pair of the consecutive views (I_1,I_2), (I_2,I_3), ..., (I_n,I_1). However, due to error accumulation, the registration error between the first and the last range data sets, i.e., I_n,I_1 will be larger than that of the others. Hence, it is desired to reduce the registration error of I_n,I_1 by appropriately distributing the errors to the registration of all the consecutive image pairs. This task can be achieved by reducing the global registration error using a global-registration algorithm. After that, rigid transformations of the range data of each view can be computed with respect to a common reference coordinate system.

In the second stage, we integrate the registered range data into a single non-redundant surface model. The overlapping parts of the 3D data obtained from different viewing directions have to be merged in this stage. In this paper, we used the marching cubes [7] method to generate a triangular mesh model. For applying this method, signed distances should be assigned to each voxel of a bounded box of the registered data set in advance. The consensus-surface algorithm [9] was used in our work for the assignment of the required signed distances.

In the third stage, the color of each triangle of the reconstructed 3D model is generated by mapping the textures onto the geometric model. In our work, when a range image is grabbed, an intensity image was captured from the same view. Since the color of a given triangle can be observed from more than one intensity images simultaneously, the textures coming from different intensity images should be blended for the generation of a unique texture map. In this paper, by computing the angle between the viewing direction and surface normal, we developed a weighted average process for blending textures.

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Through the realization of the three stages described above, we can reconstruct the object models suitable for interactive viewing in a virtual reality system. The reconstructed 3D object models include both the 3D geometric models (e.g., the triangular mesh) and the surface textures. Real experiments have been done to show the performance of our approach.

This paper is organized as follows: Section 2 introduces the 3D registration method used in this work. Section 3 introduces the 3D integration and triangle mesh generation methods. Some experimental results are shown in Section 4. Finally, Section 5 gives a summary.

2. 3D REGISTRATION

In this work, the input is multiple range images taken from 3D range data acquisition system combining laser lighting and stereo vision [4]. Range data taken in this way are all in their own relative coordinate systems with respect to the range finder. The goal of the 3D registration stage is to find the rigid-motion which can transform each of the range images to the right poses with respect to a common base view. It is desired to get the well balanced result [1], that is, the error of registration is distributed among all the range images equally. To achieve this purpose, the 3D registration stage is divided into two tasks: the task of *registration of each consecutive pair of range images* and the task of *global registration*.

2.1. Registration of A Pair of Range Images

The task of registration of a pair of range images is composed of two steps: the *coarse registration* step and the *fine registration* step. The coarse registration step is to estimate a rough rigid-transformation of a pair of partially-overlapping range images. This rigid-transformation is served as a good initial estimate of the fine registration step. Then, the fine registration step refines the transformation in an iterative way to get a better solution.

2.1.1. Coarse Registration

In this work, we used the RANSAC-based DARCES method [5] to compute the rigid transformation which registers two partially overlapped range images in a common coordinate system. The RANSAC-based DARCES method is an efficient search algorithm using the rigidity among some pre-selected control points of one range image of the pair. There are three advantages of the RANSAC-based DARCES method. First, it can ensure to obtain the correct solution in the noiseless case. Second, it can find the rigid transformation between two partially-overlapping range images which do not contain salient local features. Third, it can obtain the solution without given an initial estimation of rigid transformations. A detailed description of the RANSAC-based DARCES method can be found in Chen et al. [5].

2.1.2. Fine Registration

After finding a rigid transformation using the RANSAC-based DARCES method, the iterated closed point (ICP) method [3] was applied to refine the rigid-motion parameters. The ICP algorithm and many of its variations were widely used for the 3D registration task in the 3D computer vision community. Each iteration of the ICP algorithm contains two steps: (1) establish the point correspondence and (2) compute the rigid motion to minimize the sum of the squared distances of corresponding points. The original ICP algorithm can only process the case that the shape of one data set is part of the shape of the other data set. However, the rang images taken from different views are usually partially-overlapped. To solve the partially overlapping problem, Turk and Levoy modified the ICP algorithm by only using the pairs of corresponding points which are not in the boundary and are close enough [8]. In this work, the approach proposed by Turk and Levoy [8] was used for fine registration.

