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Express Paper

Time-to-Contact from Photometric Information

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Abstract: It is known that time-to-contact toward objects can be estimated just from changes in the object size in camera images, and we do not need any additional information, such as distance toward objects, camera speed and camera parameters. However, the existing methods cannot compute time-to-contact, if there are no geometric features in the images. In this paper, we propose a new method for computing time-to-contact by using photometric information. When a light source moves in the scene, an observed intensity changes according to the motion of the light source. In this paper, we analyze the change in intensity in camera images, and show that the time-to-contact can be estimated just from the change in intensity in images. Our method does not need any additional information, such as radiance of light source, reflectance of object and orientation of object surface. The proposed method can be used in various applications, such as vehicle driver assistance.

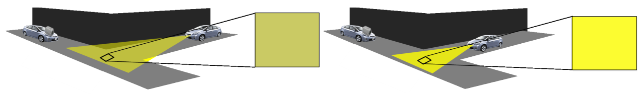
Keywords: time-to-contact, moving light source

1. Introduction

Measurement of 3D distance is one of the most important problems in computer vision. This technique can be applied to various kinds of applications such as 3D shape measurement [2], [3], making a 3D map [4], [7] and so on. In ordinary 3D measurement systems, 3D information is estimated from calibrated multiple cameras. In these systems, the distance from camera to object is measured by triangulation [2]. Similarly, 3D reconstruction by using a moving single camera is also widely studied [4], [7]. These techniques are called structure from motion (SfM) and they are useful when we can only use a single camera. For example, we can reconstruct a 3D map by using camera installed on a vehicle [4].

As we described above, the 3D measurement technique is widely used recently. However, these techniques require large computational cost for 3D measurement. In addition, we do not need explicit absolute 3D information in many applications. In particular, explicit 3D distance is not required when we just want to estimate time-to-contact of a moving camera toward objects. For this objective, several methods for estimating time-to-contact were proposed [1], [6]. In these methods, we can estimate the time-to-contact just from images. That is, we do not need any additional information such as camera parameter, 3D distance and so on. In addition, the computational cost of time-to-contact is much lower than the cost of 3D measurement.

In the existing methods for estimating time-to-contact, geometric information, such as size of object, is used. The size of the object in an image changes according to the motion of the camera. Therefore, we can estimate time-to-contact by analyzing the change in size [1]. However, the existing method cannot estimate the time when there is no geometric information in images. For example, it is hard to obtain geometric information from night images taken by ordinary cameras. In these cases, time-to-contact cannot be estimated accurately.



(a) Under a far light (b) Under a near light

Fig. 1 Change in intensity caused by the change in distance from a light source. Observed intensity (a) under a far light is darker than (b) under a near light.

On the other hand, we can obtain photometric information, such as brightness, under a light source, easily. Empirically, it is known that brightness illuminated by a light source changes according to the motion of a light source as shown in **Fig. 1**. In general, the brightness becomes darker/brighter when the distance from a light becomes longer/shorter. Therefore, distance information can be computed from a change in brightness. Furthermore, we can estimate time-to-contact from changes in brightness without explicit distance estimation.

In this paper, we propose a method which can estimate time-to-contact of a moving light source toward an object based on photometric information. The method can estimate the time just from images without any additional information such as camera parameters, radiance of light and reflectance of the object.

2. Time to Contact from Geometric Information

We first explain the estimation of time to contact from geometric information [1], [6]. In this method, we can estimate time-to-contact of a moving camera toward an object from an image taken by this camera. The method can be applied even if we do not have camera parameters, camera speed and some other information.

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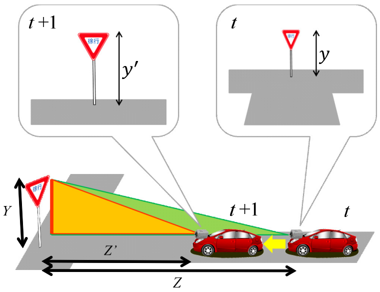


Fig. 2 Images taken by a moving camera. The size of a sign in observed images changes with time.

