An Optimal Thresholding Method for the Voxel Coloring in the 3D Shape Reconstruction

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Abstract: In this paper, we propose an optimal thresholding method for the voxel coloring in the reconstruction of a 3D shape. Our purposed method is a new approach to resolve the trade-off error of the threshold value on determining the photo-consistency in the conventional method. Optimal thresholding value is decided to compare the surface voxel of photo-consistency with inside voxel on the optic ray of the center camera. As iterating the process of the voxels, the threshold value is approached to the optimal value for the individual surface voxel. And also, graph cut method is reduced to the surface noise on eliminating neighboring voxel. To verify the proposed algorithm, we simulated in the virtual and real environment. It is advantaged to speed up and accuracy of a 3D face reconstruction by applying the methods of optimal threshold and graph cut as compare with conventional algorithms.

Keywords: voxel coloring, voxel carving, 3D reconstruction, photo-consistency, optimal thresholding

1. INTRODUCTION

The 3D reconstruction of a complex scene is the most interesting topics in the field of computer vision. Among the methods to reconstruction, we used an efficient image-based approach to compute volume models from silhouette images in a low cost measuring environment. Shape from silhouette is the method of a 3D model of an object based on a sequence of images of the object taken from multiple views. The object's silhouette represents the only interesting feature of an image and corresponds to a conic volume in the object real world space[1]. A 3D model of the object can be built by intersecting the conic volumes from all views. Additionally, the method may use voxel coloring to improve the 3D reconstruction. Voxel coloring method is a volumetric algorithm that utilizes photo-consistency. Under an appropriate reflectance model, we may analyze the photo-consistency of each voxel in a scene to reconstruct the object of surface.

Silhouette based constructions have the principal inability to detect the objects concavities. We present some new results to minimize the modeling error on critical areas using an optimal thresholding method of voxel coloring.

In recent research, Culbertson[2], Slabaugh[3] proposed a generalized voxel coloring method (GVC) that can be used in random position of a camera. The photo-consistency is decided by calculating the dissimilarity of projection point of a voxel, absolute color difference[4],[5] or standard deviation[6],[7]. If the dissimilarity is above the specific threshold value, the voxel is eliminated, otherwise the voxel is remained. And if the threshold value of dissimilarity is large, the stability of reconstruction is high, but accuracy is low. In the opposite case, accuracy is increase but stability is decrease because the trade-off of the threshold is occurred[6].

In conventional method, single threshold value of the photo-consistency was used. It was decided to eliminate the voxel or not by the threshold value. But it is difficult to find the best single threshold value. Even if the best threshold value was found, error may be occurred because the threshold value was applied to all surface voxel.

In this paper, the optimal thresholding method is proposed to resolve the problem of single threshold value of photo-consistency. And also, in order to increase stability of a 3D reconstruction, we used the graph cuts method.

In proposed method, photo-consistency was decided by not only surface voxel but also inside voxel on an optical ray. By comparing the photo-consistency value of the inside voxel with surface voxel, the threshold value was decided. That is, when the difference of compared value is small, the threshold value is decided.

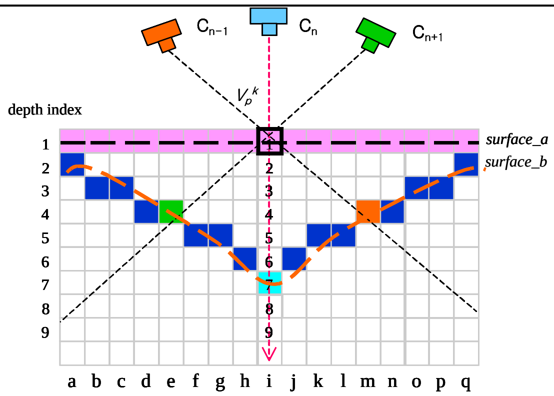
The threshold value is approached to the optimal value for the individual surface voxel by iterating comparison process. In the conventional algorithm, an irregular noise of restored surface was appeared by applying each voxel to color photo-consistency. In the proposed method, we intend to reduce the irregular noise of surface by applying graph cut method[7],[8].

