Depth Hole Filling for 3-D Reconstruction Using Color and Depth Images

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***Abstract*— Computer vision algorithms using depth and color data (RGBD image) acquired at the same time are gradually getting an attention. Depth data is useful three-dimensional (3-D) information. However, the depth data has a problem that it includes depth hole regions. In this paper, a depth hole filling method is proposed, which is suitable for 3-D reconstruction, with the detail of depth region of an object preserved.**

Keywords—depth hole; 3-D reconstruction; RGBD image; depth map enhancement

I. Introduction

Three-dimensional (3-D) information is obtained by using a range camera. The early type of range camera is composed of radio frequency (RF) modulated light sources and the receiver that includes phase detector [1]. To measure the distance between an object and a camera, this type of range camera emits RF-modulated light. Then, the receiver of a range camera measures the distance by detecting phase difference of RF-modulated light. Another type of range camera consists of structured infrared light (SIL) source and infrared camera [1]. SIL source emits regular patterns of infrared light into scene, then infrared camera produces image by detecting emitted patterns of infrared light. The distance between a range camera and an object is measured by observing patterns in the image. However, the depth image acquired by a range camera contains regions that do not have any depth information, which is called the depth hole problem. To solve the depth hole problem, various algorithms have been presented [2, 3]. To fill holes, Yang *et al.*'s method uses the distribution of the depth values around depth holes [2]. The value that fills depth holes is computed by averaging peak values of the distribution of the depth values around depth holes. After that, depth map refinement proceeds by using the color image. Xu *et al.*'s method uses the maximum depth value in a window of a certain size to fill depth holes [3].

Recently, visible-light camera and range camera are combined to obtain color and depth information at the same time [4]. This type of camera is called RGBD camera, and the acquired information is called RGBD image. RGBD image is very useful information because it represents not only color information but also 3-D information. However, RGBD image has the depth hole problem, which degrades the performance. For example, the depth hole problem is a critical factor in 3-D reconstruction. In [5], Lim *et al.* use scale invariant feature transform (SIFT) features to match multiple RGBD images acquired at different viewpoints. Most of SIFT features are located at edges of RGB image. The depth holes also lie at edges of RGB image. Thus, most of SIFT features do not have depth data. To overcome this problem, Lim *et al.* use the depth map filtering [5]. However, the depth map filtering is not sufficient, because SIFT features that are located in depth hole regions cannot be used to match multiple RGBD images. Thus, the performance of their algorithm can be improved by filling depth holes.

The rest of the paper is structured as follows. In Section II, the proposed depth hole filling algorithm is presented in detail. In Section III, the proposed and existing methods are compared. In addition, result of applying the proposed method to 3-D reconstruction algorithm [5] is shown. Finally, conclusion and further work are given in Section IV.

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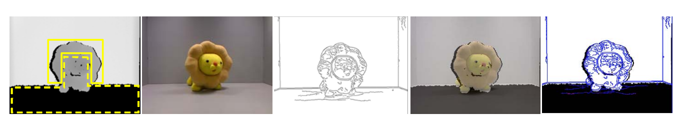
II. Proposed Dpeth Hole Filling Method

Depth image is acquired by observing phase difference of RF-modulated light or SIL patterns. The depth hole problem occurs, if RF-modulated light or SIL patterns are not sensed at surface of an object by occlusion or geometric relationship between camera and object.

Figs. 1(a) and 1(b) show depth image and RGB image, respectively. In Fig. 1(a), regions surrounded by solid and dashed lines are depth hole regions caused by occlusion and geometric relationship, respectively. Fig. 1(c) illustrates extracted edges of Fig. 1(b). The image generated by overlapping Figs. 1(a) and 1(b) is shown in Fig. 1(d), in which depth hole regions are located in outer region of extracted edges. Therefore, depth hole regions are filled with the depth values of outer region. Fig. 1(e) shows the image generated by overlapping depth holes of Figs. 1(a) and 1(c). In Fig. 1(d), depth hole regions are adjacent to some edges in Fig. 1(c). Thus, edge $l(\mathbf{x})$ that separates depth hole regions and object regions is detected by AND operation of depth hole region and detected edges, where vector $\mathbf{x}$ represents the coordinate of point of edge $l(\mathbf{x})$.

The proposed depth hole filling method is described as follows. First, it detects edge $l(\mathbf{x})$ by using Canny edge detector [6] and AND operation. Then, the searching direction $\mathbf{d}_o$ of depth value to be used to fill depth hole region is determined as normal to $\nabla l(\mathbf{x})$ at point $\mathbf{x}$, i.e., $\mathbf{d}^T \nabla l(\mathbf{x}) = 0$. To determine $\nabla l(\mathbf{x})$, the proposed algorithm uses Sobel operator. The geometrical representation of $\mathbf{d}_o$ is shown in Fig. 2. The



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

Fig. 1. RGBD images. (a) depth image, with regions surrounded by solid and dashed lines representing depth hole regions, (b) color image, (c) extracted edge of (b), (d) overlap of (a) and (b), (e) overlap of (a) and (c).