Let us consider the case where a camera is installed on a moving vehicle and it observes a sign on the road as shown in **Fig. 2**. In this scene, time-to-contact of the camera (vehicle) toward the sign is estimated. The size of the sign in an image changes according to the distance from the sign to the vehicle. The size of the sign is y at time t and it changes to y' at time $t + 1$. When the real size of this sign is Y and the distance from the sign to a vehicle changes from Z (at time t) to Z' (at time $t + 1$), y and y' can be described as follows:

$$y = f\frac{Y}{Z} \tag{1}$$

$$y' = f\frac{Y}{Z'} \tag{2}$$

where f is the focal length of the camera. In this case, time-to-contact can be estimated from distance Z and Z' as follows:

$$TC = \frac{Z'}{Z - Z'} \tag{3}$$

From Eq. (3), Eq. (1) and Eq. (2), we find that we can estimate time-to-contact just from the size of the sign in the image as follows:

$$TC = \frac{y}{y' - y} \tag{4}$$

This equation does not include focal length, real length of a sign and distance between a sign and a car. This fact indicates that we can estimate time-to-contact just from information contained in images

This method is useful because we do not need geometric calibration of cameras. However, the method cannot be applied when there is no geometric information in the images. For example, sufficient information cannot be obtained from night images. In order to avoid the problem, we propose a novel estimation method of time-to-contact. In this method, we estimate time-to-contact not from geometric information but from photometric information.

3. Reflectance Model

In order to derive a new time-to-contact based on photometric information, we first explain the reflectance model for determining observed intensity. In this paper, we assume that the reflectance model of arbitrary surface can be approximated by the Lambert model. Under this assumption, let us consider a case when there is a light source in a scene as shown in **Fig. 3**. In this case, observed intensity i can be described by a light source position $\mathbf{S}$, surface orientation $\mathbf{n}$ and observed point $\mathbf{X}$ as follows:

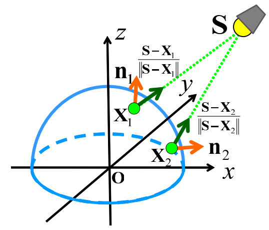
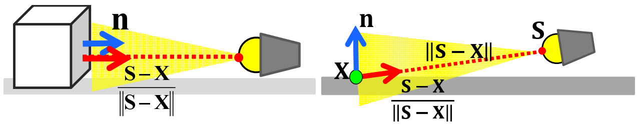


Fig. 3 Relationship between light source **S** and observed point **X**.



(a) Facing target (b) Not facing target

Fig. 4 Two cases for estimation of time-to-contact. In case (a), the light source moves toward the observed point. In case (b), the light source moves not in the direction of the observed point.

$$i = \frac{1}{\|\mathbf{S} - \mathbf{X}\|^2} E\rho \frac{\max(\mathbf{n}^\top(\mathbf{S} - \mathbf{X}), 0)}{\|\mathbf{S} - \mathbf{X}\|} \tag{5}$$

where E and ρ indicate the radiance of light source and the reflectance of the surface, respectively. When there is no negative intensity, Eq. (5) can be rewritten as follows:

$$i = \frac{1}{\|\mathbf{S} - \mathbf{X}\|^2} E\rho \frac{\mathbf{n}^\top(\mathbf{S} - \mathbf{X})}{\|\mathbf{S} - \mathbf{X}\|} \tag{6}$$

In Eq. (6), $\frac{\mathbf{S}-\mathbf{X}}{\|\mathbf{S}-\mathbf{X}\|}$ indicates the light source direction at $\mathbf{X}$. Furthermore, $\frac{1}{\|\mathbf{S}-\mathbf{X}\|^2}$ describes the attenuation of light. By this attenuation, the observed intensity is proportional to the inverse of the squared distance between the light source and the observed point. The equation shows that the observed intensity strongly depends on the distance from a light source. By using this property, Liao et al. [5] proposed a method for estimating 3D shape from observed intensities. Unlike their method, we in this paper propose a method for estimating time-to-contact from observed intensities without recovering 3D shape explicitly. In the following sections, we analyze this intensity model and derive a method for estimating time-to-contact of moving light toward the object.

