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Light Transport Refocusing for Unknown Scattering Medium

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***Abstract*—In this paper we propose a new *light transport refocusing* method for depth estimation as well as for investigation inside scattering media with unknown scattering properties. Propagated visible light rays through scattering media are utilized in our proposed refocusing method. We use 2D light source to illuminate the scattering media and 2D image sensor for capturing transported rays. The proposed method that uses 4D light transport can clearly visualize shallow depth, as well as deep depth plane of the medium. We apply our *light transport refocusing* method for depth estimation using conventional depth-from-focus method and for clear visualization by descattering the light rays passing through the medium. To evaluate the effectiveness we have done experiments using acrylic and milk-water type scattering medium in various optical and geometrical conditions. Finally, we show up the results of depth estimation and clear visualization, as well as with numeric evaluation.**

I. Introduction

Conventional cameras with lens system can capture an image by focusing at a depth of scene. Since a lens of camera can accumulate rays coming from a point on a focal plane to a pixel, it can focus at plane of interest clearly on the captured image while defocus the other planes. However, to change the focal plane it needs to adjust the lens system again before capturing image. Recently a smart capturing device called light field camera which is actually an array of tiny cameras has become commercially available. This type of camera has an advantage of refocusing after taking an image by a single shot. The light field camera can capture 4D light field [1] and it possesses each ray information individually coming from different scene points. Image focusing at arbitrary depth plane can be produced from the light field by selecting rays passing through each point of focal plane. This type of selecting arbitrary focal plane and imaging of it is quite resembles to the imaging with conventional camera using lens system. We call this popular technique *light field refocusing*.

However, this type of 4D light field (4D LF) refocusing method does not consider light attenuation and scattering in media. Hence, although the 4D LF refocusing works well in the case of transparent or open air media, it's refocusing approach does not provide clear visualization in case of scattering media, especially deep inside such medium. The reason of this unclear visualization is rays inside scattering media experience several scattering effects by striking several points and mix up with each other, and as a result the ray information in a 4D LF disrupts completely. Therefore, *light field refocusing* is not suitable for visualization inside scattering medium.

To visualize inside scattering media many researchers have proposed various techniques in broad research fields. In medical imaging or in microscopy, there are several techniques developed for better visualization. In microscopy, confocal imaging is well-known technique where only the target depth is illuminated and focused. In computer vision, an angular filtering technique has been proposed [2], where a direct ray from light sources is selected and acquired. Also, another technique using polarizers has been proposed in [3], this polarization is utilized to remove scattering lights. Although these techniques can produce clear image by descattering, but focusing is not considered as useful for some application like artistic photography and investigation at particular depth of interest.

In this paper we propose a new refocusing technique using four dimensional light transport (4D LT) called *light transport refocusing*. The light transport represents information about the light propagation through a scene consisting of several regions with distinct optical densities. As this type of 4D LT contains information about both light origin and observed points, selection of the rays coming from a desired direction in the media can be easily obtained which resembles getting ray information in *light field refocusing*. In this paper, we describe the details of the 4D LT for refocusing and the advantages of this method over *light field refocusing*. Finally, several experimental results show the refocused images and applicability of the proposed method for depth estimation.

II. Related Work

A. Light Field Photography

The 4D LF measuring allows to estimate amount of light traveling along each ray that intersects the sensor. Obviously such 4D LF contains more details about the scene. At first Levoy *et al.* [1] used moving camera to capture the light field and it is a time-consuming process. The other method proposed by Wilburn *et al.* [4] is to use a large camera array. Both methods require huge equipments and can only work in a particular environment. Some hand held light field acquisition cameras later presented in [5]–[9]. In [5], a microlens array is inserted in front of the sensors. Each microlens samples the radiance at the position. In [6], a programmable aperture with an electronically controlled liquid crystal array is designed. The coded apertures are used in a time-multiplexed post-processing technique of light field. In [7] a technique of using cosine mask is proposed, in which, the results are computed in frequency domain instead. Moreno-Noguer *et al.* [8] calculated

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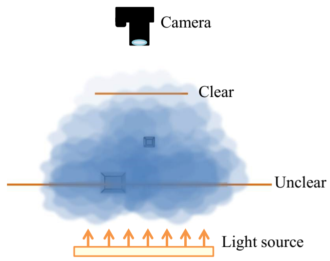


Fig. 1: Imaging of scattering media. Image becomes more clear at shallow depth than deep depth.