2. THE OPTIMAL THRESHOLDING METHOD

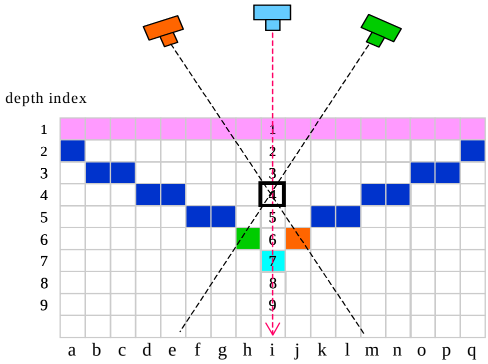
Generally, volume intersection method makes errors of image acquisition and concave of object modeling. To solve the problem, we describe the optimal thresholding method.

In fig. 1 (a), we assume that *surface_a* is reconstructed surface that is derived by the volume carving method and *surface_b* is the real surface of object at the camera C_{n-1} ,C_n ,C_{n+1}. A voxel, V_n^{xy}, is defined as the voxel located on the optical axis of center camera C_n to be located by coordinate (*x*,*z*) of *x*-*z* axis. Given any voxel, we can obtain two voxels on the real surface through the voxel, V_n^{xy}, from two camers, C_{n-1} ,C_{n+1}. Using the photo-consistency of the two voxels, we can obtain the dissimilarity of the voxel. In the Fig.1(b), using the voxel, V_n^{i4} and two cameras, C_{n-1} ,C_{n+1}, we can obtain two voxels, V_{n+1}^{h6} and V_{n-1}^{j6} on the real surface. From the photo-consistency of V_{n+1}^{h6} and V_{n-1}^{j6}, we can get the dissimilarity of V_n^{i4}. V_{n+1}^{h6} and V_{n-1}^{j6} are closing to V_n^{i7} on the real surface, the dissimilarity of V_n^{i4} is more decreasing.

At a voxel, V_n^{i7}, in Fig. 1(c), we can obtain the lowest dissimilarity, because the voxel V_n^{i7} is correct voxel on real surface. At a voxel V_n^{i9}, in Fig. 1(d), the dissimilarity was calculated by higher value than V_n^{i7}.



(a)



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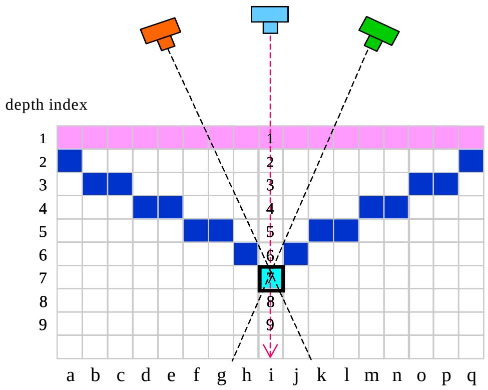
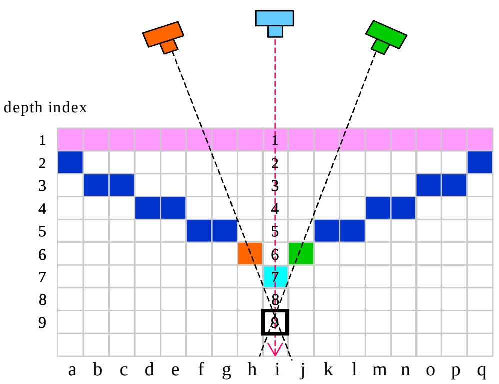


(c)



(d)

Fig. 1 Dissimilarity calculation at the center camera on the optical ray.

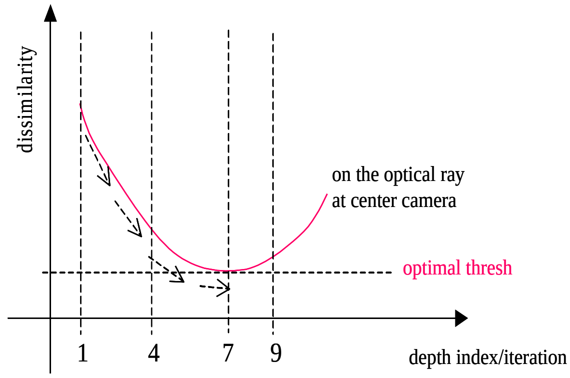


Fig. 2 Relationship between depth index and dissimilarity of voxel.