2.2. Global Registration

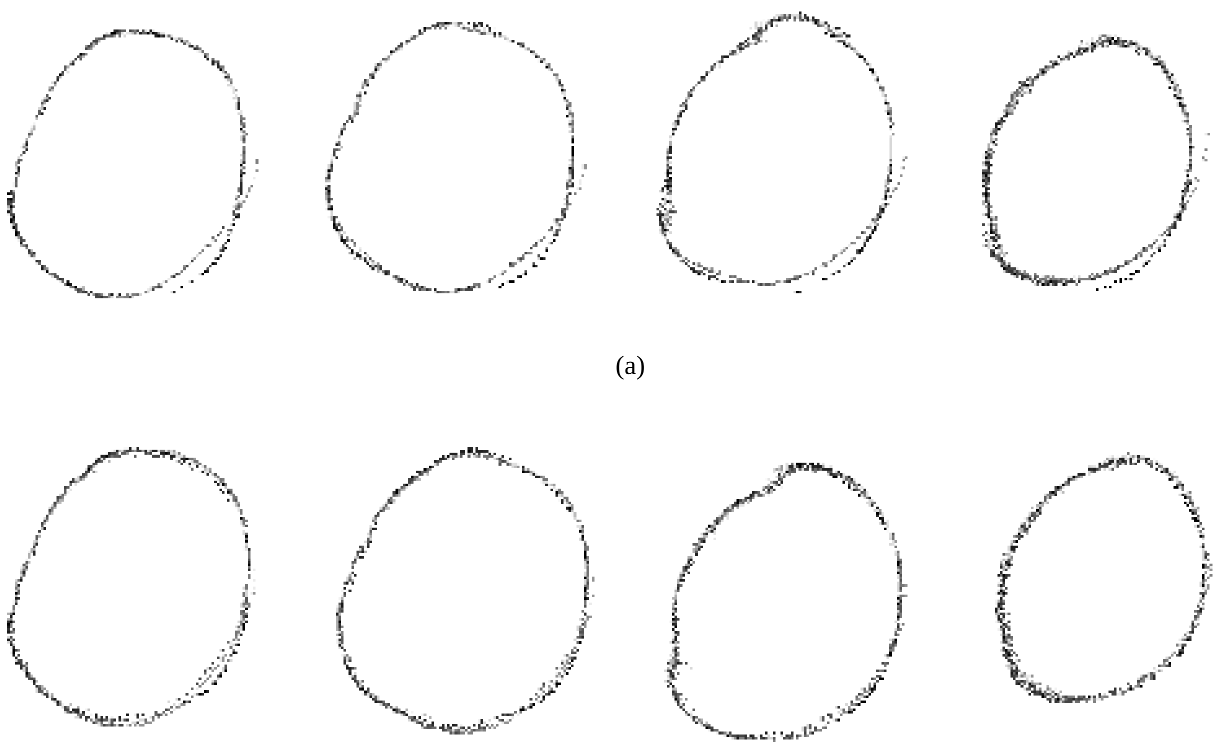
In the global registration stage, we first choose a range image as the *base view*. The base view is regarded as the world reference frame. All the rigid-motion parameters of other range images are calculated with respect to the base view. The global registration method used in this work is similar to that proposed by Bergevin et al., [2] unless that we used the ICP algorithm instead of the using of the Chen and Medioni algorithm [6] in the 3D registration of consecutive views. We call it the *circular ICP* procedure in this paper.

Given a sequence of range views of an object, namely, V_1 V_2, ...,V_n, grabbed from different views. The method introduced in Section 2.1 is used to register each pair of the consecutive views (V_1, V_2), (V_2, V_3), ..., (V_n, V_1), and find the initial transformation matrix of each pair of the consecutive views. Assume that V_c is the base view. The matrix $M_{i,0}$ ($i=0,1,\ldots, N-1$) denotes the initial transformation matrix between view V_i and view V_c.

1. $k=1$; dT_i = an arbitrary matrix but not the identity matrix.

2. While($dT_i \neq$ the identity matrix, for some $i=0,1,\ldots, N-1$) {
  2.1. For ($i=0;i<N;i++$) {
    2.1.1. if($V_i \neq V_c$) {
      2.1.1.1. $R=(i+1) \bmod N$;
      2.1.1.2. $L=(i-1) \bmod N$;
      2.1.1.3. Transform V_L to be the reference frame of V_i using the matrix $T_L = (M_{i,k-1})^{-1}M_{L,k-1}$. That is, $V'_L = T_L V_L$.
      2.1.1.4. Find the pairs of the corresponding points between view V_i and view V'_L using the method introduced in Section 2.1.2 (i.e., the one proposed by Turk and Levoy [8]).
      2.1.1.5. Transform V_R into the reference frame of V_i using the matrix $T_R = (M_{i,k-1})^{-1}M_{R,k-1}$. That is, $V'_R = T_R V_R$.
      2.1.1.6. Find the pairs of the corresponding points between view V_i and view V'_R using the method introduced in Section 2.1.2 (i.e., the one described by Turk and Levoy [8]).
    2.1.2. }
    2.1.3. Find an incremental matrix dT_i of view i to minimize the sum of the squared distances between all the pairs of the corresponding points found in steps 2.1.1.4 and 2.1.1.6, using the Arun method [1].
  2.2. }
3. $k=k+1$;
4. }

