Recovering 3D Structure of Multilayer Transparent Objects from Multi-view Ray Tracing

Atsunori Maeda, Fumihiko Sakaue and Jun Sato
Department of Computer Science and Engineering, Nagoya Institute of Technology,
Gokiso, Showa, 466-8555, Nagoya, Japan
maeda@cv.nitech.ac.jp, {sakaue, junsato}@nitech.ac.jp

Keywords: Transparent Objects, Ray Tracing, Multilayer, 3D Reconstruction.

Abstract: 3D reconstruction of object shape is one of the most important problems in the field of computer vision. Although many methods have been proposed up to now, the 3D reconstruction of transparent objects is still a very difficult unsolved problem. In particular, if the transparent objects have multiple layers with different refraction properties, the recovery of the 3D structure of transparent objects is quite difficult. In this paper, we propose a method for recovering the 3D structure of multilayer transparent objects. For this objective we introduce a new representation of 3D space by using a boxel with refraction properties, and recovering the refraction properties of each boxel by using the ray tracing. The efficiency of the proposed method is shown by some preliminary experiments.

1 INTRODUCTION

3D reconstruction of object shape is very important topic in computer vision, and vast amount of methods have been proposed up to now. Although the 3D shape of ordinary objects can be recovered accurately by the state of the art methods (Agarwal et al., 2009; Heinly et al., 2015), the reconstruction of transparent objects is still a difficult problem. In particular, the recovery of 3D structures of multilayer transparent objects is quite difficult and is still an unsolved problem.

The ray tracing technique is often used for recovering transparent objects (Wetzstein et al., 2011; Shan et al., 2012; Qian et al., 2016). The light rays are refracted at the boundary of two matters, whose refraction coefficients are different from each other. As a result, the images observed through transparent objects are distorted. Since the image distortions depend on the 3D structure of transparent objects, we can obtain useful information on the 3D structure of transparent objects from the image distortions.

Many methods have been proposed for reconstructing transparent objects by using their refractive properties. However, most of the methods assume that the refraction of light rays occur just once before observing the light rays (Shan et al., 2012; Wetzstein et al., 2011; Ding et al., 2011; Miyazaki and Ikeuchi, 2007; Tsai et al., 2015). Recently Qian et al. (Qian et al., 2016) proposed a method for recovering more complex 3D structures of transparent object by using the ray tracing method. However, the number of refractions is limited to two, and if the transparent object has multiple layers, their method cannot be applied.

In this paper, we propose a method for recovering 3D structure of multilayer objects, where the number of light ray refractions can be arbitrary. For recovering multilayer structures of transparent objects, we introduce a novel method for representing the refraction properties of the 3D space. In our method, we consider that the 3D space consists of a set of boxels, and each boxel has a refraction coefficient as shown in Fig. 1. Furthermore, each boundary of two adjacent boxels has a surface normal. If two adjacent boxels have different refraction coefficients, the light ray is refracted at the boundary of these two boxels according to their refraction coefficients and the surface normal. Thus, we in this paper estimate the refraction coefficient of each boxel and the surface normal of each boundary in the boxel space. By obtaining the refraction coefficients of all the boxels in the boxel space, we can recover the whole 3D structure of the transparent objects, since the boundaries of refraction coefficients can be considered as the boundaries of transparent objects as shown in Fig. 1.

Maeda A., Sakaue F. and Sato J.
Recovering 3D Structure of Multilayer Transparent Objects from Multi-view Ray Tracing.
DOI: 10.5220/0006265905230527
In *Proceedings of the 12th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2017)*, pages 523-527
ISBN: 978-989-758-227-1

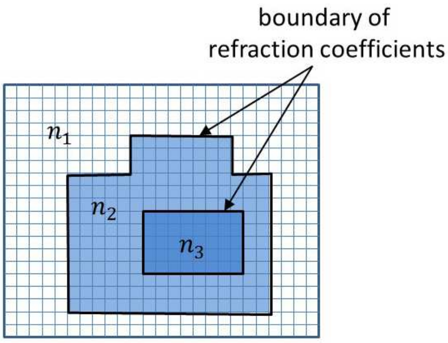


Figure 1: Boxel space and the boundary of transparent objects. All the boxels in the boxel space have their own refraction coefficients, such as n_1, n_2 and n_3. The boundaries of these refraction coefficients can be considered as the boundaries of transparent objects.

