Time-to-Contact in Scattering Media

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Abstract: In this paper, we propose a method for estimating time-to-contact in scattering media, such as fog. Images taken in the scattering media are unclear, and thus, we cannot detect appropriate geometric information from images for computing 3D information. In this paper, we consider not geometric information but photometric information such as observed intensity. In our method, we can eliminate the effect of scattering media and estimate the time-to-contact toward objects without any prior knowledge.

1 INTRODUCTION

Recently, computer vision techniques are widely used for video surveillance, object recognition and many other applications. In particular, 3D distance measurement is one of the most important problems in the field of computer vision.

When we measure 3D distance by using a stereo camera system, a set of image correspondences are required. In ordinary case, image features points are extracted by using feature point detectors, such as SIFT and SURF, and then 3D distance is estimated from the extracted points. Although the stereo method works well if we have proper images as shown in Fig.1 (a), it does not work well when the input images are unsuitable for feature point detection. For example, if there is fog or smoke in the input scene as shown in Fig.1 (b), the feature points may not be extracted sufficiently and accurately. This is because the light rays reflected from the object surface are scattered by micro particles as shown in Fig.5. In this case we cannot obtain original colors, feature points and much other visual information properly. These kinds of media, which scatter light rays such as fog and smoke, are called as scattering media.

In the scattering media, many existing compute vision techniques do not work well. In order to avoid this problem, many methods which eliminate the effect of scattering media are proposed (Schechner et al., 2001; Namer and Schechner, 2006; Kopf et al., 2008; Narasimhan and Nayar, 2003a; Narasimhan and Nayer, 2001; Narasimhan and Nayar, 2003b; Fattal, 2008; He et al., 2011; Tarel and Hautiere, 2009; Narasimhan et al., 2005). In these methods, the scattering media is considered as obstacles for observing proper images, and the effect of the scattering media is eliminated. One of the most popular techniques for eliminating the effect of scattered media is to control the light(Narasimhan et al., 2005). In this method, a controllable light source, such as projector is used for eliminating the effect of scattering media. By using the method, we can separate observed intensity into a direct component which does not include the effect of scattering media, and an indirect component which is generated by the scattering media. Although their method is useful, it requires a controllable light source, and thus it cannot be used in the ordinary light source environment.

In this paper, we propose a new approach to estimate the distance from a camera to an object in the scattering media. From the images taken in scattering media, we can obtain image intensity, even if image feature points cannot be extracted properly. Furthermore, the image intensity in scattering media changes according to the distance from the camera to the object because of the scatter of light. Thus the change in intensity is an important clue to obtain the 3D information. Thus, we in this paper consider a method for estimating time-to-contact toward objects from the change in image intensity obtained in scattering media.

The estimation of time-to-contact is a traditional technique, which estimates a time toward collision of a moving camera to an object. In the existing methods, the time-to-contact is estimated by using the change in size of geometric features, such as distance between two image points in consecutive images. In recent years, Watanabe et al. (Watanabe

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(a) Clear environment (b) Scattering media

Figure 1: Difference of observed images in clear environment and in scattering media.

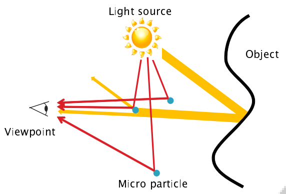


Figure 2: Light scatter in scattering media. The light rays from a light source are reflected at an object surface and scattered by micro particles.

et al., 2014) proposed a method for estimating time-to-contact from the change in intensity in images. Their method does not require geometric image features, and hence it can be used even if the geometric features are not available in images, such as night images. In this paper, we extend their method and propose a new method for estimating time-to-contact, which can be used even in the scattering media, such as fog and smoke. By using the proposed method, we can estimate time-to-contact even if we cannot obtain correspondences from image taken in scattering media. The proposed method does not need the reflectance of object surface, the properties of light source and the property of scattering media. Thus, the method can be applied to various applications in scattering media.

2 ESTIMATION OF TIME-TO-CONTACT

In the existing methods, the time-to-contact is estimated from geometric information, such as object size in images(Cipolla and Blake, 1992; Subbarao, 1990; Horn et al., 2007). In this section, we revisit the basic theory of the estimation of time-to-contact.