Some experimental results of the global registration stage is presented in Figure 1 by showing some horizontal slices of the aligned range data. From Figure 1, one can observe that the gap between the first and the last range images can be reduced using global registration, and the distribution of the registration error is much more balanced among views.



(a)

(b)

Figure 1. Four horizontal slices generated from the aligned range images . (a) before global registration. (b) after global registration.

3. 3D INTEGRATION AND TRIANGLE MESH GENERATION

After the registration stage, we have a set of aligned range views which are represented by a unified coordinate system. In the integration stage, we want to reconstruct the shape of the object by merging all the aligned range views into a single triangulated mesh. After that, we also reconstruct the texture of the object by blending and mapping the intensity images taken from different views of the object.

3.1. Marching Cube Method and Consensus Surface Algorithm

The marching cubes algorithm [7] was used to generate the triangulated mesh in this paper. The marching cubes algorithm was widely used for creating the triangle model of constant density surfaces from multiple 2D slices of computer tomography (CT), magnetic resonance imaging (MRI), and single-photon emission computed tomography (SPECT). Marching cubes algorithm locates the surface using a logical ``cube" that are formed by eight vertices. For each vertices contained in the cube, a signed distance should be given in advance. By examining the signed distances of the eight vertices of a cube the topology of surface intersection in the cube will be determined, and the intersection location will then be generated using interpolation. Each vertex of a cube is considered only in one of the two states: either inside or outside the object surface. Therefore, there are only 256 configurations of a given cube. The simplest idea to implement the algorithm is to build a table with 256 entries, and each entry contains the edges intersected with the surface. Triangles can be generated in 256 ways depending on the configuration of a cube. However, it will be tedious to do all the 256 ways to produce triangles. Two symmetry properties, complemented and rotational symmetry, reduce the 256 cases into 15 patterns. For any given cube, the topology of surface intersection in the cube can be easily determined using a lookup table [7].

To use the marching cubes method for the generation of a triangulated surface model, signed distances have to be given for each vertices contained in the cube. In this paper, we used the consensus surface algorithm proposed by Wheeler, Sato, and Ikeuchi [9] to generate a signed distance map from the aligned range views. Some of the experimental results of the consensus surface algorithm are shown in Figure 2. After a distance map has been generated, a triangulated mesh of the object can then be reconstructed using the marching cubes method.

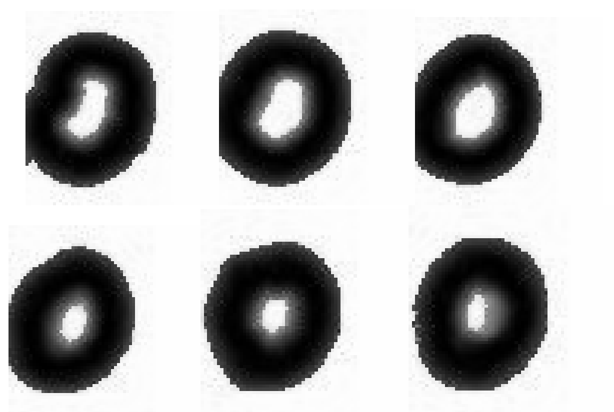


Figure 2. Six slices of the distance map generated using the consensus surface algorithm. The darker is the color, the closer is the distance to the object surface.

3.2. Texture Mapping and Blending

During the acquisition of range images, the associated intensity images are also grabbed from the range finder system from the same view. The main problem of texture mapping is that for any given point on the surface of the object model, the point could be visible by different views and the associated intensity values of these different views would be different. Therefore, the texture intensities have to be blended before being mapped onto the object model. Consider a typical case shown in Figure 3. If C is visible from both views $V1$ and $V2$, then the intensity value of C is set to be

$$I_C = wI_{C,V1} + (1-w)I_{C,V2}.$$

where

$$\omega = \frac{\cos(A_1)}{\cos(A_1) + \cos(A_2)}$$

That is, the smaller the view angle, the larger the weighting values used in the intensity blending.