2 BOXEL SPACE FOR TRANSPARENT OBJECTS

For recovering multilayer transparent objects, we in this paper consider a boxel space with transparent coefficients and surface normals. Each boxel in the boxel space has a refraction coefficient n, and each boundary of a pair of adjacent boxels has a surface normal $\mathbf{N}$.

Suppose we have a 3D boxel space, which consists of N boxels b_i $(i = 1, \cdots, N)$. Since each boxel is a cube, there exist boundaries in X, Y and Z directions at each boxel. The total number of boundaries is denoted by M. Let n_i be a refraction coefficient of boxel b_i, and Let $\mathbf{N}_{ij}$ be a surface normal at the boundary of two boxels, b_i and b_j.

If we have a set of boxels which have homogeneous refraction coefficients and are connecting to each other, the set of boxels can be considered as a single transparent object, and the boundary of two homogeneous sets of boxels can be considered as the boundary of two transparent objects.

Even if we have a multilayer transparent object, it can be represented by a multilayer structure of homogeneous refraction coefficients in the boxel space. Thus, this new representation of transparent objects is very useful for representing complex multilayer structures of transparent objects.

3 REFRACTION OF LIGHT RAYS IN THE BOXELS SPACE

We next consider refraction of light rays in the boxel space. Since the boxel space is the quantization of a 3D space, the refraction of light rays in the boxel space is also quantized according to the boxel.

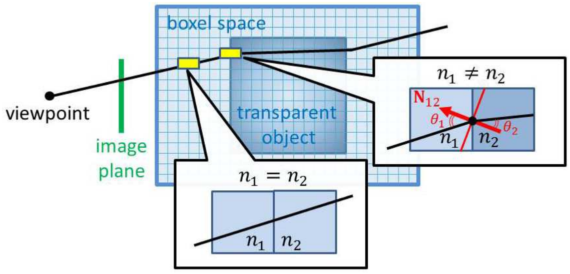


Figure 2: Refraction of light ray in the boxel space.

Suppose a light ray comes into a boxel b_2 from a boxel b_1 as shown in Fig. 2. If the refraction coefficients of these two boxels are identical to each other, i.e. $n_1 = n_2$, then the light ray is not refracted at the boundary of these two boxels.

However, if n_1 and n_2 are different from each other, i.e. $n_1 \neq n_2$, the light ray is refracted at the boundary of these two boxels according to the refraction coefficients, n_1 and n_2, and the surface normal $\mathbf{N}_{12}$ as shown in Fig. 2.

This refraction can be described by the Snell's law as follows:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

where, θ_1 and θ_2 denote angles between the surface normal $\mathbf{N}_{12}$ and light rays before and after the refraction.

Since these light rays and the surface normal are coplanar in the 3D space, Eq.(1) can be rewritten as follows:

$$n_1(\mathbf{V}_1 \times \mathbf{N}_{12}) = n_2(\mathbf{V}_2 \times \mathbf{N}_{12}) \tag{2}$$

where, $\mathbf{V}_1$ and $\mathbf{V}_2$ denote unit vectors, which represent the direction of light rays before and after the refraction respectively.

In this research we consider Eq.(2) at all the boundary of boxels in the boxel space. Hence, all the boxels have possibilities to refract light rays depending on the difference of refraction coefficients with adjacent boxels. In the next section, we describe a method for estimating the refraction coefficient and the surface normal of these boxels.

4 ESTIMATING REFRACTION COEFFICIENT AND SURFACE NORMAL OF BOXELS

We next consider a method for estimating the refraction coefficient of each boxel and the surface normal at each boundary in the boxel space. Our method is

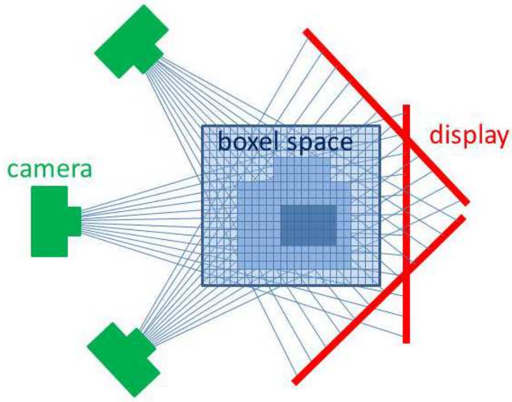


Figure 3: Multiple observations of the boxel space.

based on the rendering of hypothetic images and their comparison with real observations.