Let us consider the case where an object whose width is W is observed by a camera as shown in Fig.3(a). When the distance between the camera and the object is Z, the apparent width w of the observed object in a camera image can be described as follows:

$$w = \frac{fW}{Z} \tag{1}$$

where f is a focal length of the camera. We next consider the case where the camera moves with ΔZ toward the object as shown in Fig.3(b). Then, the observed length w' after the motion can be described as follows:

$$w' = \frac{fW}{Z+\Delta Z} \tag{2}$$

In this case, the time-to-contact is $T = Z/\Delta Z$. The time-to-contact can be estimated from just observed images as follows:

$$T = \frac{w'}{w'-w} \tag{3}$$

In this equation, we do not need any information, such as the focal length f, distance Z and the real width of object W for estimating time-to-contact. We just need w and w' in observed images. The technique is very useful, since we can estimate time-to-contact without calibrating cameras and without knowing 3D geometry. Furthermore, we can reconstruct a real distance Z if we have the relative speed ΔZ of the camera with respect to the object.

However, this technique cannot be used when we cannot obtain appropriate geometric information, such as corners and edges, in images. For example, we cannot observe geometric features appropriately in night images in general, and thus we cannot estimate time-to-contact from these images. In order to avoid the problem, Watanabe et al. (Watanabe et al., 2014) proposed a method for estimating time-to-contact from photometric information. They focused not on geometric information but on photometric information in images for estimating time-to-contact. By using their method, we can estimate time-to-contact even if we cannot obtain geometric features, such as corners and edges.

Now, let us consider the case where the objects are in a scattering media, such as fog and smoke, as shown in Fig.1 (b). In this case, we cannot observe geometric information appropriately like a night scene. In addition, the change in intensity caused by the camera motion cannot be described by a simple point light source model unlike (Watanabe et al., 2014). Therefore, we cannot estimate time-to-contact from the existing geometric and photometric methods. Thus, we in this paper propose a new method for estimating time-to-contact in scattering media. In

(a) image at time t (b) image at time $t+1$

Figure 3: Geometric information for estimating time-to-contact.

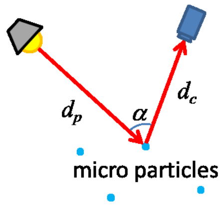


Figure 4: Light ray reflection by scattering media.

this method, we do not need any information on target object, such as reflectance of object surface. Furthermore, we do not need any information on the scattering media, such as scattering coefficients. Even if we do not have these informations, we can estimate time-to-contact just from observed images.

3 LIGHT RAY SCATTER IN SCATTERING MEDIA

3.1 Single Scattering Model

Now, let us consider a representation of observed intensity in scattering media. In this paper, we assume that the scattering media is homogeneous, and its density is not so high. In this case, the behavior of light rays in scattering media can be represented by a single scattering model. Thus, we consider the single scattering model (Narasimhan et al., 2005) in this section.

In the single scattering model, input light rays are reflected by micro particles only once. Note that the reflected light rays go forward not to a single direction but to all directions from the micro media. This property is represented by using a phase function $\mathcal{P}$. In this paper, we use the first-order approximation of the phase function (Narasimhan et al., 2005) as follows:

$$\mathcal{P}(g,\alpha) = \frac{1}{4\pi}(1+g\cos\alpha) \tag{4}$$

where $g \in (-1,1)$ indicates a parameter controlling shape of phase function. The α represents angle between an input light ray and reflected direction as shown in Fig.4.

By using the function $\mathcal{P}$, observed intensity of light reflected by a media is described as follows:

$$I_m = \frac{1}{d_p^2} E\tau\mathcal{P}(g,\alpha)e^{-\tau(d_p+d_c)} \tag{5}$$

where τ is a scattering coefficient, E is a radiance of light ray and d_p and d_c are distances from the light source to the particle and the particle to the camera respectively.

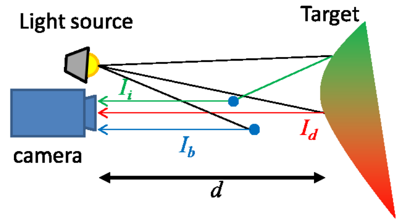


Figure 5: Light ray scatter by scattering media. The light rays reflected by objects are diffused by micro particles in scattering media.

3.2 Direct and Back-Scattered Components

We next consider reflection in scattering media. In this paper, we assume that a camera and a light source are very close to each other. In addition, they are fixed as shown in Fig.5. This assumption is reasonable, since in many cases light sources and cameras are fixed to each other, such as a head lump and a camera on a vehicle.