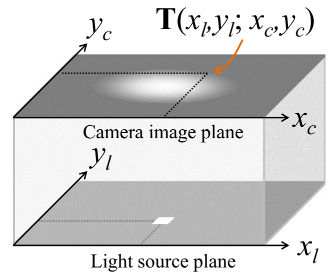


Fig. 2: Transmissive light transport measuring framework. The scattering medium is illuminated from bottom and transmitted rays are captured from top. 2D light source position and 2D captured image pixel position represent a ray.

depth of focus based on the defocus of a sparse set of dots projected onto the scene. Levin *et al.* [9] placed a patterned mask within the aperture of the camera lens. However, the above discussed methods has similarity with our proposed *light transport refocusing* method.

B. Light Transport Sensing

Light transport represents how light rays propagate in a scene. Such light propagation in scattering media like biological tissue, has been described through various theories, the transport theory is usually applied to describe transport of energy through a medium containing scattering particles. The transport theory can be modeled through stochastic methods, such as Monte Carlo sampling, and deterministic methods which are based on describing particles transport with partial differential equations [10]. An 8D entity that abstracts light transport through a scene in terms of incident and outgoing illumination, but capturing and handling these 8D fields is difficult. Therefore, most methods consider a reduced approximation and this approximation was proposed by Debevec *et al.* [11]. The reduced reflectance field is then sampled using a Light Stage. A light source is moved to a finite number of positions (2D) around the subject, and many images are captured. Each image represents a 2D slice of the 4D reflectance field. For our refocusing method we also use similar setup to capture 4D LT through scattering scene.

C. Depth Estimation

Diffuse Optical Tomography (DOT) [12]–[15] is a promising technique to map molecular contrast, encoded into an optical variation, throughout a biological organism. These DOT implementations have advantages of non-invasive, non-ionizing and highly selective. However low spatial resolution is its main drawback due to the strong multiple scattering with in scattering media. However, in computer vision field high dimensional information about scenes can help estimate the depth of objects in the scenes. Adelson *et al.* used a lenslet array to acquire a 4D light field as a single image [16] and showed depths estimated by depth-from-focus method. Later modified version of this method was proposed by Ng *et al.* [5]. These type of refocusing methods can give better focusing result only for shallow depth of focus (DOF) compared to the deep DOF in case of scattering media.

However, in our proposed *light transport refocusing*, we can focus at several depth planes in scattering media and by comparing the contrast of each plane, we can estimate the depths. Beside that, according to dual photography theory [17] our method also produces clear images at deeper DOF.

III. Light Transport Refocusing

A. Problem Setting and Our Objectives

Suppose there is an unknown scattering medium and also there are some obstacles inside it as shown in Fig. 1. According to this set up where camera and light source are placed in opposite side of the medium, when we capture transmissive light image of the scene, the image becomes blurred due to various type of scattering effects inside the medium. Although shallow depth of such medium gives little bit clear visibility, deep depth parts get almost invisible depending on the optical density of the medium. However, this type of blurred image gives neither clear visibility nor positional information of obstacles inside such medium.

Focusing at any depth inside unknown scattering can gives details information about that depth. Our primary goal is to imaging inside scattering medium by refocusing at several arbitrary depth planes by utilizing light transport through the medium. This type of refocusing can give clear visibility by selecting the direct light rays which can be done if the DOF is extended enough. However, refocusing approach inside medium can also produce focal stack and from this focal stack we can estimate depth of obstacles inside unknown scattering medium by applying conventional depth-from-focus method.

B. Definition of Light Transport for Refocusing

Light transport describes the relationship between originated light at the source and observed light at the sensor end. Light rays passing through any media can be absorbed, reflected, refracted, and scattered, as well as those light rays can also interfere with each other depending on the medium properties. Light transport corresponding to particular media could be defined using several dimensions, but such light transport contains rich information about the medium through which it is propagated.

In this research we use 4D light transport $T(x_l, y_l; x_c, y_c)$ that represents the relationship between 2D light source plane (x_l, y_l) and 2D image plane (x_c, y_c) as shown in Fig. 2. When incident light illuminates scattering media at a point, the scattered light propagates inside the media and captured by

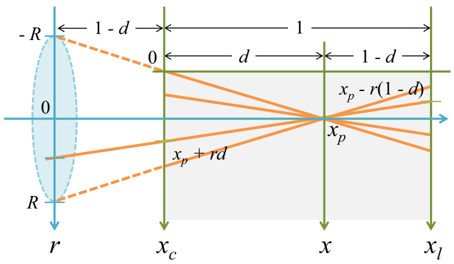


Fig. 3: Illustration of *light transport refocusing* technique. The new focal plane (x) depth is represented by ratio $1-d$ to entire thickness of medium (1).