The image D is shown by a display and is observed by a camera through the transparent objects in the boxel space. The image intensity of ith pixel of the observed image I is denoted by I_i. Now, we render a hypothetic image $R(\mathbf{n},\mathbf{S})$ from the display image D based on the estimated refraction coefficients $\mathbf{n} = [n_1,\cdots,n_N]$ and surface normals $\mathbf{S} = [\mathbf{N}_1,\cdots,\mathbf{N}_M]$, where $\mathbf{N}_j$ denotes the jth surface normal. We use the ray tracing method for rendering images. The image intensity of ith pixel of the rendered image $R(\mathbf{n},\mathbf{S})$ is denoted by $R_i(\mathbf{n},\mathbf{S})$. Then, we can define the following cost function E_1 for evaluating the accuracy of rendered images.

$$E_1 = \sum_{i=1}^{P}(R_i(\mathbf{n},\mathbf{S}) - I_i)^2 \quad (3)$$

where, P is the number of image pixels. If the estimated refraction coefficients $\mathbf{n}$ and the surface normals $\mathbf{S}$ are correct, the cost function E_1 is equal to zero except the quantization error of boxel space. Thus, by estimating $\mathbf{n}$ and $\mathbf{S}$ which minimize E_1, we can obtain the refraction coefficients and the surface normals of the boxel space.

For obtaining the coefficients and normals of all the boxels from Eq.(3), we need at least $N+2M$ measurements, since we have N coefficients and M normals with 2 DOF. Thus the following inequality must hold:

$$P \geq N + 2M \quad (4)$$

However, $N+2M$ is quite large in general, and it is not easy to satisfy Eq.(4) just from a single image observation. Furthermore, the light rays observed at a single viewpoint do not pass all the boxels in general, while the light rays must pass all the boxels for estimating the coefficients of all boxels. Thus, we observe the boxel space from several different viewpoints.

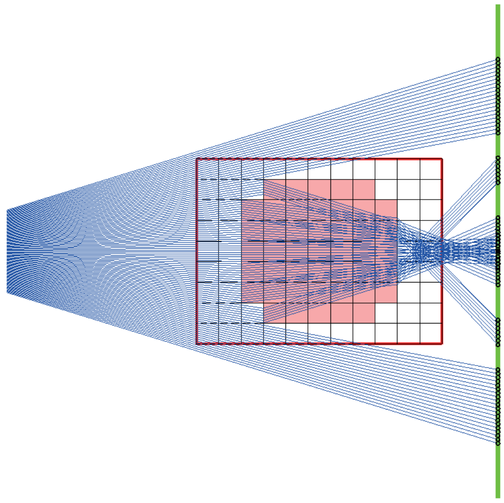


Figure 4: Our experimental set up. A single transparent object exists in a 11×9 boxel space. The light rays are refracted at the boundary of boxels according to refraction coefficients n_i and surface normals $\mathbf{N}_j$.

To make the observation more efficient, we rotate the boxel space, i.e. transparent object, which is put between the display and the camera, or rotate the display with a camera around the boxel space as shown in Fig. 3. By rotating the boxel space relative to the camera, and observing the boxel space from V different viewpoints, we can define the following cost function:

$$E_2 = \sum_{k=1}^{V}\sum_{i=1}^{P}(R_i^k(\mathbf{n},\mathbf{S}) - I_i^k)^2 \quad (5)$$

where, R_i^k denotes the image intensity of ith pixel of the rendered image at kth viewpoint, and I_i^k denotes the image intensity of ith pixel of the observed image at kth viewpoint. By estimating $\mathbf{n}$ and $\mathbf{S}$ which minimize E_2, we can obtain the refraction coefficients and the surface normals of all the boxels in the boxel space.

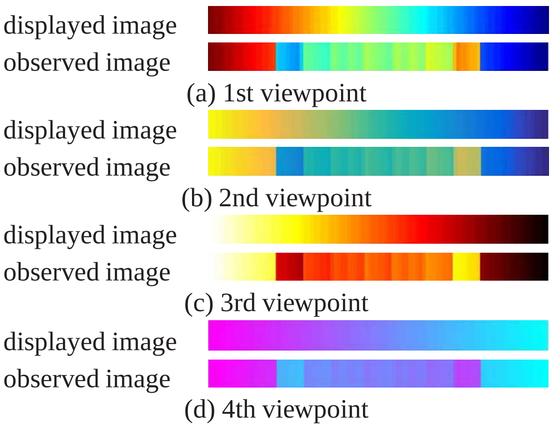
In this case, the coefficients and normals of all the boxels can be estimated, if the following inequality holds:

$$PV \geq N + 2M \quad (6)$$

For raising the stability of estimation, we also introduce a regularization term on the smoothness of object shape as follows:

