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Colorization of 3D Geometric Model utilizing Laser Reflectivity

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Abstract— **In this paper, we propose a new technique for adding color to a surface of a 3D geometrical model utilizing laser reflectivity. A time-of-flight laser scanner obtains a range image from the sensor toward the target by measuring the round-trip time of a laser pulse. At the same time, for most laser scanners, the reflectance image (which is the strength of the reflected light) is available as a by-product of the range value. The proposed technique first assigns appearance information to a 3D model by colorizing a reflectance image based on the similarity of color and reflectance images. Then the color information is transfered to the corresponding range image, and the colorized 3D model is obtained. We carried out experiments using a laser scanner and showed the performance of the proposed technique in several conditions.**

I. Introduction

Three-dimensional geometric modeling of a real object using a laser scanner has been used in many applications such as Virtual Reality (VR), digital archives of cultural heritages [1], and remote control of a rescue robot in a hazardous environment [2]. Moreover, to display a 3D model with high realism, it is effective to add color and texture information to the surface and provide not only a geometry but also appearance information. For instance, it is quite helpful to control a rescue robot in a dark and hazardous environment appropriately if a colored 3D model around a rescue robot is displayed for an operator. Texture mapping [3], which maps a color image obtained by a camera to a 3D geometric model, has been widely used for creating photo-realistic models. However, if a color image and a 3D geometric model are captured by different sensors such as a digital camera and a laser scanner, precise calibration between these sensors must be performed. Moreover, multiple color images are required to add surface appearance to an entire or large-scale 3D model, and small registration errors or changes in lighting conditions cause an unsatisfactory gap and discontinuity due to human perception.

In this paper, we propose a new technique for adding color to a 3D geometric model utilizing laser reflectivity [4]. A time-of-flight laser scanner obtains a range image from a sensor toward a target by measuring the round-trip time of a laser pulse. At the same time, laser reflectivity which indicates the power of the reflected laser is also obtained as a side product of distance value. Therefore, each pixel in the range image has a corresponding reflectance value. In other words, the range image and the reflectance image are precisely aligned.

Focusing on the characteristics of laser reflectivity, we propose a new technique for creating a realistic 3D model with appearance information. First, we colorize the reflectance image by a non-calibrated color image based on the similarity of color and reflectance images. Second, the color information is transfered to the corresponding range image, and the colorized 3D model is obtained. As mentioned above, range and reflectance images can be considered to be calibrated precisely, so we just need to copy each color value of the pixel in the reflectance image to the corresponding pixel in the range image without determining correspondence between range and reflectance images.

The rest of this paper is organized as follows. In Section 2, an overview of the previous approaches will be presented. In Sections 3, we will propose a new colorization technique for a 3D geometric model using a reflectance image. In Section 4, we carry out some experiments using a laser scanner, and verify the performance of the proposed technique.

II. Related Research

Texture mapping [3], which is a fundamental technique for creating a photo-realistic 3D model, has been widely used in the field of computer vision. In some applications, it maps a color image on a range image and creates a colored 3D model. Usually range and color images are captured from different viewpoints by two independent sensors, such as a laser scanner and a digital camera. Therefore, it is necessary to determine the correspondence between range and color images in order to map color information on the 3D geometric model precisely.

For aligning a 3D model and a color image, Yoshida et al. [5] proposed an alignment technique by assigning several matching points between range and color images manually. Neugebauer et al. [6] proposed a similar technique that calculates suitable camera parameters according to the interactive choice of corresponding points between 3D range data and a 2D color image.

In contrast, techniques that align range and color images automatically have been developed by several researchers. Viola et al. [7] proposed a technique that utilizes statistical characteristics of both images. Stamos et al. [8] also proposed a method that extracts several planes from the range data and edges in the color image, and calculates the intersection lines of the planes and the edges. Some approaches that compare a 2D image contour with a silhouette image of the 3D geometric model have been proposed. Iwakiri et

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al. [9] proposed a real-time texturing method that aligns a color image and an image of a 3D geometric model from a virtual camera. Lensch et al. [10] proposed a silhouette-based algorithm that determines the camera transformation based on an XOR-operation between a silhouette image of a 3D model and a color image.

Some registration techniques that exploit reflectance images have been proposed. Reflectance image, obtained as a by-product of a range image for most laser scanners, has a similar appearance to a color image. Focusing on that, some approaches make use of reflectance images for the registration between a 2D image and a 3D geometric model for texture mapping. Boughorbal et al. [11] utilized the similarity between the reflectance image and the intensity image based on the χ^2-metric. Umeda et al. [12] proposed a technique to determine relative relations between a range sensor and a color sensor based on the gradient constraint between reflectance and color images. On the other hand, local features in both images are effective to estimate the correspondence between reflectance and color images. Kurazume et al. [4] proposed a calibration method for texture mapping that minimizes the error between edges extracted from reflectance and color images respectively using the robust M-estimator. Boehm et al. [13] utilized SIFT(Scale-Invariant Feature Transform) [14] to estimate extrinsic parameters by matching them in reflectance and color images. Inomata et al. [15] proposed a SIFT-based technique that calculates not only the extrinsic parameters but also the intrinsic parameter and the distortion of the camera lens simultaneously. This method uses Soft-matching that retains correct matches while removing false matches between reflectance and color images according to the similarity of the appearances based on Bhattacharyya distance.