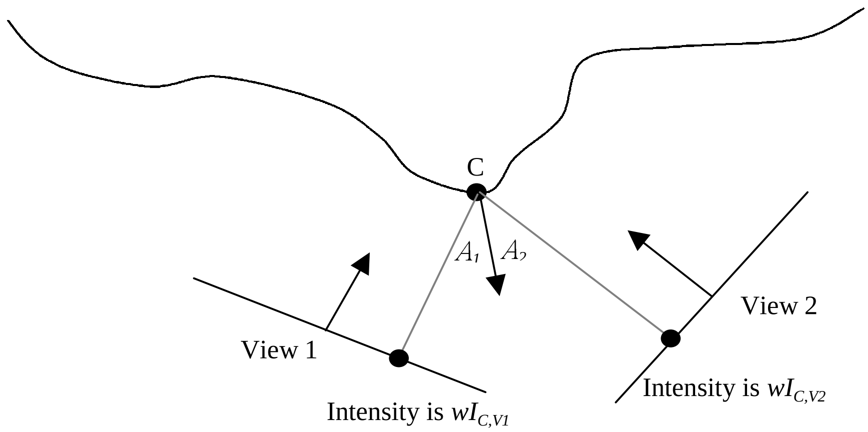


Figure 3. The intensity value of *C* is generated with a weighted average of the intensities $I_{C,V1}$ and $I_{C,V2}$.

4. EXPERIMENTAL RESULTS+

Figure 4(a) shows twelve range images taken from different view points of a toy. Figure 4(b) are their intensity images taken from the same views. After 3D registration, Figure 4(c) shows the aligned range data from two selected views. Figure 5(a) is the triangulated model generated using the consensus surface algorithm and the marching cubes method (shown from three selected views and the resolution is 128 x 128 x 128). Figure 5(b) are the triangulated model generated using a coarser cube (shown from two selected views and the resolution is 64 x 64 x 64). Figure 5(c) shows the results after texture blending and mapping.

5. SUMMARY

In this paper, we developed a systematic approach to reconstruct an object model from multiple range images taken from different views. We first use the sequential registration to get the initial estimate of the rigid-motion parameters. In this work, by using the RANSAC-based DARCES method, we do not need the initial estimations of the rigid-motion parameters. Then, we apply global registration algorithm to estimate the parameters of all the range images. In the 3D integration stage, we used the marching cubes and the consensus surface algorithm for the generation of a triangle mesh. By applying the consensus surface algorithm, the signed distance of each voxel can be computed. The consensus surface algorithm eliminates the effects caused by the noise of range images and the registration error successfully to calculate the signed distance. After the signed distance of each voxel is determined, the marching cubes algorithm is then applied to generate a triangle model. The resolution of the object model can be determined via the voxel density in the 3D space used in the marching cubes algorithm. Finally, a photo realistic graphic model can be generated by blending and mapping the intensity images onto the reconstructed geometrical shape.

ACKNOWLEDGEMENT:

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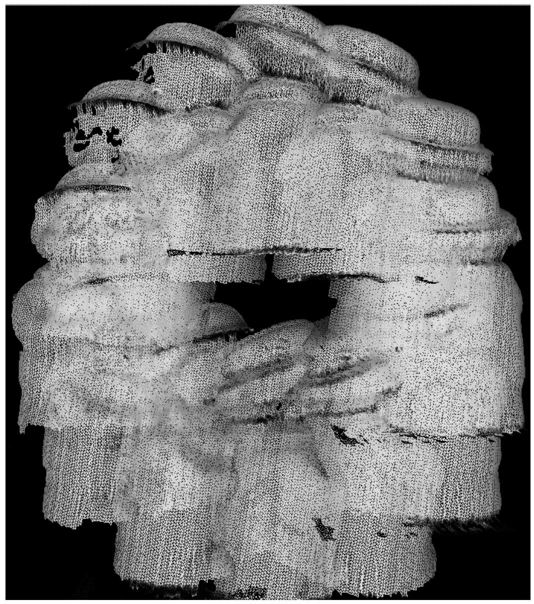
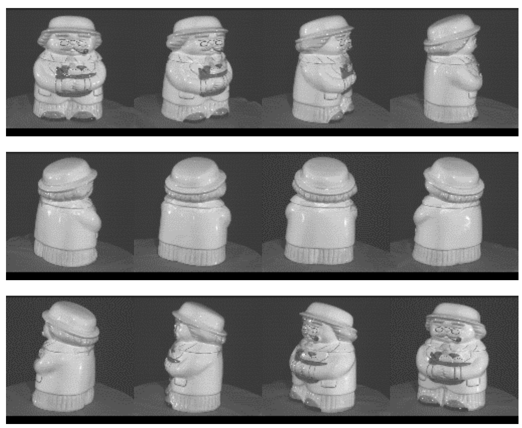
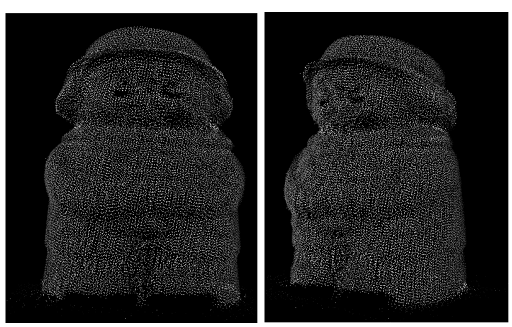