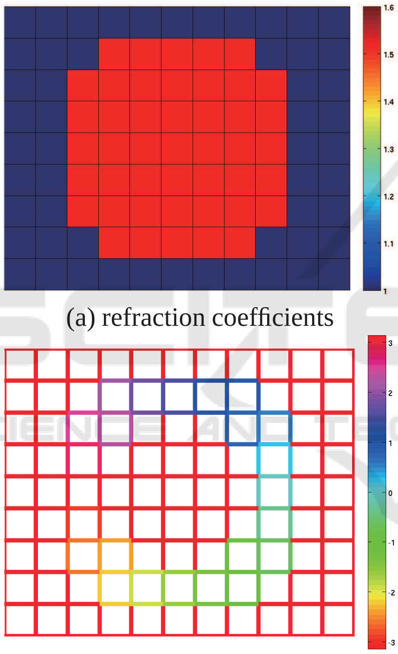
$$E_3 = \sum_{k=1}^{V}\sum_{i=1}^{P}(R_i^k(\mathbf{n},\mathbf{S}) - I_i^k)^2 + \lambda \sum_{j=1}^{M}|\Delta\mathbf{N}_j|_2 \quad (7)$$

where, $\Delta\mathbf{N}_j$ denotes the variation of $\mathbf{N}_j$ in X, Y and Z directions in the boxel space, and $|\cdot|_2$ denotes an L_2 norm. In the end, we estimate $\mathbf{n}$ and $\mathbf{S}$ which minimize E_3.



(a) 1st viewpoint (b) 2nd viewpoint (c) 3rd viewpoint (d) 4th viewpoint

Figure 5: Displayed images and observed images through a transparent object at 4 different viewpoints.



(a) refraction coefficients

(b) surface normals

Figure 6: The refraction coefficients and surface normals estimated from the proposed method. The color bars on the right show the measures of refraction coefficients and surface normals. The unit of the surface normals is radian.

Since the proposed method enables us to estimate all the refraction coefficients in the 3D space, complex transparent objects with multiple layers can be reconstructed.

5 EXPERIMENTS

We next show the efficiency of the proposed method from synthetic image experiments. In this experiment, we synthesized camera images of multilayer

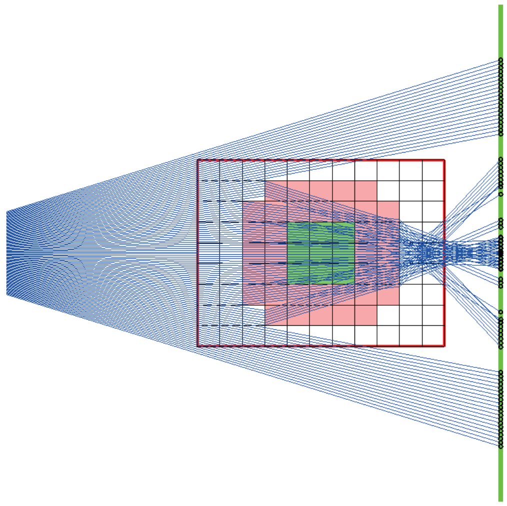
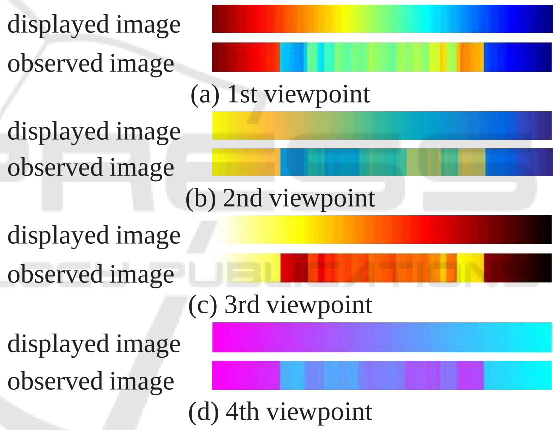


Figure 7: Our experimental set up. Multilayer transparent objects exist in a 11×9 boxel space. The light rays are refracted at the boundary of boxels according to refraction coefficients n_i and surface normals $\mathbf{N}_j$.