4. Time-to-Contact from Intensity

In this section, we propose a method for estimating time-to-contact from image intensity in two different cases.

We first consider the case where the light source moves toward the observation point $\mathbf{X}$ as shown in **Fig. 4** (a), and we next generalize the problem and consider the case where the light source does not move toward the observation point $\mathbf{X}$ as shown in Fig. 4 (b).

4.1 Time-to-Contact under Special Case

We first consider a method for computing time-to-contact from image intensities in the case where the light source moves toward the observation point $\mathbf{X}$. We assume that radiance E and reflectance ρ are constant during the light source motion. In this case, the angle between a normal surface and the orientation of the light source is constant. Therefore, we can rewrite Eq. (6) as follows:

$$i = \frac{k}{\|\mathbf{S} - \mathbf{X}\|^2} = \frac{k}{d^2} \tag{7}$$

where k is constant, since it depends only on the reflectance of surface and the radiance of a light source. d indicates the distance between $\mathbf{X}$ and $\mathbf{S}$.

The intensity is inverse proportional to squared distance, and thus, we consider square root of intensity as follows:

$$\sqrt{i} = \frac{k'}{\|\mathbf{S} - \mathbf{X}\|} = \frac{k'}{d} \tag{8}$$

where $k' = \sqrt{k}$. Since $\sqrt{i}$ is inverse proportional to distance d the same as Eq. (1), we can estimate time-to-contact TC from image intensity as as follows:

$$TC = \frac{\sqrt{i}}{\sqrt{i'} - \sqrt{i}} \tag{9}$$

where i' indicates the observed intensity at time $t + 1$. By using the method, we can estimate time-to-contact just from intensity without any other prior knowledge.

4.2 For Below Observed Point

We next generalize the method derived in the previous section, and propose a method for computing time-to-contact in the case where the light source moves not in the direction of observation point $\mathbf{X}$ as shown in Fig. 4 (b). In this case, not only distance but also angle between the normal surface and the light source orientation changes according to the motion of the light source. We first rewrite distance $\|\mathbf{S} - \mathbf{X}\|$ by horizontal distance d and vertical distance h. When a normal surface $\mathbf{n}$ is perpendicular to the moving direction of light source $\mathbf{S}$, Eq. (6) can be rewritten as follows:

$$i = \frac{E\rho h}{(d^2 + h^2)^{\frac{3}{2}}} \tag{10}$$

Since the light source moves only in a horizontal direction, vertical distance h is constant. We next compute the derivative of intensity i with respect to horizontal distance d as follows:

$$\frac{di}{dd} = \frac{-3E\rho hd}{(d^2 + h^2)^{\frac{5}{2}}} = j \tag{11}$$

Note that, the denominator of the derivative is exponentiation of the denominator of an intensity i shown in Eq. (10). Thus, we can eliminate $(d^2 + h^2)$ by computing I as follows:

$$\begin{aligned} I &= \frac{i^{\frac{5}{3}}}{j} \\ &= -\frac{(E\rho h)^{\frac{2}{3}}}{3} \cdot \frac{1}{d} \\ &= \frac{k''}{d} \end{aligned} \tag{12}$$

where k'' is constant, since it depends only on radiance E, reflectance ρ and vertical distance h. The I computed by this equation is inverse proportional to horizontal distance d, and thus, we can estimate time-to-contact by using I as follows:

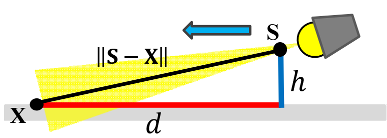


Fig. 5 Horizontal distance d and vertical distance h.