All the methods mentioned above assume that color images which correspond to range images are captured. However, in some cases, it is difficult or almost impossible to provide color images perfectly, for example, in dark and wide areas. The proposed technique in this paper gives a solution for providing a colored 3D model even in these conditions.

III. Colorization of 3D Geometric Model utilizing Laser Reflectivity

In this section, we propose a new colorization technique for a 3D geometric model using a reflectance image. The proposed technique is based on a local similarity between color and reflectance images. First, both images are divided into small regions and local features are calculated. Then the correspondences of these small regions between color and reflectance images are determined considering a similarity of local features. Next, the reflectance image is colorized using color information assigned in the regions using the image colorization method. Finally, color in the reflectance image is transfered to a range image and the colorized 3D model is obtained.

The proposed technique does not require a precise calibration between color and range images which is required for the conventional texture mapping. Thus the gap or discontinuity in appearance can be avoided even if several images must be registered on a model. Moreover, the appearance of the entire surface of a model can be assigned from a partial view of the model only if the appearance does not change significantly in the entire model.

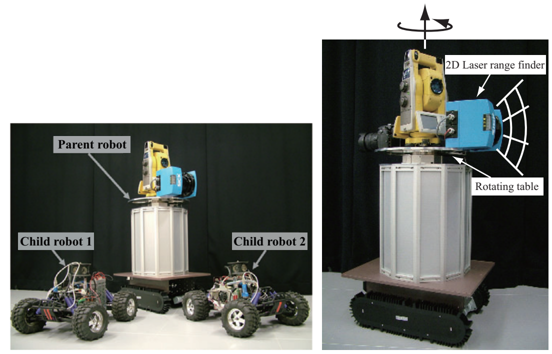
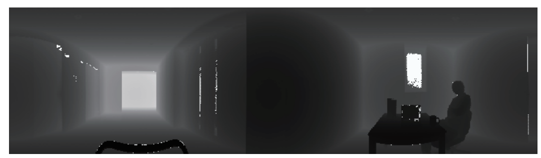


Fig. 1: Acquisition system of a panoramic range image [1]



(a) Range image

(b) Reflectance image

Fig. 2: Range and reflectance images

A. Reflectance image

A time-of-flight range sensor, such as a laser scanner, obtains range data by measuring the round-trip time of a laser pulse reflected by an object. Fig. 2(a) shows an example of a range image acquired by a 3D laser scanner (Fig. 1 [1]). On the other hand, the most range sensors provide the strength of the reflected laser pulse (reflectivity). Fig. 2(b) shows a reflectance image that depicts reflectance values as a grayscale image. As mentioned above, an unique reflectance value is determined for each pixel in the range image. In other words, the range image and the reflectance image are fundamentally aligned.

B. Image colorization

Image colorization is a technique for adding color to a monochrome image and has been used in some specific applications, such as coloring monochrome movies or creating color-coded images for electron photomicrograph or X-ray imaging. Since adding color values to a monochrome image has no general solution, the current approaches attempt to estimate the entire colors based on some clues given as seed points manually [16] [17] or automatically [18] [19] [20].

Yatziv et al. [21] proposed a fast image colorization technique using Dijkstra's distance [22]. This technique estimates the color at each pixel in a grayscale image by calculating a weighted average of Dijkstra's distances from each seed point which has chromatic information. Dijkstra's distance is computed considering changes in luminance in the monochrome image. If the change in luminance from the seed point is small, the chromatic information at the seed point is mainly copied to the pixel. More precisely, if the color is described in YCbCr color space, the color of each monochrome pixel is estimated using Dijkstra's distance as follows:

$$c_i = \frac{\sum_{j \in \Omega_c} w(i,j) c_j}{\sum_{j \in \Omega_c} w(i,j)} \tag{1}$$

$$w(i,j) = {r_{ij}}^{-\alpha} \tag{2}$$

$$r_{ij} = \operatorname{argmin} E_{ij} \tag{3}$$

$$E_{ij} = \sum_{k=1}^{n-1} |Y_{p_{k+1}} - Y_{p_k}|_{p_{k+1} \in N(p_k), p_1 = i, p_n = j} \tag{4}$$

Where, c_i is the estimated color value(CbCr) in pixel i, Ω_c is a set of seed points which have color information, r_{ij} is Dijkstra's distance from pixel i to pixel j, α is a gain parameter that controls the effect of weighting function $w(i,j)$ based on Dijkstra's distance, and Y_{p_k} and $N(p_k)$ are the intensity and the neighbor pixels of the pixel p_k.

Equation (2) indicates that the seed point, which has a small Dijkstra's distance to the target pixel, is preferentially selected to colorize the monochrome pixel in the grayscale image. In contrast, a seed point which has a Dijkstra's path with large luminance change contributes little to the color estimation of the monochrome pixel.

C. Colorization of range image using reflectance image

Based on the image colorization technique described above, we propose a new colorization technique for a 3D geometric model utilizing a reflectance image and a color image. The basic idea of the proposed technique is as follows; since reflectance and range images are fundamentally and precisely aligned, we colorize the reflectance image using its similarity with a color image at first, then transfer the color to the range image. In the following sections, we introduce our techniques, which determines correspondences in reflectance and color images using HOG features [23].