The smaller value of the dissimilarity, the closer the voxel is located at the real surface. Therefore, the dissimilarity of any voxel V_n^{xy} has to compare the dissimilarity of another voxel on the optical axis. And if the dissimilarity of the V_n^{xy} is larger than the dissimilarity of next voxel on the optical axis, the voxel should be eliminated. This process should iteratively be performed until finding the minimum dissimilarity to estimate the voxel. In the Fig.2, the characteristic change of dissimilarity was shown. When depth index is 7, the dissimilarity of a voxel has the lowest value. So we decided the voxel V_n^{i7} to real surface voxel. From all center camera position, dissimilarity was calculated, and then optimal threshold value was decided.

This method can be decrease in modeling error compared with conventional method using the single-fixed threshold because of multi-variable threshold of the all voxels.

3. VOXEL COLORING METHOD OF OPTIMAL THRESHOLDING

Fig. 3 is the flowing chart of voxel coloring method using optimal thresholding method. It is basically a form of GVC algorithm[2], the proposed optimal threshold method is added. V_p is 3D voxel matrix that is reconstructed by the carving method using the projection of images. P_θ is camera projection matrix at the Θ angle, and I_{obj}^{θ} is the image of the object projected at the Θ angle. First of all, we calculate the camera position from camera matrix of the Θ angle. And then we search the surface voxel in the reconstructed voxel data that is derived by carving method. Next, we search the visible voxels for each camera. And we calculate the visible center camera for the voxel. And next, optical ray of each voxel is calculated from center camera position.

Photo-consistency is calculated at the voxel on which the optical ray. Finally, we used the graph cut algorithm to eliminate the surface noise of a voxel. This routine is performed for all visible surface voxel until real surface voxel is decided.

3.1 Calculating camera position

Given the camera projection matrix P, the camera position *C* is calculated by Eq. (1).

$$PC=0 \qquad (1)$$

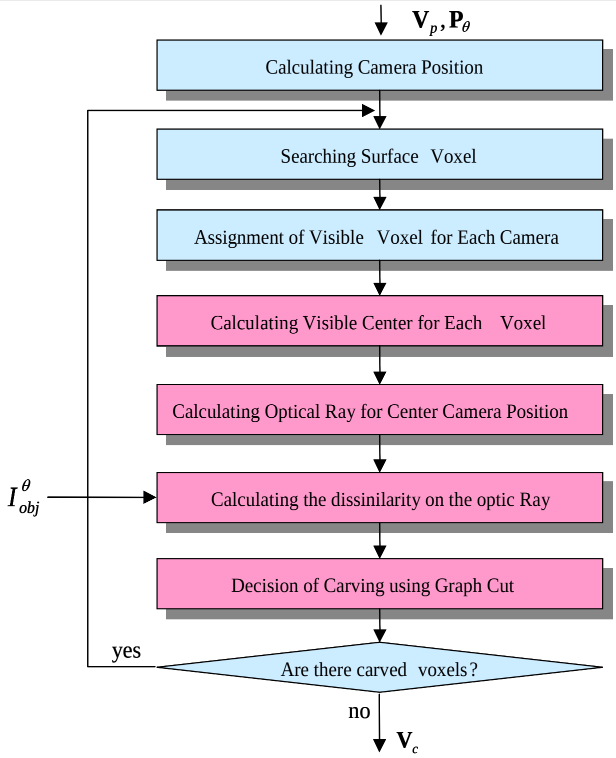


Fig. 3 The flow chart of proposed voxel coloring.

3.2 Searching surface voxel

We intend to search the surface voxel which put on 3D voxel matrix that is reconstructed by carving method. The 3D voxel matrix has the information that if the voxel is carved, the voxel value is 1, otherwise is 0. To search surface voxel, if the value of itself would be 1 and the one of 6-connected neighbor voxels would be at least 0, we will allocate a voxel V_{pi}^k to surface voxel, in the Eq. (2).

$$V_{sur}^k = \left\{ V_{pi}^k \middle| V_{pi}^k = 1 \wedge \exists V_{pj \in Ni}^k = 0 \right\} \qquad (2)$$

Where, V_{pi}^k is the voxel of 3D voxel matrix at arbitray position i, V_{pj}^k is the neighbor voxel of V_{pi}^k. Fig. 4 is 6-connected neighbor voxels.