$$TC = \frac{I}{I' - I} \tag{13}$$

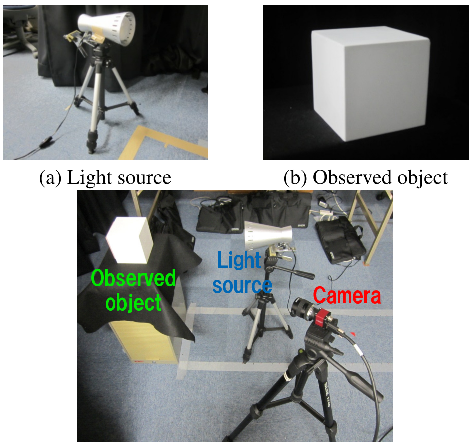
where I' is computed by Eq. (12) from intensity at time $t + 1$. By using the method, we can estimate time-to-contact of a moving light even if the light source does not face to the object.

5. Experimental Results

5.1 In the Case of a Facing Target

In this section, we show experimental results from our proposed method. First, we show experimental results when a light source faces to the object. The experimental environment is shown in **Fig. 6** (c). In this experiment, the light source shown in Fig. 6 (a) was used and a camera observed a plaster cube shown in Fig. 6 (b). The light source illuminated the plaster cube as shown in Fig. 6 (c), and moved horizontally toward the plaster cube. The distance from the light to the object changes from 2.0 m to 0.5 m. The moving speed of the light was 0.1 m/sec. Images were taken by a fixed camera every second. Examples of observed images are shown in **Fig. 7**. Intensities used for estimating time-to-contact were computed by averaging the intensity in 100 × 100 area at the image center. From these images time-to-contact was estimated by using Eq. (9). The estimated results are shown in **Fig. 8**.

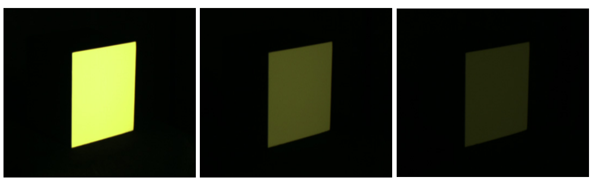
As shown in this figure, the estimated results are similar to the ground truth. The result indicates that our proposed method can estimate time-to-contact even if we do not have any information such as reflectance, radiance and camera parameters. When the distance from a light to the target becomes short, the estimated result becomes worse. This was caused by image noises and it can be suppressed by using a larger area for computing average intensity.



(a) Light source (b) Observed object

(c) Environment

Fig. 6 Experimental devices and environment.



(a) 50cm (a) 100cm (a) 150cm

Fig. 7 Examples of images taken at each distance.

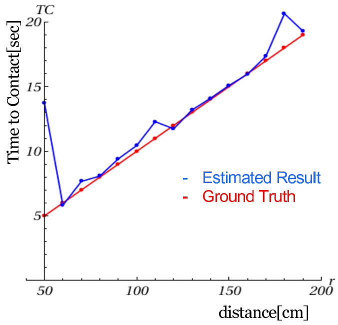


Fig. 8 Estimated time to contact: the estimation were done by Eq. (9).

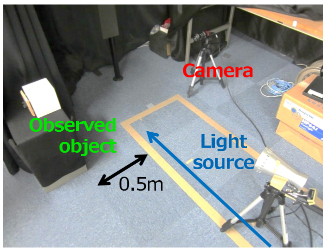


Fig. 9 Experimental environment.

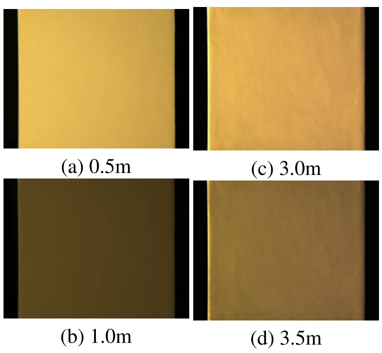


Fig. 10 Examples of images: Camera parameter for brightness was changed automatically in order to obtain appropriate image.