1) Assignment of seed points in a reflectance image: We colorize a reflectance image obtained by a laser scanner based on Yatziv's method [21] shown in Section III-B. Firstly, we assign some seed points which have chromatic information in the reflectance image. We adopt the following two approaches for assigning seed points.

(i) Manual assignment by human intervention
(ii) Automatic assignment by determining the corresponding regions between reflectance and color images

In the manual assignment, a 3D geometric model is colorized according to the human instruction. Several seed points

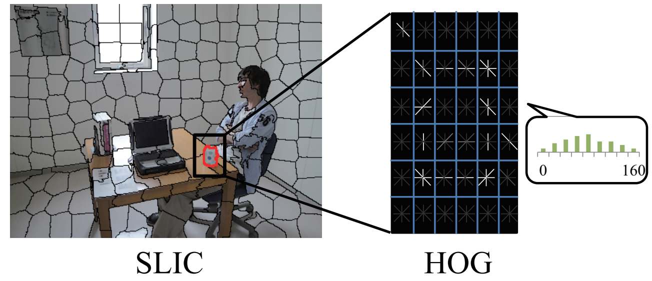


Fig. 3: Assignment of seed points by local features with SLIC and HOG

are selected manually in a reflectance image, and color information in a color image is assigned to these seed points.

On the other hand, the automatic assignment determines the correspondences of small regions between reflectance and color images automatically utilizing SLIC [24] and HOG features [23], and then transfers chromatic information from a color image to a reflectance image. SLIC (Simple Linear Iterative Clustering) proposed by Achanta et al. [24] is a technique to divide an image into small segments with similar size called "superpixels". Each segment extracted by SLIC holds pixels that have similar intensity or color. The HOG (Histogram of Oriented Gradients) feature is proposed by Dalal et al. [23] for pedestrian detection in camera images. HOG is able to describe local object appearances robustly according to the distribution of gradient orientation of the intensity.

First, we divide reflectance and color images into small segments with SLIC, and then the local features are extracted by applying HOG to small regions around the segments. Now we use canny-filtered reflectance and color images for feature extraction in order to compare the outlines of objects in these images. Finally, based on the similarities of HOG features between the small regions in reflectance and color images, the correspondences of the regions in both images are determined (Fig. 3). Seed points in the reflectance image are chosen at the center of the segmented regions and the chromatic information is copied from the center of the corresponding regions in the color image.

2) Colorization of reflectance image using range image: Once the seed points are determined by the method mentioned above, the Yatziv's method in Section III-B can be applied to a reflectance image simply in the same way as for a monochrome image. However, as you can see in Fig. 2(b), jump edges in a reflectance image are obscure in many cases. Thus, if we apply the Yatziv's method to the reflectance image directly, the color information will be spread beyond these jump edges and unsatisfactory results will be obtained.

On the other hand, a range image contains jump edges clearly as shown in Fig. 2(a) and these edges can be detected easily. Since the range image and the reflectance image are fundamentally aligned precisely, we can utilize the jump edges in the range image as the additional edges for colorizing the reflectance image.

To take these edges in the range image into account, we define a new energy function using a quadratic function instead of Eqs. (3), (4) as follows.

$$r_{ij} = \text{argmin}\, E'_{ij} \tag{5}$$

$$E'_{ij} = \sum_{k=1}^{n-1} \left\{ \beta (D_{p_{k+1}} - D_{p_k})^2 + 1 \right\} |Y_{p_{k+1}} - Y_{p_k}| \tag{6}$$

Where, D_{p_k} is an intensity value at pixel p_k in a range image, and β is a gain parameter to control the effect of the range image for color estimation. Equation (6) means that if no jump edge exists along the path from a seed point to a target pixel in both reflectance and range images, the Dijkstra's distance becomes small and the seed point affects the color estimation of the target pixel in the reflectance image significantly. In contrast, the seed point with a small Dijkstra's distance due to jump edges in a reflectance and/or a range image slightly influence to the color estimation.

3) Proposed method: Consequently, the proposed colorization techniques for a 3D geometric model are summarized as follows. Note that the YCbCr color space is used in this paper, however, the proposed technique works in other color spaces such as YUV or $l\alpha\beta$.

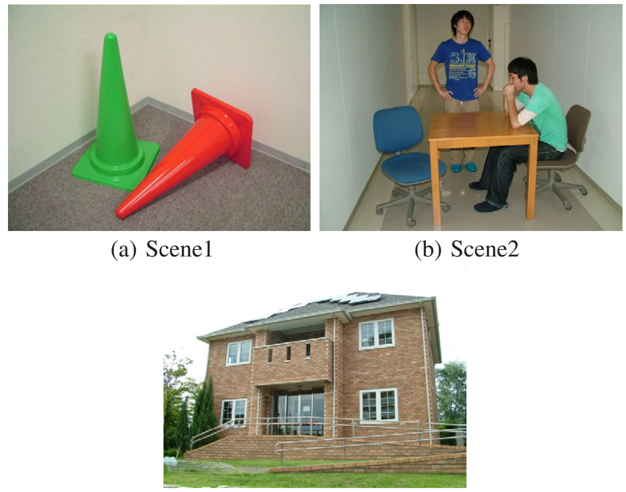
Method 1 : Manual assignment of seed points

- (i) Acquire range and reflectance values and a color image by a laser scanner and a digital camera, respectively.
- (ii) Create range and reflectance images in which gray values of each pixel are proportional to the measured range and reflectance values.
- (iii) Assign seed points in the reflectance image manually according to the correspondence between the reflectance and the color images.
- (iv) Apply the proposed colorization technique in Eqs. (1), (5), and (6) using range and reflectance images, and obtain a colorized reflectance image. Luminance Y in the colorized reflectance image is determined by a reflectance value.
- (v) Transfer the color value of each pixel in the colorized reflectance image to the corresponding range image and construct a colorized 3D model from the range image.