searching direction is not uniquely determined, with two candidates $\mathbf{d}$ and $-\mathbf{d}$. To determine $\mathbf{d}_o$, the proposed algorithm finds adjacency depth hole region. If adjacency depth hole region is located along $\mathbf{d}$ direction, $\mathbf{d}_o$ is determined as $\mathbf{d}$, otherwise, as $-\mathbf{d}$. Second, to fill the depth hole region, the proposed algorithm finds valid depth value by referencing $\mathbf{d}_o$ and detecting non-zero depth value. Then, the proposed algorithm fills depth holes with valid depth value that is found first. Finally, it performs refinement process that fills the rest of depth hole regions by using the filled value of neighboring pixels. Pseudo code of the proposed depth hole filling method is described in Algorithm 1.

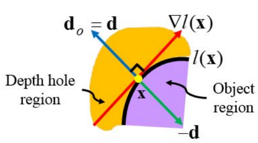
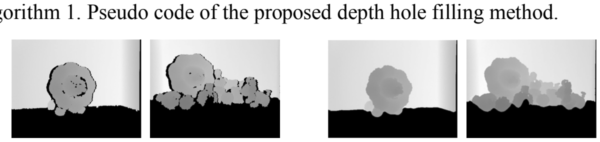


Fig. 2. Geometrical representation of the searching direction $\mathbf{d}_o$.

Begin
  Detect depth hole region in depth image (Fig. 1(a))
  Detect edge in RGB image (Fig. 1(c))
  Calculate $l(\mathbf{x})$ by using AND operation
  Calculate $\nabla l(\mathbf{x})$
  Repeat
    If $l(\mathbf{x})$ is equal to one
      Determine searching direction $\mathbf{d}_o$
      Find valid depth value by referencing $\mathbf{d}_o$
      Fill depth hole region with found valid depth value
    End if
  Until all points in depth image are processed
  Perform refinement process
End

Algorithm 1. Pseudo code of the proposed depth hole filling method.



(a) (b)

Fig. 3. Two examples of depth hole filling. (a) two depth images, (b) results of depth hole filling.

III. EXPERIMENAL RESULTS AND DISCUSSIONS

To show the performance of the proposed algorithm, three experiments are performed. Fig. 3 shows two results of depth hole filling by using the proposed method. Input images and output images of the proposed algorithm are illustrated in Figs. 3(a) and 3(b), respectively. In Fig. 3(b), depth holes that are surrounded by valid depth regions are eliminated. However, depth hole regions located in the bottom region of two images of Fig. 3(b) are not filled. These depth hole regions do not need to be filled, because depth information of these regions can be acquired from other images that are captured at different viewpoints.

Fig. 4 shows the performance comparisons of the proposed and two existing methods. The depth hole region is shown in red box. Red boxes in Figs. 4(c), 4(d), and 4(e) show results of Yang *et al.*'s [2], Xu *et al.*'s [3], and the proposed methods, respectively. In Fig. 4(c), depth map is divided into three regions: background, object, and filled depth hole region, Note that the depth hole region is filled with the average of peak values around depth hole region. The filled region degrades the performance of 3-D reconstruction, because the region of

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

Fig. 4. Performance comparison of the proposed method and existing methods. (a) depth hole region (cropped image from Fig. 1(a)), (b) color image corresponding to (a) (cropped image from Fig. 1(b)), (c) result of Yang *et al.*'s method [2], (d) result of Xu *et al.*'s method [3], (e) result of the proposed method.

(a) (b) (c)

Fig. 5. Result of 3-D reconstruction. (a) lion and octopus image (modified Lim *et al.*'s method), (b) lion and octopus image (Lim *et al.*'s method [5]), (c) multi-object image (modified Lim *et al.*'s method).

Fig. 4(a) is composed of background and object as shown in Fig. 4(b). Thus, Yang *et al.*'s method is not suitable for 3-D reconstruction. Figs. 4(d) and 4(e) are properly divided into two regions. However, Fig. 4(d) loses the detail of depth region of an object. On the other hand, Fig. 4(e) preserves the detail of depth region of an object.

To fill depth hole regions, the modified Lim *et al.*'s method uses the proposed depth hole filling method instead of depth map filtering [5]. Figs. 5(a) and 5(b) show results of 3-D reconstruction by using original and modified Lim *et al.*'s methods, respectively. Fig. 5(a) has more information of objects and background than Fig. 5(b). The performance of 3-D reconstruction by the modified Lim *et al.*'s method is improved by applying the proposed depth hole filling method to Lim *et al.*'s method [5]. In addition, the modified Lim *et al.*'s method can reconstruct 3-D scene by using image that contains several objects, as shown in Fig. 5(c).

IV. CONCLUSION

In this paper, a depth hole filling method that is suitable for 3-D reconstruction is proposed. The proposed method gives better performance of 3-D reconstruction by filling depth hole regions. In addition, the result of the proposed method preserves the detail of the depth region of an object. Further work will focus on application of the proposed method to other research field such as action recognition.

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