In this case, observed intensity I_o consists of three components as follows:

$$I_o = I_d + I_b + I_i \tag{6}$$

where I_d is a direct reflection of the light from object surface, $_b$ is a back-scattered component from scattering media and I_i is an indirect reflection from object surface as shown in Fig.5.

Let us consider the detail of these components. We first consider the direct component I_d. In this component, light rays from the light source are reflected at the object surface, and are observed by the camera as shown in Fig.5. The light rays are attenuated by scattering in the scattering media. In addition, the magnitude of light is inversely proportional to squared distance from the light source. Suppose d_l and d_c indicate distances from the light source to the surface and distance from surface to camera respectively. Then, the observed intensity I_d can be described as follows:

$$I_d = E\rho\cos\theta\frac{1}{d_l^2}e^{-(d_l+d_c)\tau} \tag{7}$$

where E denotes a power of light, ρ denotes a reflectance of object surface, θ denotes an angle between the light direction and a surface normal and τ denotes an attenuation coefficient of the scattering media. In this paper, we assume that the light source and the camera are very close to each other, and thus the distance d_c and d_l can be described by a single component d approximately. Therefore, Eq.(7) can be rewritten as follows:

$$I_d = E\rho\cos\theta\frac{1}{d^2}e^{-2d\tau} \tag{8}$$

In addition, we assume that the camera and light source face to the object, i.e. $\theta \sim 0$, in this paper. Under this assumption, Eq.(8) can be rewritten as follows:

$$I_d = E\rho \frac{1}{d^2} e^{-2d\tau} \tag{9}$$

In this paper, we use Eq.(9) as a representation of the direct component.

We next consider the back-scatter components I_b. In this component, light rays from the light source are reflected by micro particles and observed by the camera. Note that observed light rays are the integration of reflected light rays by all the particles. Therefore, observed I_b can be represented as follows:

$$I_b = \int_0^d \frac{1}{x^2} E\tau \mathcal{P}(g,\alpha) e^{-2\tau x} dx = B(d) \tag{10}$$

As described above, positions of the light source and the camera are the same, and thus the angle α is 0 approximately. In this case, I_b depends only on the distance d, and hence we describe it as $B(d)$.

Finally, we consider the indirect component I_i. In this component, light rays from the light source are reflected on a object surface. After that, the reflected light rays are scattered by micro particles. In general, the effect of this component is sufficiently small comparing with the other components, since the amount of light reflected by the object surface is much smaller than the light rays from the light source. Thus we ignore the indirect component in this paper.

Therefore, by substituting (9) and (10) into (6), the observed intensity I_o in scattering media can be described as follows:

$$I_o = E\rho \frac{1}{d^2} e^{-2d\tau} + B(d) \tag{11}$$

In the next section, we derive a method for estimating time-to-contact in scattering media by using the observed intensity I_o shown in (11).

4 TIME-TO-CONTACT IN SCATTERING MEDIA

Let us consider the estimation of time-to-contact in scattering media. For estimating time-to-contact, we assume that the observed object faces to the camera and the light source. Thus, the angle between a surface normal and a light source direction is equal to 0. Also, the object has a texture, which are the reflectances at two different points are different from each other, although these reflectances are unknown.

Let $\rho(\mathbf{x}_1)$ and $\rho(\mathbf{x}_2)$ denote reflectance at point $\mathbf{x}_1$ and $\mathbf{x}_2$. In this case, observed intensity $I(\mathbf{x}_1)$, $I(\mathbf{x}_2)$ of these two points can be described as follows:

$$I(\mathbf{x}_1) = E\rho(\mathbf{x}_1) \frac{1}{d^2} e^{-2\tau d} + B(d) \tag{12}$$

$$I(\mathbf{x}_2) = E\rho(\mathbf{x}_2) \frac{1}{d^2} e^{-2\tau d} + B(d) \tag{13}$$

Since these equations have the same component $B(d)$, the back-scattered component $B(d)$ can be eliminated as follows:

$$\begin{aligned} I(\mathbf{x}_1) - I(\mathbf{x}_2) &= E(\rho(\mathbf{x}_1) - \rho(\mathbf{x}_2)) \frac{1}{d^2} e^{-2\tau d} \\ &= E\bar{\rho} \frac{1}{d^2} e^{-2\tau d} = \bar{I} \end{aligned} \tag{14}$$