Method 2 : Automatic assignment of seed points

To assign seed points automatically, we roughly determine the correspondence between reflectance and color images using HOG features. To do so, (iii) in the method 1 is replaced as follows.

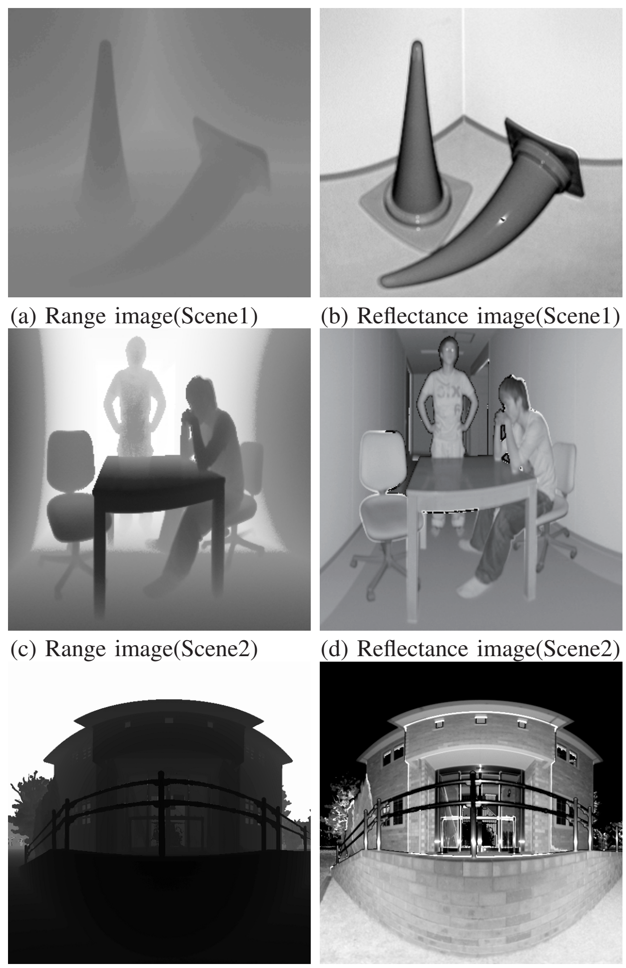
- (iii) Divide reflectance and color images in small segments using SLIC, and determine the correspondence between segments according to HOG features. Then, assign the color information to the center pixel of each segment in the reflectance image from the corresponding region in the color image.



(a) Scene1 (b) Scene2

(c) Scene3

Fig. 4: Experimental setup



(a) Range image(Scene1) (b) Reflectance image(Scene1)

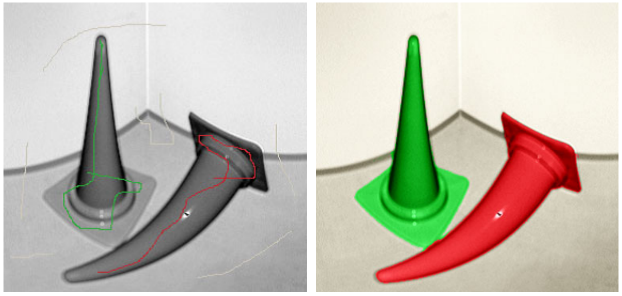
(c) Range image(Scene2) (d) Reflectance image(Scene2)

(e) Range image(Scene3) (f) Reflectance image(Scene3)

Fig. 5: Range and reflectance images

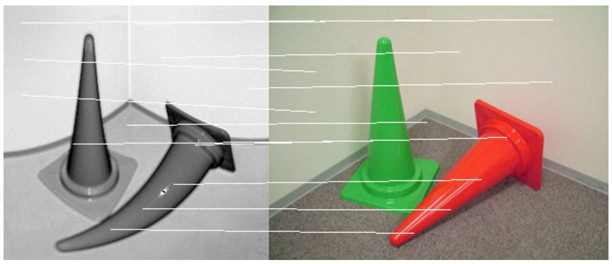
IV. Experiments

This section introduces the results of the colorization experiments. Range and reflectance images are obtained by the 3D laser measurement robot CPS-V shown in Fig. 1 [1]. This robot captures surrounding range and reflectance data by rotating the laser scanner (SICK, LMS151) on a rotary table. The image size is 760×1135 pixels. Color images are taken by a digital camera (Fujifilm, FinePix S7000) by