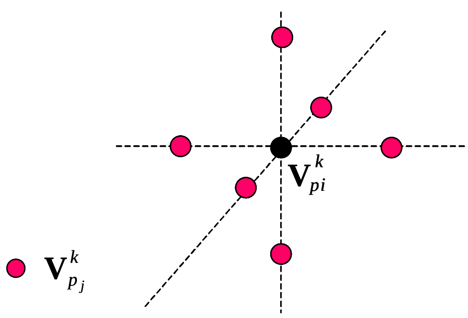


Fig. 4 6-connected neighbor voxels.

3.3 Searching visible surface voxel

The searched surface voxel is projected on a image plane to search visible surface voxel. If voxels of the two overlaps, voxel index be saved in the visible index buffer with minimum depth from camera center like Fig. 5.

After projecting all surface voxel, there is the only one index of the voxel which is seen from a camera in the visible index buffer. After this process is performed, the information of all voxel is acquired at each camera.

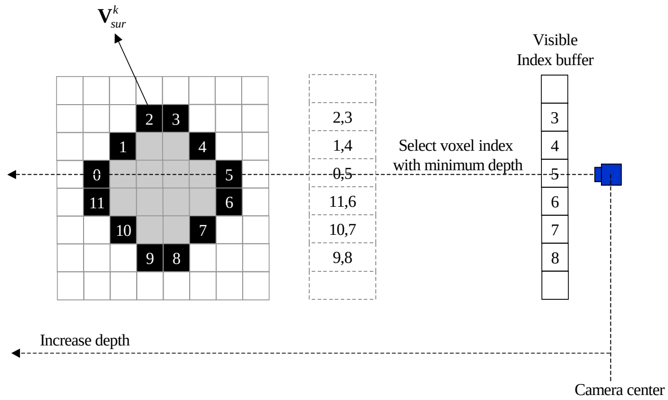


Fig. 5 Estimation of a visible surface voxel.

3.4 Calculation of the center camera

To decide the center camera $\mathbf{C}^k$, we search visible camera at a voxel surface. If voxel 3 is seen at the 6,7 and 8 camera, center camera will be become 7, like Fig. 6.

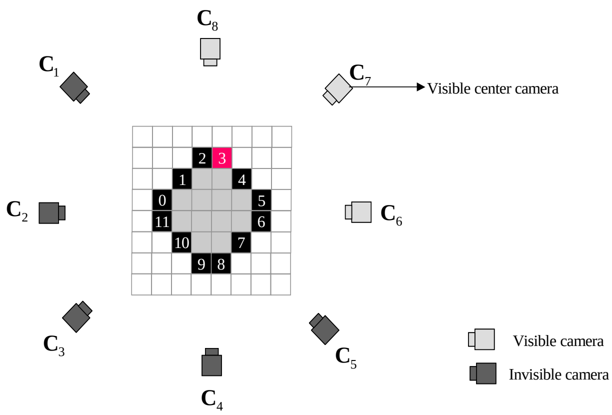


Fig. 6 Calculation of center camera.

3.5 Calculation of optical ray

We calculate optical ray from visible center camera. At first, unit vector $\mathbf{n}^k$ is calculated with Eq. (3).

$$\mathbf{n}^k = \frac{\mathbf{C}^k - \mathbf{V}_{sur}^k}{\left\| \mathbf{C}^k \cdot \mathbf{V}_{sur}^k \right\|} \qquad (3)$$

Where, $\mathbf{C}^k$ is visible center camera, V_{sur}^k is visible surface voxel.

The Fig. 7 is shown that $\mathbf{n}^k$ is unit vector on the optical ray at a visible center camera, V_{sur}^{k} is surface voxel and V_{in}^{k} is the inside voxel of V_{sur}^{k}.

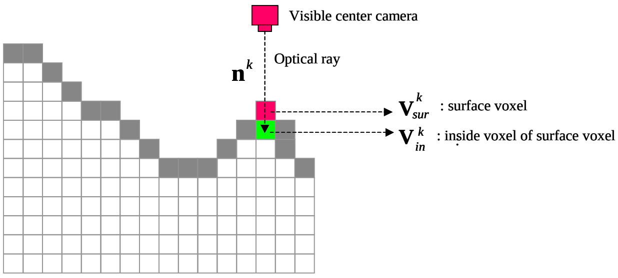


Fig. 7 Voxels on the optical ray.