We next consider the case where the light source and the camera move with the speed of Δd toward the object. Then, the observed intensities $I'(\mathbf{x}_2)$ and $I'(\mathbf{x}_2)$ after the motion with Δd are described as follows:

$$I'(\mathbf{x}_1) = E\rho(\mathbf{x}_1) \frac{1}{(d+\Delta d)^2} e^{-2\tau(d+\Delta d)} + B(d+\Delta d) \tag{15}$$

$$I'(\mathbf{x}_2) = E\rho(\mathbf{x}_2) \frac{1}{(d+\Delta d)^2} e^{-2\tau(d+\Delta d)} + B(d+\Delta d) \tag{16}$$

From these intensities, we can compute $\bar{I}'$ after the motion as follows:

$$\begin{aligned} I'(\mathbf{x}_1) - I'(\mathbf{x}_2) &= E(\rho(\mathbf{x}_1) - \rho(\mathbf{x}_2)) \frac{1}{(d+\Delta d)^2} e^{-2\tau(d+\Delta d)} \\ &= E\bar{\rho} \frac{e^{-2\tau\Delta d}}{(d+\Delta d)^2} e^{-2\tau d} = \bar{I}' \end{aligned} \tag{17}$$

By dividing $\bar{I}$ by $\bar{I}'$, we can eliminate the reflectance and the light power as follows:

$$\frac{\bar{I}}{\bar{I}'} = \frac{(d+\Delta d)^2}{d^2} e^{2\tau\Delta d} \tag{18}$$

Similarly, we compute $\bar{I}'/\bar{I}''$ as follows:

$$\frac{\bar{I}'}{\bar{I}''} = \frac{(d+2\Delta d)^2}{(d+\Delta d)^2} e^{2\tau\Delta d} \tag{19}$$

where, $\bar{I}''$ denotes $\bar{I}$ after the camera motion with $2\Delta d$. Equation(18) and Eq.(19) includes the same unknown component $e^{2\tau\Delta d}$. Thus, we eliminate it by taking a ratio between $\frac{\bar{I}}{\bar{I}'}$ and $\frac{\bar{I}'}{\bar{I}''}$ as follows:

$$\frac{\bar{I}'^2}{\bar{I}\bar{I}''} = \frac{d^2(d+2\Delta d)^2}{(d+\Delta d)^4} \tag{20}$$

Squared root of this equation can be represented as follows:

$$J = \sqrt{\frac{\bar{I}'^2}{\bar{I}\bar{I}''}} = \frac{d(d+2\Delta d)}{(d+\Delta d)^2} \tag{21}$$

By using the time-to-contact T, the distance d can be described as $d = T\Delta d$. Thus, Eq.(21) can be rewritten by using T as follows:

$$\begin{aligned} J &= \frac{T\Delta d(T\Delta d + 2\Delta d)}{(T\Delta d + \Delta d)^2} \\ &= \frac{T(T+2)}{(T+1)^2} \end{aligned} \tag{22}$$

Finally, we can derive the estimation of time-to-contact T from the solution of Eq.(22) as follows:

$$T = \frac{-J+1 \pm \sqrt{-J+1}}{J-1} \tag{23}$$

Note that, the equation has two solutions. One of them indicates time-to-contact when the observed intensities changed from I to I' and I'' and the other one indicates when the observed intensities changed from I'' to I' and I. If the light source moves forward to the object, one of them is positive and the other one is negative. Therefore, we choose positive one for estimation of time-to-contact.

As shown in the above equation, we do not need any information about the observed object, camera and the scattering media, and we can estimate time-to-contact just from the observed intensities. In the following section, we show experimental results by using the proposed method.

5 EXPERIMENTAL RESULTS

5.1 Environment

We show some experimental results by using the proposed method. In this experiment, we utilized synthesized images in order to control the dense of the scattering media accurately. We assume that a target object as shown in Fig.6 was situated in scattering media. The object was taken by orthogonal camera, and thus the position and the scale of the object are unchanged, even if the distance from the object to the camera and the light is changed. This is because the main focus of this paper is the estimation of time-to-contact from intensities. The number of bits of these images is 12. The correspondence problem is not considered in this experiment. The distance from the camera/light to the object was changed from 20 cm to 10 cm with the speed of 1 cm/sec. Images were taken by the camera in each second. Examples of the taken images are shown in Fig.7. The scattering coefficient τ was changed from 0.05 to 0.20 as shown Fig.7. When τ becomes large, the object intensity decreases rapidly. From these images, the time-to-contact was estimated by using the proposed method.