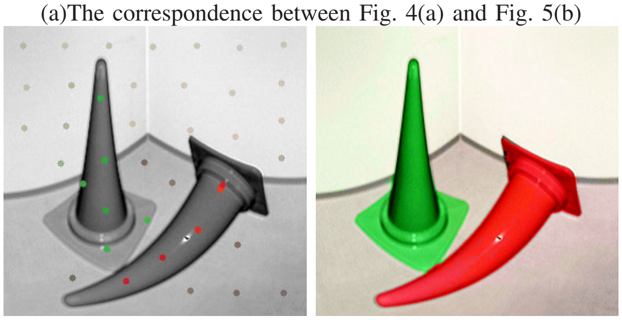


(a)Seed points assigned manually. (b)Colorization result

Fig. 6: Proposed method 1 in scene 1 (manual)

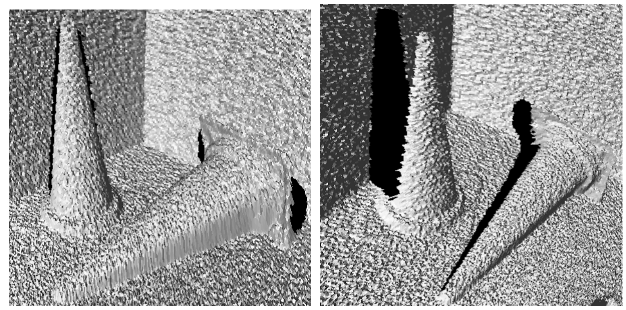


(a)The correspondence between Fig. 4(a) and Fig. 5(b)

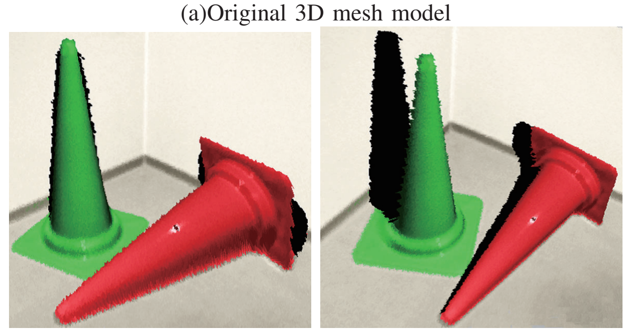


(b)Seed points assigned automatically. (c)Colorization result

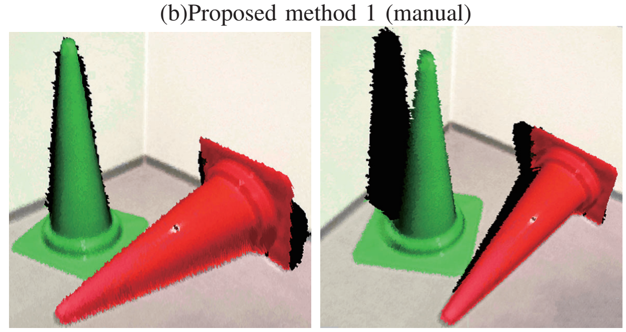
Fig. 7: Proposed method 2 in scene 1 (automatic)



(a)Original 3D mesh model



(b)Proposed method 1 (manual)



(c)Proposed method 2 (automatic)

Fig. 8: Colorized 3D geometric model in scene 1

hand. In the experiments, the range and reflectance images are normalized from 0 to 255, and the parameters are set as $\alpha = 6$ and $\beta = 1.0$.

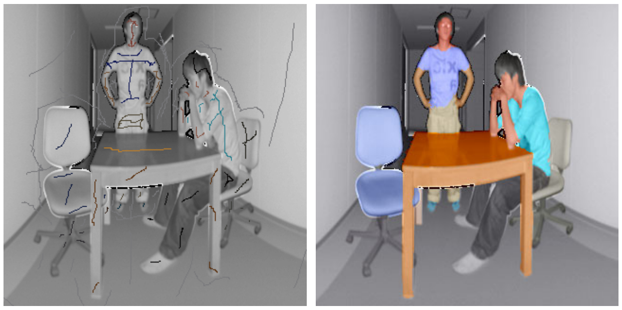
Fig. 4 shows three experimental conditions: a simple environment with two road cones of different colors (scene 1), a complex environment with a human and other objects (a table and chairs) (scene 2), and a house made of red bricks (scene 3). Fig. 5 shows the range and reflectance images of these scenes captured by the measurement robot.

First, we assigned seed points to the reflectance images in Fig. 5(b) manually (Fig. 6) and automatically (Fig. 7). Fig. 6(a) and Fig. 7(b) show the seed points in the reflectance image in both methods. Colorized reflectance images are shown in Fig. 6(b) and Fig. 7(c), respectively. Fig. 8(a) is the 3D mesh model constructed from the range image shown in Fig. 5(a). Fig. 8(b) and Fig. 8(c) show the 3D mesh model colorized by the method 1 (manual) and the method 2 (automatic), respectively. It is clear that the proposed methods successfully add color information to the surface of the 3D geometric models without accurate pose estimation.

Next, we carried out the experiments using a reflectance image and a color image taken in scene 2 (Fig. 4(b)). Similar to the experiments in the scene 1, we assigned seed points manually (Fig. 9) or automatically (Fig. 10). Fig. 9(a) and Fig. 10(b) show assigned seed points in both methods. Colorized reflectance images are shown in Fig. 9(b) and Fig. 10(c), respectively. The colorized 3D model for scene 2 is shown in Fig. 11. Fig. 11(a), (b), and (c) are the 3D mesh model constructed from the range image (Fig. 5(c)), the 3D mesh model colorized by the method 1 (manual) , and the one colorized by the method 2 (automatic), respectively. From these results, we verified that the proposed methods are capable of creating colorized 3D geometric models in more complex scene.