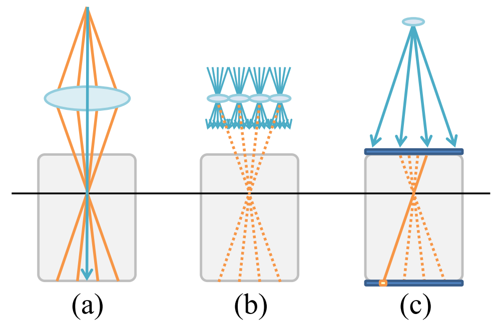


Fig. 4: Comparison of ray gathering methods among (a) single lens focusing, (b) light field refocusing, and (c) light transport refocusing. Blue rays represent viewing rays for camera pixels, yellow lines represent actually gathered rays for the viewing rays (blue), and the yellow dotted lines represent gathered rays for refocusing.

the camera. Hence, we can get rays passing through scattering media in one direction using two points (x_l, y_l) and (x_c, y_c) in $T(x_l, y_l; x_c, y_c)$. We capture light transport by sliding a point light source in x_l and y_l direction on 2D illuminating plane and simultaneously taking image by the camera on (x_c, y_c) image plane.

C. Expressions of Refocusing Method

Our *light transport refocusing* method is illustrated in Fig. 3. In this figure x_c and x_l denote camera line plane and light source line plane respectively and x denotes an arbitrary new focal line plane. Each pixel of this new focal plane is estimated by calculating the effect of rays passing through that pixel. In this figure the pixel x_p is constructed by some light rays passing through it, yellow lines are indicating those light rays. By the similar manner all pixels on the new focal plane can be constructed which resembles the light field refocusing that utilizes the directional and strength information of reflected light rays to calculate the corresponding pixels on new focal plane. As there are point to point correspondences between light origin and observed light in T, the pixels computation on new focal plane can be done by appropriate formulation.

In this *light transport refocusing*, some selected rays in light transport are summed up to create one pixel value of refocused image $I(x, y, d, R)$, where (x, y), d, and R denote pixel coordinate, relative depth of focal plane, and aperture size, respectively. Rays selection and integration is done by

$$I(x, y, d, R) = \iint_{-R}^{R} T(x - r_x(1-d), y - r_y(1-d); x + r_x d, y + r_y d)\, \mathrm{d}r_x \mathrm{d}r_y. \quad (1)$$

In refocusing technique, changing R that represents width of selected ray range, we can create defocusing effect like changing aperture size in conventional lens camera. In this way, we can also create all-in-focus images by setting small R value for calculating the pixels of image.

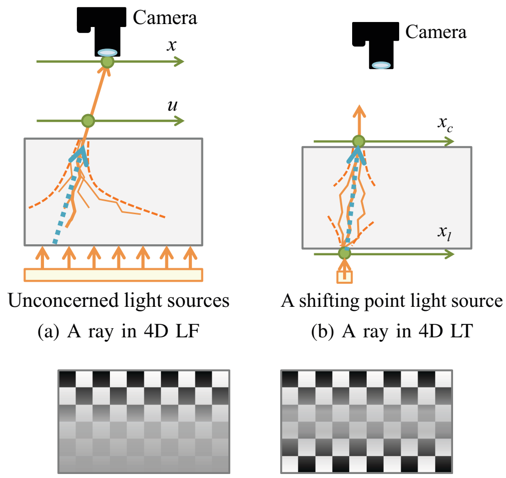
D. Advantages of Light Transport Refocusing

Generally, focusing effect, where in-focus objects are clearly observed and out-of-focus objects are blurry observed, is created by a lens system, because a lens gathers rays passing through a point in various directions as shown in Fig. 4 (a). To mimic this for refocusing, we need every directional ray information passing through the observed scene. As shown in Fig. 4, both the 4D LF in (b) and the 4D LT in (c) have such information. 4D LF directly has ray information that individually provide information of rays gathered by a lens. On the other hand, ray directions in 4D LT are defined by the observed and illuminating positions.