(a)

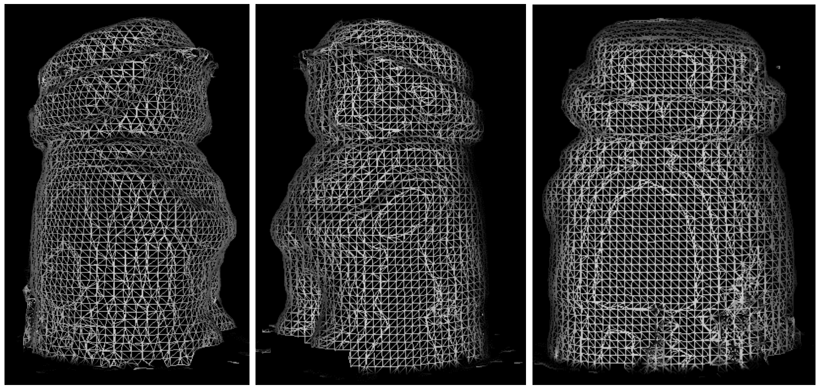


(b)

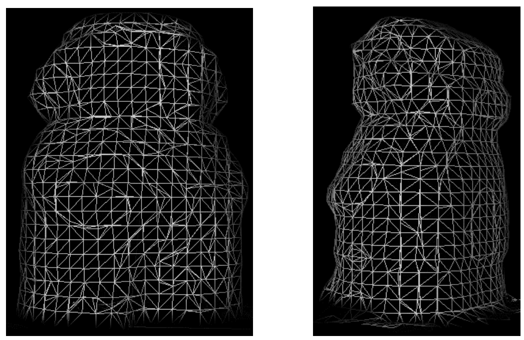


(c)

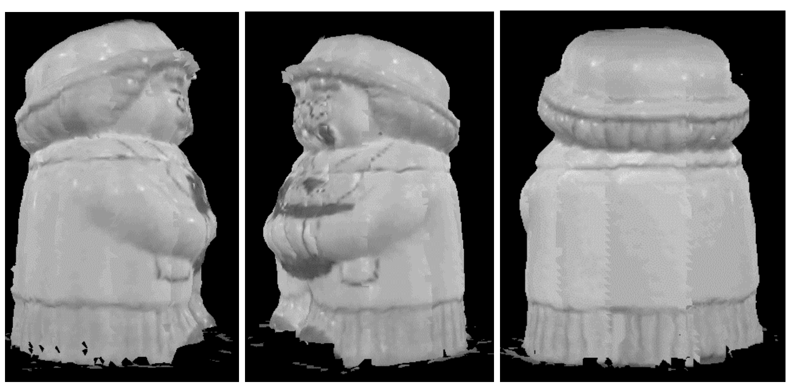
Figure 4. (a) Twelve range images of a toy. (b) The twelve intensity images taken from the same view points of (a). (c) The overlapped results after 3D registration.



(a)



(b)



(c)

Figure 5. (a) Triangle mesh generated by combining the consensus surface algorithm and the marching cube method (observed from three different views and the resolution is 128 x 128 x 128）. (b) Triangle mesh generated by combining the consensus surface algorithm and the marching cube method (observed from two different views and the resolution is 64 x 64 x 64). (c) Results of texture blending and mapping.