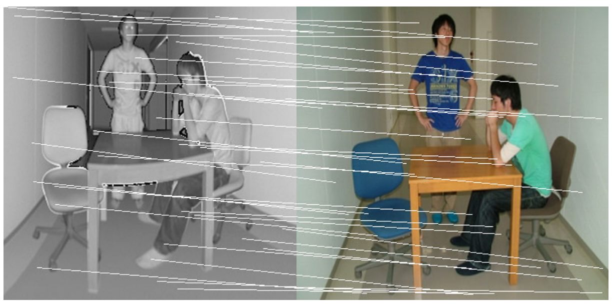
Finally, we carried out experiments in scene 3 (Fig. 4(c)). In this experiment, we colorized an entire 3D geometric model of a house made of red bricks with a partial view of the house shown in Fig. 4(c). The entire 3D geometric model is created from four range and reflectance images shown in Fig. 5(e) and Fig. 5(f). Fig. 12 shows colorized reflectance images using the method 1 manually, and the method 2 automatically.

The colorization results of the 3D geometric model (Fig. 13(a)) in scene 3 are shown in Fig. 13(b) and (c). In addition, we show the colored model using three color images by

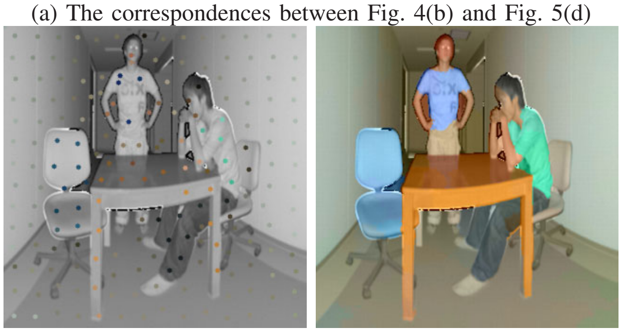


(a) Seed points assigned manually. (b) Colorization result

Fig. 9: Proposed method 1 in scene 2 (manual)



(a) The correspondences between Fig. 4(b) and Fig. 5(d)



(b) Seed points given automatically. (c)Colorization result

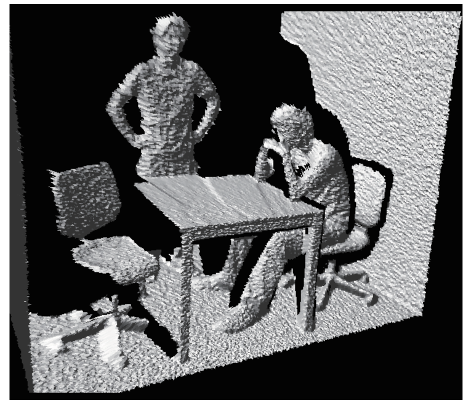
Fig. 10: Proposed method 2 in scene 2 (automatic)

the proposed method 2 in Fig. 13(d). You can see that the colored regions increase by using several color images taken from different viewpoints. Consequently, we successfully colorized the entire geometric model using a partial view of the target house.

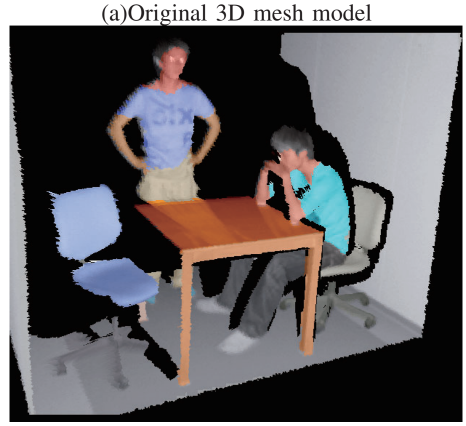
V. Conclusion

In this paper, we proposed a new colorization technique for a 3D geometric model acquired by a laser scanner utilizing laser reflectivity. The proposed technique is able to add color information on the surface of the 3D geometric model by colorizing the reflectance image manually or automatically. The automatic colorization is easy but needs enough correspondence between reflectance and color images. On the other hand, the manual colorization gives a colored model even if the correspondence is slight between these images.

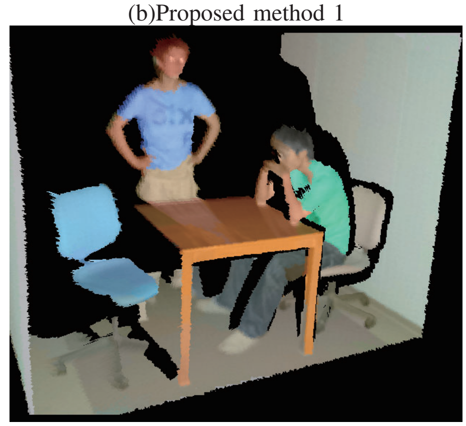
Precise calibration between color and range images, which is indispensable for the conventional texture mapping, is not required. Thus a gap or discontinuity in appearance can be avoided even if several images must be registered on a model. Moreover, the appearance of the entire surface of a model



(a)Original 3D mesh model



(b)Proposed method 1



(c)Proposed method 2

Fig. 11: Colorized 3D geometric model in scene 2

can be assigned from a partial view of the model if the appearance does not change significantly in the entire model.