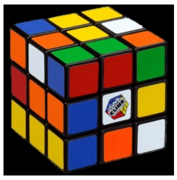
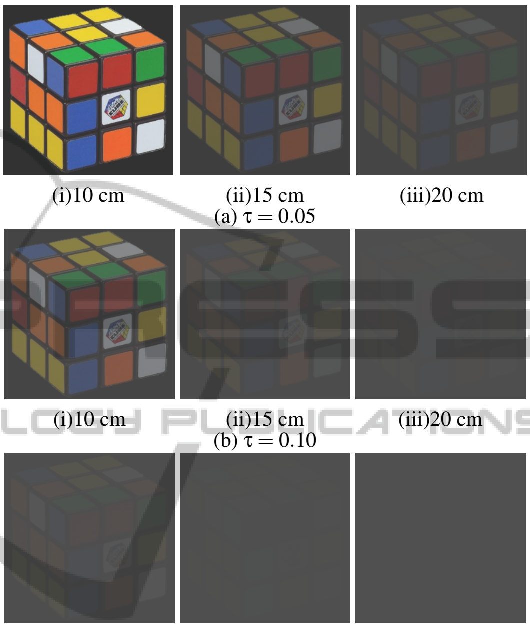


Figure 6: Target object.



(i)10 cm (ii)15 cm (iii)20 cm
(a) $\tau = 0.05$

(i)10 cm (ii)15 cm (iii)20 cm
(b) $\tau = 0.10$

(i)10 cm (ii)15 cm (iii)20 cm
(c) $\tau = 0.20$

Figure 7: Examples of input images: (a), (b) and (c) show images in scattering media with τ of 0.05, 0.1 and 0.2 respectively.

5.2 Results

We next show the experimental results from the proposed method. Figure8 shows estimated time-to-contact by the proposed method. Note that estimated time-to-contact does not appear sometimes in this figure, since the time-to-contact is not computed when the change in intensity is smaller than a threshold. This is because our method is based on the change in intensity, and thus it cannot provide valid results when the change in intensity is extremely small.

From these results, we find that our method can estimate time-to-contact when the distance is small under small scattering coefficient. However, the estimated results become unstable when the distance is large or the scattering coefficient is very small. This is because the change in intensity becomes very small under these conditions. In these cases, the estimated results are affected by various kinds of noise including the quantization error.

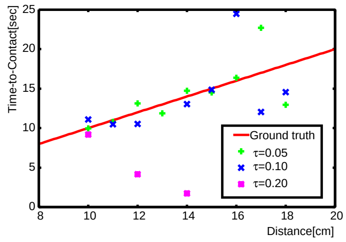


Figure 8: Estimated time-to-contact under $\tau = 0.05$, $\tau = 0.10$ and $\tau = 0.20$.

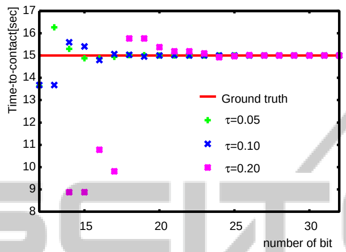


Figure 9: Relationship between the estimated time-to-contact and the number of bits. The distance from the light to the object was 15 cm.

In order to clarify the relationship between the number of bits and the accuracy of estimation, time-to-contact was estimated with different number of bits. Figure 9 shows the relationship between the number of bits and the accuracy of estimation. In this experiment, distance between the light and the target was 15 cm, and thus the ground truth of time-to-contact was 15 seconds. In this experiment, we could not estimate time-to-contact correctly when a number of bits are small because of the quantization error. However, we can estimate the time-to-contact correctly when the number of bits becomes large. These results indicate that the proposed method can estimate time-to-contact from high accuracy images even if the scattering coefficient is high.

6 CONCLUSION

In this paper, we proposed a method for estimating time-to-contact in scattering media. In the scattering media, the behavior of light rays is very complex, and we need a lot of information on the scattering media and objects for obtaining 3D information in general. In spite of the complexity in scattering media, the proposed method can estimate time-to-contact easily even if we do not have any information about observed objects, cameras and scattering media. The method is very useful, since we does not need any priory knowledge for estimating the time-to-contact. Thus, the method can be applied to various applications in scattering media.

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