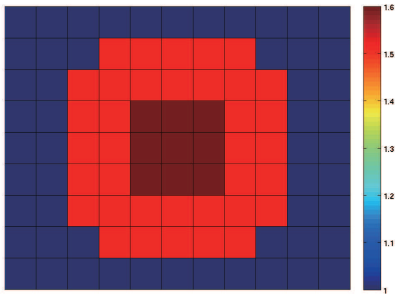


(a) 1st viewpoint (b) 2nd viewpoint (c) 3rd viewpoint (d) 4th viewpoint

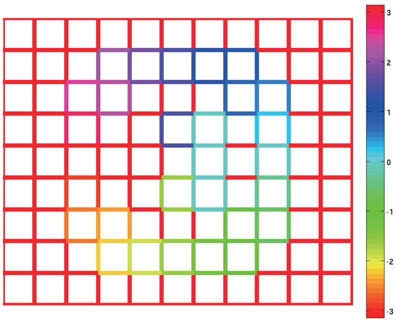
Figure 8: Displayed images and observed images through a transparent object at 4 different viewpoints.

transparent objects as well as a single transparent object viewed from several different viewpoints, and used these images for recovering the structure of the transparent objects by using the proposed method. For simplifying our experiments, we in this paper consider a 2D space, and project the 2D space into a 1D camera.

Fig. 4 shows our experimental setup, in which a transparent disk exists in a 11×9 boxel space. The 1D image on a display is observed through the transparent disk by a 1D camera with 100 pixels. The object is rotated and observed from 4 different viewpoints. The displayed image and an observed image are shown in Fig. 5. The refraction coefficients and the surface normal of the boxel space are computed from these observed images by using the proposed method. The



(a) refraction coefficients



(b) surface normals

Figure 9: The refraction coefficients and surface normals estimated from the proposed method. The color bars on the right show the measures of refraction coefficients and surface normals. The unit of the surface normals is radian.

estimated refraction coefficients and the surface normals of all the boxels are shown in Fig. 6. As shown in this figure, the boundary of the refraction coefficients in the boxel space coincide with the original shape of the transparent object shown in Fig. 4, and we find that the structure of the transparent object can be recovered by using the proposed method.

We next show the results from multilayer transparent objects shown in Fig. 7. The observed images are shown in Fig. 8, and the refraction coefficients and surface normals recovered from the proposed method is shown in Fig. 9. As shown in Fig. 9, the estimated refraction coefficients represent the complex structure of the original multilayer transparent object shown in Fig. 7.

Although the experimental results are still limited, they show that the proposed method can recover complex multilayer structure of transparent objects.

6 CONCLUSION

In this paper, we proposed a method for recovering the 3D structure of multilayer transparent objects. For this objective we introduced a new representation of 3D space by using boxel space with refraction properties and surface normals. Based on the new representation of 3D space, we proposed a method for recovering the refraction properties and surface normals of all the boxels in the boxel space. The efficiency of the proposed method was shown by some preliminary experiments.

REFERENCES

Agarwal, S., Snavely, N., Simon, I., Seitz, S., and Szeliski, R. (2009). Building rome in a day. In *Proc. ICCV*.

Ding, Y., Li, F., Ji, Y., and Yu, J. (2011). Dynamic fluid surface acquisition using a camera array. In *Proc. ICCV*.

Heinly, J., Schonberger, J., Dunn, E., and Frahm, J. (2015). Reconstructing the world in six days. In *Proc. Conference on Computer Vision and Pattern Recognition*, pages 3287–3295.

Miyazaki, D. and Ikeuchi, K. (2007). Shape estimation of transparent objects by using inverse polarization ray tracing. *Trans. PAMI*, pages 2018?–2030.

Qian, Y., Gong, G., and Yang, Y. (2016). 3d reconstruction of transparent objects with position-normal consistency. In *Proc. Conference on Computer Vision and Pattern Recognition*.

Shan, Q., Agarwal, S., and Curless, B. (2012). Refractive height fields from single and multiple images. In *Proc. Conference on Computer Vision and Pattern Recognition*.

Tsai, C., Veeraraghavan, A., and Sankaranarayanan, A. (2015). What does a light ray reveal about a transparent object? In *Proc. ICIP*.

Wetzstein, G., Roodnick, D., Heidrich, W., and Raskar, R. (2011). Refractive shape from light field distortion. In *Proc. ICCV*.