The reflectance image is not affected by the lighting conditions and thus can be acquired in day and night. Therefore, even if a clear color image is not available due to bad light conditions, it is possible to colorize 3D geometric models utilizing color images from websites such as Flickr.

In the future, we will perform quantitative evaluation of the proposed technique for a variety of scenes, and extend the technique to super-resolution of reflectance images for realizing more realistic appearance.

ACKNOWLEDGMENT

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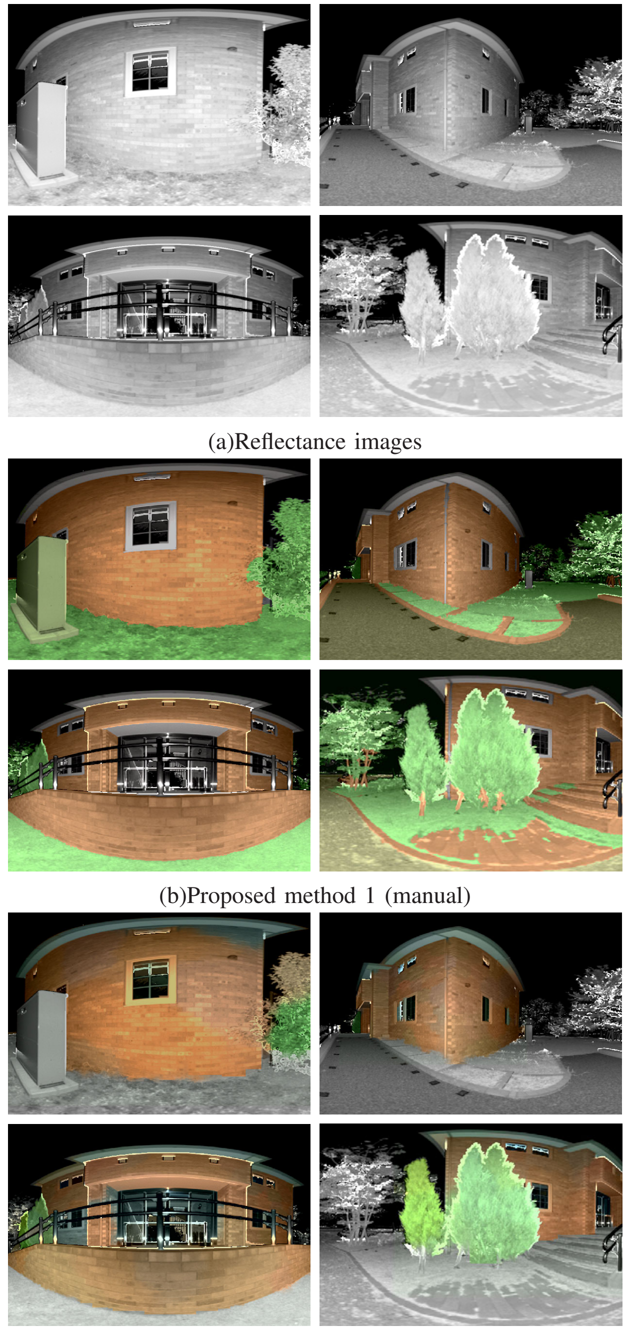

(a)Reflectance images

(b)Proposed method 1 (manual)

(c)Proposed method 2 (automatic)