3.6 Calculation dissimilarity on the optical Ray

To decide the threshold value, we calculate dissimilarity on the optical ray. In the conventional voxel coloring method, dissimilarity was calculated of visible surface voxel. But in this paper, in order to solve the single-fixed threshold problem, dissimilarity is calculated of not only surface voxel but also inside voxel on optical ray in the Fig. 7.

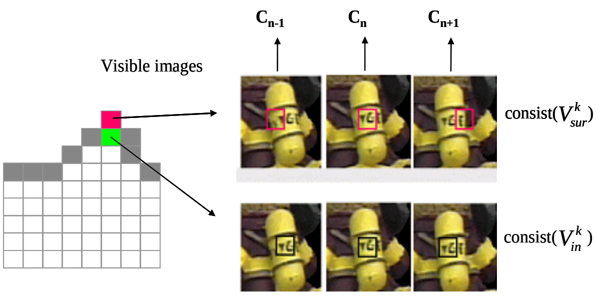


Fig. 8 Calculation of dissimilarity for voxels on optical ray.

Dissimilarity is calculated between surface voxel V_{sur}^{k} and inside voxel V_{in}^{k} by using the photo-consistency.

The relation of photo-consistency and dissimilarity is as following Eq. (4).

$$consist(\mathbf{V}_n) = \frac{a}{dissimilarity(\mathbf{V}_n)+1} \tag{4}$$

Where, $consist(\mathbf{V}_n)$ is photo-consistency value, a is arbitrary constant, and $dissimilarity(\mathbf{V}_n)$ is dissimilarity value. And $dissimilarity(\mathbf{V}_n)$ can be represented following equation, Eq. (5).

$$dissimilarity(\mathbf{V}_r^k) = \sum_{i,j}\left\{\left|\mu_i^{red}-\mu_j^{red}\right| + \left|\mu_i^{green}-\mu_j^{green}\right| + \left|\mu_i^{blue}-\mu_j^{blue}\right|\right\} \tag{5}$$

Where, i, j represents the index of surface and inside voxel . $\mu_i^{red}, \mu_i^{green}$, μ_i^{blue} are the average value of RGB of surface voxel. The dissimilarity of V_{sur}^{k} and V_{in}^{k} on the optical ray is calculated. If the dissimilarity of V_{sur}^{k} is larger than V_{in}^{k}, the V_{sur}^{k} is considered model error and the voxel is eliminated. The other case, the V_{sur}^{k} is considered the surface voxel of real object and the voxel is reminded. After this process is performed iteratively, the only real surface voxel is remained at the optimal threshold.

3.7 Decision of voxel elimination using graph cut

We used the graph cut method to finally decide surface voxel. We classified surface voxel into two label, Opaque and Carving node as like Fig. 9(a). The result is shown in Fig. 9(b)

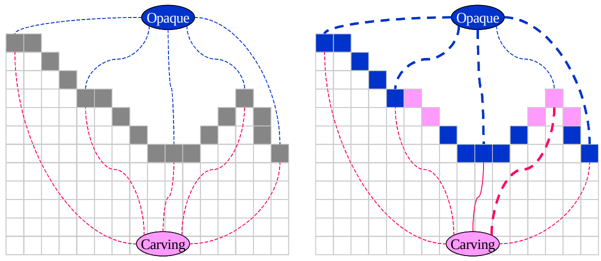


Fig. 9 Construction of graph cut for voxel coloring.
(a) Construction of graph.
(b) Voxel labeling resulting graph cuts.