Although ray direction definition in 4D LT is different from that in a lens system or 4D LF, we can refocus at a given depth using 4D LT because 4D LT has 4D ray directional information as the same as 4D LF. In case of optically transparent media, both refocusing methods using 4D LF and 4D LT create similar refocused images, because the imaging rays dependent only on whether they are blocked by objects in the scene or not in both methods.

However, there are fundamental differences between rays in 4D LF and 4D LT if the target media are translucent. Although both of them have the same number of dimensions, but 4D LF does not consider the nature of light rays propagation in scatteing medium and considers only incoming directions from the medium, as shown in Fig. 5 (a). On the other hand, 4D LT has more information about light propagation in the medium, because light ray's origin and destination are used for defining the directions of rays as shown in Fig. 5 (b). Obviously, both methods can create a refocused image using scattered lights in the medium, but the scattered light paths in 4D LT (b) are almost along the given direction while that in 4D LF (a) diverge near the light source. Thus, it is possible to refocus inside scattering media with unknown scattering properties using 4D LT refocusing method by reducing the scattering effect and this method produces more clear image than the refocusing method that uses 4D LF.

The descattering effect also can be explained by Helmholtz reciprocity where the measured intensity does not change when the positions of light source and imaging device are exchanged. According to this theory, Sen et al. has proposed the dual photography [17], where the positions and dimensions of light source and imaging device can be exchanged. Obviously,



(a) A ray in 4D LF (b) A ray in 4D LT

(c) Certainty of being along the ray direction

Fig. 5: Fundamental difference between rays in 4D LF and 4D LT. A definition of rays in 4D LF (yellow) does not guarantee that path is along the viewing direction (blue), while that in 4D LT guarantees that the path is approximately along the defined direction.

object at shallow depth in scattering media is clearly visible and objects at deep depth disappear due to scattered light. So, exchangeability of light source and imaging device provides high clarity at deep depth objects in refocused image produced by 4D LT refocusing method as illustrated in Fig. 5 (c).

From the above discussion, our proposed *light transport refocusing* method is advantageous than refocusing method based on 4D LF for the reasons that descattering effect and dual photography effect make both side of the media clear.

IV. Experiments

This section describes experimental evaluations for representing the performance of proposed refocusing method, as well as it also demonstrates applicability of the proposed method to estimate the depth of obstacles (optically denser than medium) and clear visualization inside scattering medium.

A. Setup

We use an LCD as flat panel illumination to create sliding point light source and we placed target scattering media on the display. The point light source which is a bunch of some illuminated pixels slides in x and y directions along the bottom surface of target media. While the point light source slides in x, y directions to capture transmissive light transport, we mount a camera on top of the target media as shown in Fig. 6. The display is Logitec LCM-T102AS and the camera is PointGrey Grasshopper2 GS2-FW-14S5M.

B. Numerical Evaluation

For numeric evaluation we prepare a target object with unknown scattering properties, but known dimension. We also insert some obstacles inside this target object at some known depth levels. The target object consists of four translucent

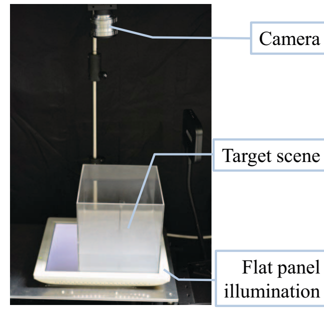


Fig. 6: Light transport measuring setup.

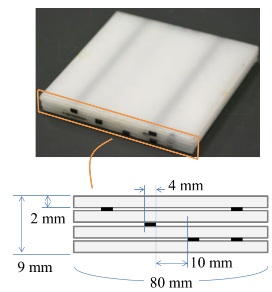
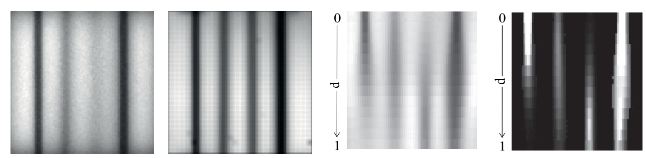


Fig. 7: Target object consists of four acrylic plates and five obstacles for numerical evaluation. Obstacles are inserted (from left most) in top level, middle level, bottom level, and both top & bottom levels.