5.2 In the Case of a Not Facing Target

We next show experimental results in the case where the observed point is not in the direction of the light source motion. The experimental environment is shown in **Fig. 9**. In this environment, the observed object is set in the side of a light source and a fixed camera takes the images from the front of the object. This environment simulates the case of Fig. 4 (b). The light source moved along with the blue arrow changing the distance from 3.5 m to 0.5 m. Examples of observed images are shown in **Fig. 10**. Note that, camera parameters for determining image brightness were changed every 2 seconds automatically in order to obtain sufficiently bright images. Without the intensity adjustment, obtained images become too dark to estimate the time-to-contact. Note that, although we do not have any information of change in camera parameters, a set of two images for estimating time-to-contact were taken under the same camera parameters, and thus there is no problem for estimating time-to-contact from the proposed method. The average intensity of 300×300 area at the image center was used for estimating time-to-contact from Eq. (13). The derivative of intensity was computed numerically by using the average intensity of 300×300 area shifting 200 pixel from the image center. The speed of the light source motion was 0.5 m/sec and images were taken every second. The horizontal distance (which is equivalent to the vertical distance in **Fig. 5**) between the light source and an observed object was 0.5 m and it was fixed.

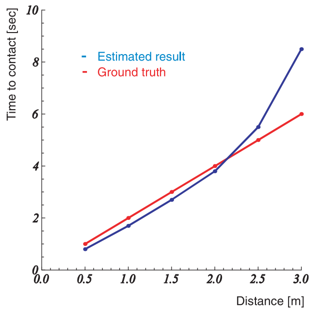


Fig. 11 Estimated time to contact.

The Estimated time-to-contact is shown in **Fig. 11**. As shown in this figure, estimated times-to-contact is similar to the ground truth. This result indicates that our proposed method works well even if the light source does not face toward the observed point. When the distance from a light source to an observed point becomes larger, the estimated error becomes worse. This is because the change of intensity is very small when the distance from the light to the objects is large, and the signal to noise ratio becomes worse. However, our method can estimate time-to-contact accurately at almost all the distances. The result indicates that our proposed method is very efficient for estimating time-to-contact.

6. Conclusion

In this paper, we proposed a new method for computing time-to-contact by using photometric information. When a light source moves in the scene, an observed intensity changes according to the motion of the light source. In this paper, we analyzed the change in intensity in camera images, and showed that the time-to-contact can be estimated just from the change in intensity in images. Our method does not need any additional information, such as radiance of light source, reflectance of object and orientation of object surface. The proposed method can be used in various applications, such as vehicle driver assistance.

References

[1] Cipolla, R. and Blake, A.: Surface orientation and time to contact from image diver-gence and deformation, *Proc. European Conference on Computer Vision*, pp.465–474 (1992).

[2] Hartley, R. and Zisserman, A.: *Multiple View Geometry in Computer Vision*, Cambridge University Press (2000).

[3] Izadi, S., Kim, D., Hilliges, O., Molyneaux, D., Newcombe, R., Kohli, P., Shotton, J., Hodges, S., Freeman, D., Davison, A. and Fitzgibbon, A.: KinectFusion: Real-time 3D Reconstruction and Interaction Using a Moving Depth Camera, *Proc. 24th Annual ACM Symposium on User Interface Software and Technology, UIST '11*, pp.559–568 (2011).

[4] Klingner, B., Martin, D. and Roseborough, J.: Street View Motion-from-Structure-from-Motion, *Proc. ICCV2013*, pp.953–960 (2013).

[5] Liao, M., Wang, L., Yang, R. and Gong, M.: Light Fall-off Stereo, *Proc. International Conference on Computer Vision* (*CVPR'07*), pp.1–8 (2007).

[6] Muller, D.: Time to contact estimation using interest points, *Proc. Intelligent Transportation Systems*, pp.1–6 (2009).

[7] Newcombe, R., Lovegrove, S. and Davison, A.: DTAM: Dense Tracking and Mapping in Real-Time, *Proc. ICCV2011*, pp.2320–2327 (2011).

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