We used the *E(f)* to minimize the energy of surface voxel. The Eq. (6) appeared energy function.

$$E(f) = \sum_{\mathbf{V}_n \in \mathbf{V}_{sur}^k} D_{\mathbf{V}_n}(f_{\mathbf{V}_n}) + \sum_{\{\mathbf{V}_n,\mathbf{V}_q\}\in N} V_{\{\mathbf{V}_n,\mathbf{V}_q\}}(f_{\mathbf{V}_n}, f_{\mathbf{V}_q}) \tag{6}$$

In the above energy function, $D_{V_n}(f_{V_n})$ is the expense of data term and $V_{\{V_n,V_q\}}(f_{V_n}, f_{V_q})$ is the expense of smooth term of the surface voxel. $D_{V_n}(f_{V_n})$ can be divided into two cases. One is that f_{V_n} was assigned to Opaque, the other is Carving. In Eq. (7), the expense of data term has the following form when f_{V_n} is assigned to Opaque.

$$D_{V_n}(f_{V_n}) = \begin{cases} 0 & if\ consist(V_{sur}) > avg\_consist \\ 1 & if\ consist(V_{sur}) \le avg\_consist\ \&\ consist(V_{sur}) \ge consist(V_{in}) \\ 2 & if\ consist(V_{sur}) \le avg\_consist\ \&\ consist(V_{sur}) < consist(V_{in}) \end{cases} \tag{7}$$

Where, the *avg_consist* is photo-consistency value of all surface voxels like Eq. (8)

$$avg\_consist = \frac{1}{N}\sum_{V_n \in \mathbf{V}_{sur}^k} consist(V_n) \tag{8}$$

In Eq. (7), if the condition is $consist(V_{sur}) > avg\_consist$, the expense of surface voxel is made a low value, 0, not to cut the voxel at the graph because the photo-consistency of V_{sur} is high. Else if the condition is $consist(V_{sur}) \le avg\_consist$, the expense is decided by considering the photo-consistency of inside voxel on the optical ray. That is, if the condition is $consist(V_{sur}) \ge consist(V_{in})$, the condition is assigned in lower value, 1, more than $consist(V_{sur}) < consist(V_{in})$ because photo consistency of V_{sur} is larger than V_{in}. If the condition is $consist(V_{sur}) < consist(V_{in})$, the highest expense value, 2, is assigned. If f_{V_n} is assigned to Carving level, the expense is applied to the opposite of Opaque case.

Expense of smoothing term, $V_{\{V_n,V_q\}}(f_{V_n}, f_{V_q})$, is as like the following, Eq. (9).

$$V_{\{V_n,V_q\}}(f_{V_n}, f_{V_q}) = \begin{cases} 0 & if\ f_{V_n} = f_{V_q} \\ 1 & if\ f_{V_n} \neq f_{V_q} \end{cases} \tag{9}$$

Where, the V_q means 6-coupled neighbor voxel of V_n.

To find the minimum energy, we used the graph cut algorithm that is proposed by Kolmogrov[8].

4. EXPERIMENTS

In this experiment, the color CCD camera, JAI CV-S3300 was used. The acquisition image is 24bit colors, its size is 640*480. We used the Visual C++ for compiler and the OpenGL to display 3D image. The Pentium4 computer was used to simulate. We acquired the silhouette images from a real 3D object. The images are 40 image slides with the angle of about 9° . Following images are some of the acquisition images, in the Fig. 10. We used the images for the input images.

0° 90° 180° 270°

Fig. 10 Input images.

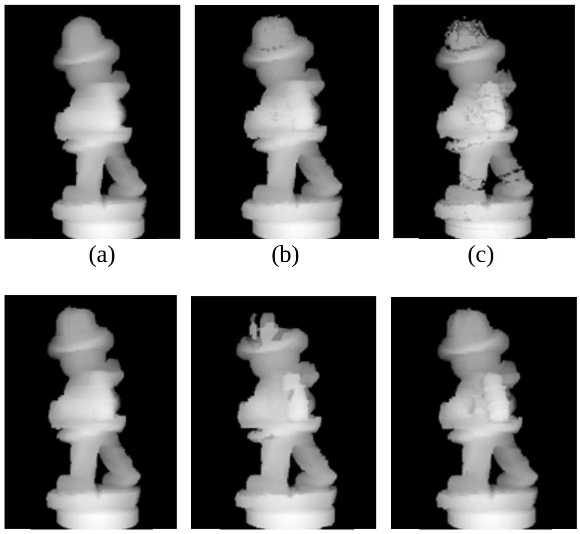
To evaluate the proposed optimal threshold method using the voxel coloring, experimental conditions are showed in the table 1.