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

Fig. 8: Experimental result of acrylic plates. (a) normal illumination image, (b) descattered image, (c) focal stack (d = 0 to 1), and (d) likelihood of depth map (d = 0 to 1).

acrylic plates each has thickness of 2mm and we put five stripe shaped obstacles at different places and levels in between the those scattering plates. We insert obstacles in bottom, middle, top level and we also insert other two obstacles in bottom and top level to create overlapped obstacles. The details of our target object is depicted in Fig. 7.

In this experiment the input light transport (T) resolution is $31 \times 31 \times 93 \times 93$. The normal illuminated image is showing in Fig. 8(a), where the far depth obstacle almost disappears, while the shallower depth obstacles is representing better contrast. However, the descattered image (Fig. 8(b)) produces by applying *light transport refocusing* method gives better visibility of obstacles at different depth levels compared to the normal illumination image (Fig. 8(a)). Also by applying our refocusing method at various depth levels focal stack is produced as shown in Fig. 8(c). To construct this focal stack we take some particular rows from each focus plane and stack

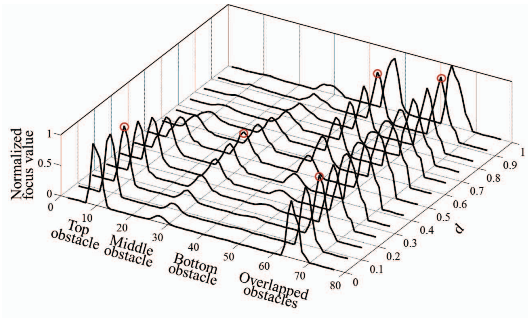


Fig. 9: Graphical representation of estimated depth of obstacles. Red circles indicating the obstacles position and corresponding depth axis showing their estimated depth.

TABLE I: Comparison of estimated depth with ground truth.

Obstacle's level	Top	Middle	Bottom	Top (overlapped)	Bottom (overlapped)
Estimated depth (d)	0.17	0.50	0.91	0.17	0.91
Ground truth	0.25	0.50	0.75	0.25	0.75
RMS error	0.08	0.00	0.16	0.08	0.16

them according to relative depth 0 to 1. Using wavelet based focus measuring method proposed by Yang *et al.* [18] on focal stack we estimate the depth of obstacles inside scattering medium and construct the likelihood of depth map (Fig. 8(d)). Here, the top surface of medium is considered as zero depth and depth increases toward bottom surface. The estimated depths of obstacles at various levels are presented by graph in Fig. 9. This graph for each obstacle is produced from focus measure value at each depth level. The estimated depths are evaluating by comparing with ground truth with error rates as shown in Table. I.

C. Robustness of Depth Estimation

To evaluate the robustness of our proposed *light transport refocusing* method against the variation of medium density, as well as the inhomogeneity we conduct three experiments with same tilted bar shaped obstacle and with the unchanged position and orientation. In those experiments we use milk-water solution as scattering medium with dimension 150 mm × 150 mm × 46 mm and milk concentration 0.25%, 0.35% and 0.5%. One end of the bar touches the top surface of medium and other end on bottom surface. As the medium is liquid, the density continuously and unevenly varies from place to place with time. This type of change is completely unknown. In this experiments the light transport (T) resolution is 36 × 36 × 118 × 118. The experimental results are shown in Fig. 10. The almost similar results for clear visualization and depth estimation in three media with different optical densities indicate the robustness of our proposed *light transport refocusing* method. However, the results slightly differ from medium to medium and the reason is sparse light point positioning in illuminating plane.