Fig. 12: Colorization of reflectance images from an only single picture

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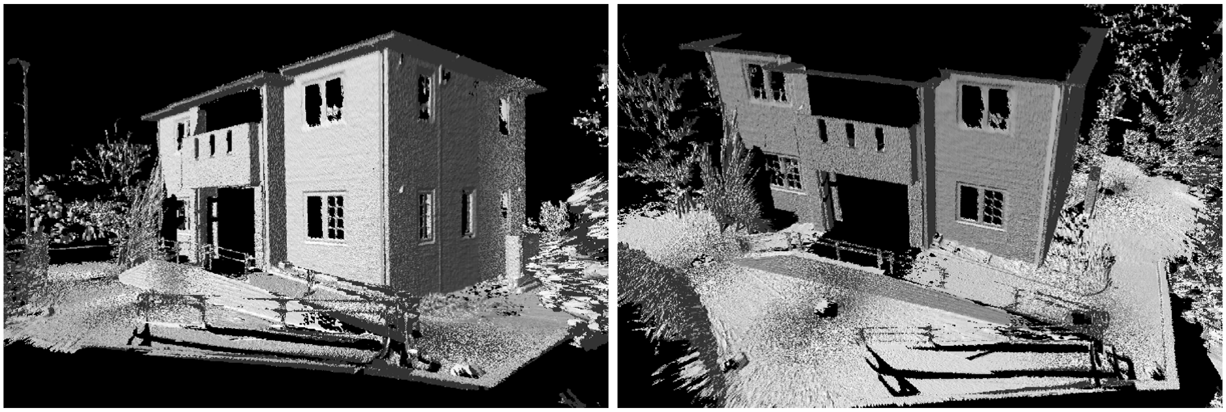
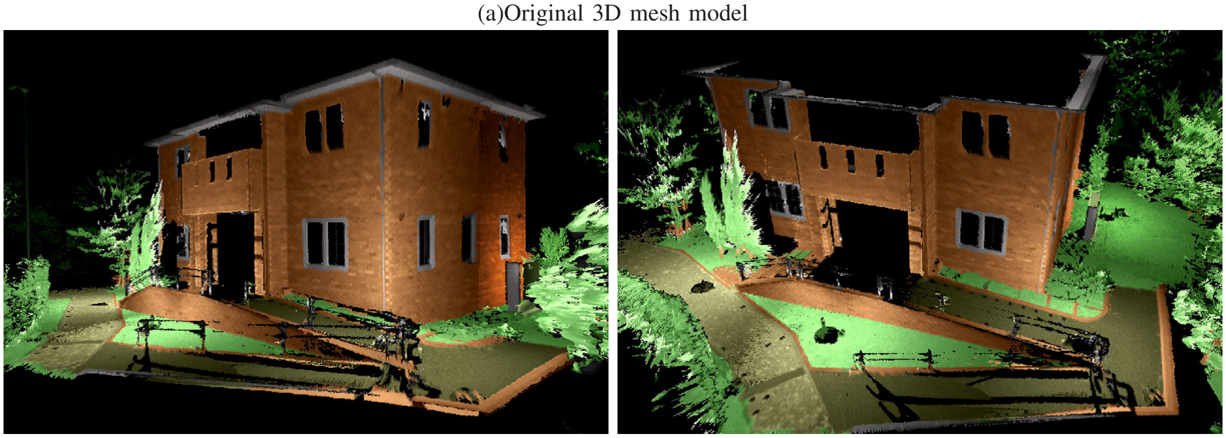
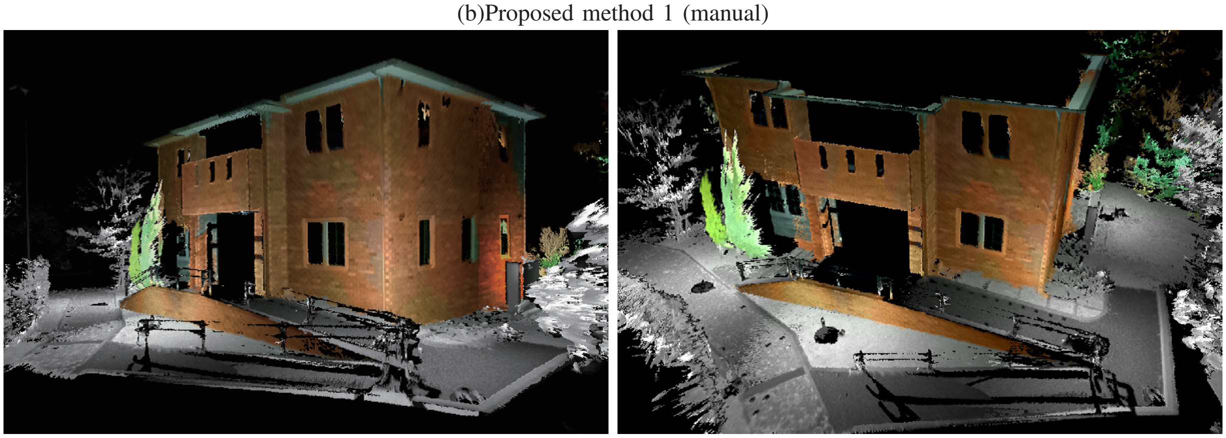


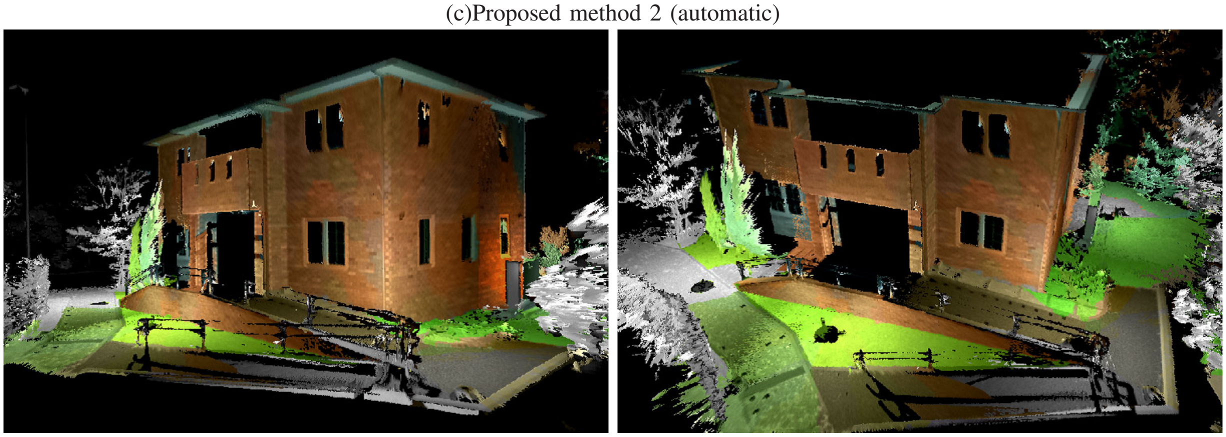
(a)Original 3D mesh model



(b)Proposed method 1 (manual)



(c)Proposed method 2 (automatic)



(d)Proposed method 2 using three pictures taken from difference viewpoints

Fig. 13: Colorization of the entire 3D geometric model