Table 1. Experimental conditions of voxel coloring.

	Algorithm	Threshold	Graph Cuts
(a) VI	Volume Intersection	--	--
(b) GVC_Th50	Generalized Voxel Coloring	50	×
(c) GVC_Th25	Generalized Voxel Coloring	25	×
(d) GVC_GC_Th50	Generalized Voxel Coloring	50	O
(e) GVC_GC_Th25	Generalized Voxel Coloring	25	O
(f) OTVC	Optimal Voxel Coloring	×	O

In the table 1, VI means the volume carving method of Szeliski[10] and is used for criterion to evaluate the effect of optimal threshold method.

The experimental conditions (b), (c) used the general voxel coloring method of Culbertson's[1] and the threshold value of dissimilarity was set to 50 and 25. Threshold value means dissimilarity of the surface voxel. If the threshold value is small, the photo-consistency is high, and the other case the photo-consistency is low. The relation of between photo-consistency and dissimilarity is inverse proportion. We also applied the experimental condition (d), (e) to graph cut method at the same condition (b), (c). The experimental condition (f) is optimal threshold method using voxel coloring.



(a) (b) (c) (d) (e) (f)

Fig. 11 Depth map of the reconstructed of experimental conditions.
(a) VC, (b) GVC_TH50, (c) GVC_TH25
(d) GVC_GC_TH50, (e) GVC_GC_TH25, (f) OTVC.

We appeared reconstructed results by using depth map of each experimental condition, in Fig. 11. Fig. 11 (a) is the reconstructed shape using VI. It shows model errors because of concave surface.

In experimental conditions (b), (c), the larger the threshold value of dissimilarity is, the smaller the reducing rate of model error is, but the stability of reconstruction is low. The smaller the threshold value of dissimilarity is, the larger model error is, but the validity of reconstruction is low. Experimental conditions (d),(e) is similar to (b),(c), additionally graph cut method was applied. The result of conditions (d),(e) is that the surface noise is eliminated compared with conditions (b),(c). But model error was large. Fig. 11(f) was shown the result to using optimal thresholding value at the condition (f).

We decreased the model error by using the optimal thresholding method, and stability of reconstruction was high by using the graph cut method.

Fig. 12 presents the average dissimilarity of reconstructed 3D shape by using the experimental conditions shown Table 1. We know that the smaller the dissimilarity value is the closer the voxel is. And also we found optimal thresholding value at the minimum dissimilarity. In this paper, proposed algorithm is better result than convention method.

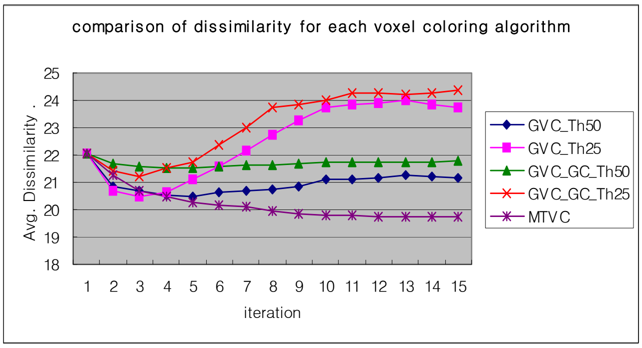


Fig. 12 Comparison graph of dissimilarity for experimental conditions.

5. CONCLUSIONS

We proposed improved optimal thresholding method using the voxel coloring algorithm for the image-based 3D shape reconstruction. The proposed voxel coloring algorithm presented good result compared with conventional voxel coloring algorithm using the single-fixed threshold value.

The thresholding value is approached to the optimal value as the dissimilarity of voxel is small. The process is iterated to find out the optimal thresholding value. And to eliminate the noise of surface voxel, we applied the graph cut method. Graph cut algorithm was used to minimize energy, and irregularities of surface were eliminated by energy of smooth term. Experiments were performed with conventional and proposed method under various conditions. In conventional voxel coloring algorithm, the trade-off problem of accuracy and stability was caused by the single-valued threshold of dissimilarity. We resolved the problem by using optimal thresholding and graph cut method.

The reconstruction efficiency of proposed algorithm is much better than conventional one.

ACKNOWLEDGMENTS

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