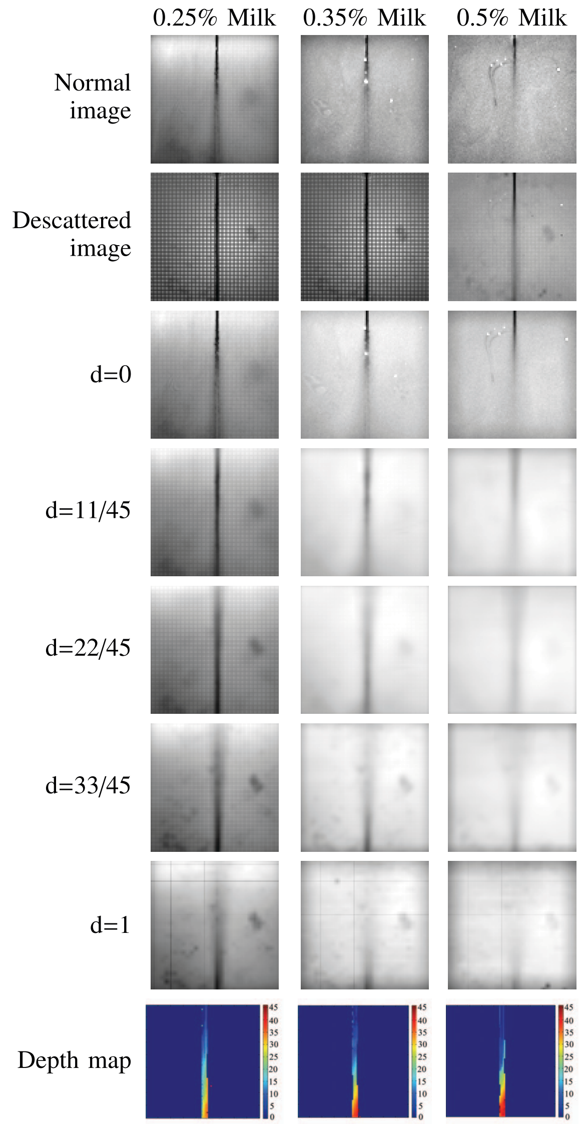


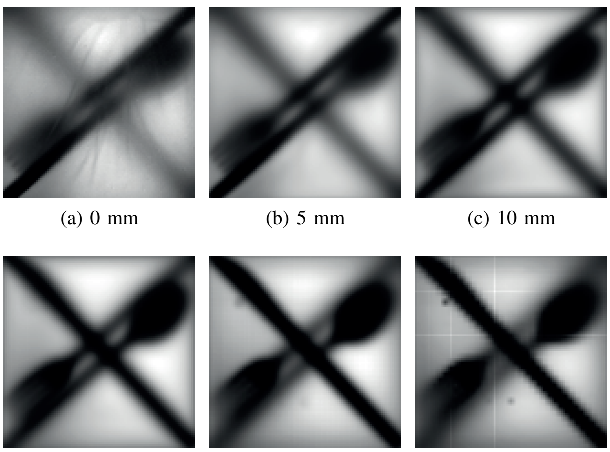
Fig. 10: Performance of *light transport refocusing* method when medium density is different.

D. Applying to Complex Scene

In this experiment we use some opaque household objects like knives, fork, and spoon in scattering media with dimension 150 mm × 150 mm × 24 mm. Here we use 1.4% milk-water solution as scattering media. By applying *light transport refocusing* method we produce descattered image for clear visualization and focal stack. The resolution of T is 36 × 36 × 118 × 118. Fig. 11 shows familiar target objects and medium in open air, in milk-water, and it also showing de-scattered image as a result of *light transport refocusing* method. In Fig. 12 some images of the focal stack are represented. Fig. 12 (a) is showing the image when the focus plane is the top surface of the medium. Gradually the focal plane going deeper and upper part of obstacles getting blurred. When the focal plane is at 24mm depth (Fig. 12 (f)) the knives becomes clearly visible

(a) (b) (c)

Fig. 11: Complex target medium and obstacles. (a) top view of target scene, (b) normal illumination image of scattering medium, and (c) de-scattered image produced by applying *light transport refocusing* method.



(a) 0 mm (b) 5 mm (c) 10 mm

(d) 15 mm (e) 20 mm (f) 24 mm

Fig. 12: Focal stack of a complex target scene.

because the knives is on the bottom surface of the scattering medium.

V. Conclusion

We have proposed the *light transport refocusing* method to exploit more strict ray paths in light transport than those in light field. That is why the main advantages of our method is, it works well for refocusing in unknown scattering medium. Our method has several applications in computer vision field such as measurement, investigation, better visualization etc. However, for depth estimation purpose we have used conventional wavelet based focus measuring method. In future we will develop suitable focus measuring method that will be perfectly compatible to our developed refocusing method for more accurate depth estimation and 3D rendering of scattering media. In this research we have discussed about the merits of our proposed method in comparison with traditional light field refocusing method. We have provided some experimental results in some possible conditions to evaluate our method. We also showed that our method is robust about the density of medium, as well as obstacles distribution inside it.

However, our method has some limitations. It takes longer time for light transport acquisition, though it depends on the light plane resolution. In our experiments the light plane resolution was smaller than the image plane resolution. If the light plane and image plane resolution become same, it will give the better result for refocusing and for clear visualization, but the time cost will be high.

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