Light transport measurement using ToF camera

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Abstract

The time-of-flight camera was originally developed for depth sensing but can be used for different purposes by utilizing the principle. This paper introduces two applications based on light transport measurement using the time-of-flight camera. One is the recovery of the temporal point spread function, while the other is material classification. The presented applications show the future possibilities of the time-of-flight camera.

1 Introduction

A Time-of-Flight (ToF) camera can measure a range image based on the delay of reflected light. The emitted light is amplitude-modulated and the algorithm for depth estimation assumes that the modulated light returns to the camera. However, the modulated light is distorted by multipath interference, such as interreflection and scattering, as shown in Fig. 1. Incorrect depths are computed as a result. We refer to this error as depth distortion.

Depth distortion is problem in the field of depth sensing. However, depth distortion contains rich geometric and optical information of the scene. We regard the distortion as a temporal light transport of the emitted light. That is, the ToF camera can be directly or indirectly used for temporal light transport measurement. This paper introduces two examples of temporal light transport measurement using the ToF camera. One is the recovery of the temporal point spread function (PSF). We show that the temporal PSF of the scene can be recovered by combining a commercially available ToF camera with a simple delay circuit. The other is a material classification. We show that the depth distortion depends on the properties of subsurface scattering. Material can thus be classified according to the depth distortion as a clue.

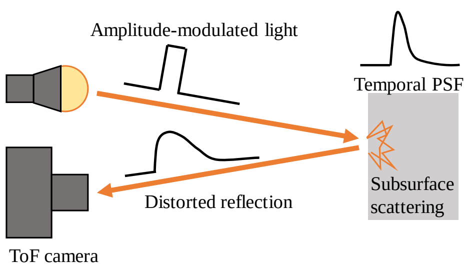


Figure 1: Distortion of the amplitude-modulated light due to subsurface scattering.

2 Recovering Temporal PSF using ToF Camera with Delayed Light Emission[1]

Recovering the temporal PSF is important for various applications, especially the analysis of light transport. Some methods that use amplitude-modulated continuous-wave ToF cameras have been proposed to recover the temporal PSF, archiving resolution of several nanoseconds. In contrast, we show that sub-nanosecond resolution can be achieved using a pulsed ToF camera and an additional delay circuit. The delay circuit is inserted before the illumination so that the emission delay can be controlled on a sub-nanosecond scale as shown in Fig.2. We recover a temporal PSF of sub-nanosecond resolution from observations for various delay settings.

Figure 3 shows the experimental results. (a) shows the target scene, which includes a mirror and translucent objects. Strong interreflection and subsurface scattering occur in this scene. (b) shows the observed reflection and recovered temporal PSF. (c) compares the recovered temporal PSFs of different translucent materials. (d) shows the recovered PSFs for all pixels, known as transient images. Light propagation of the scene is thus visualized.

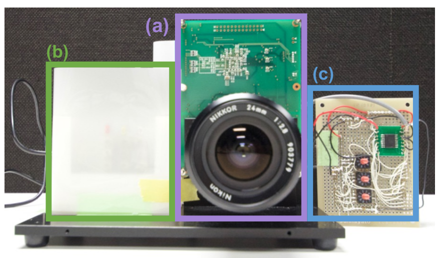
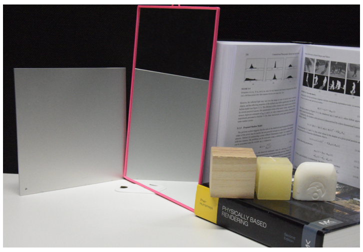
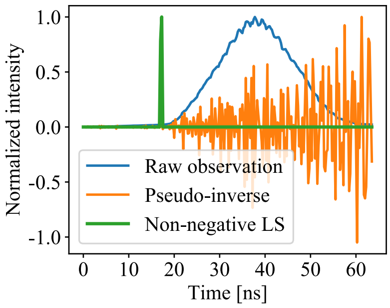


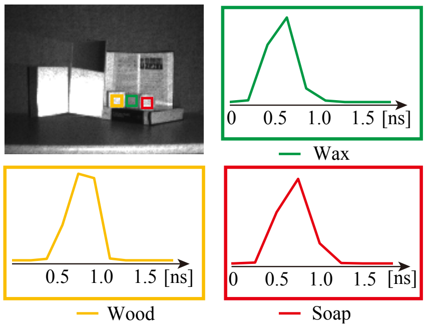
Figure 2: Experimental setting. (a) ToF camera. (b) light source. (c) delay circuit with a controller.



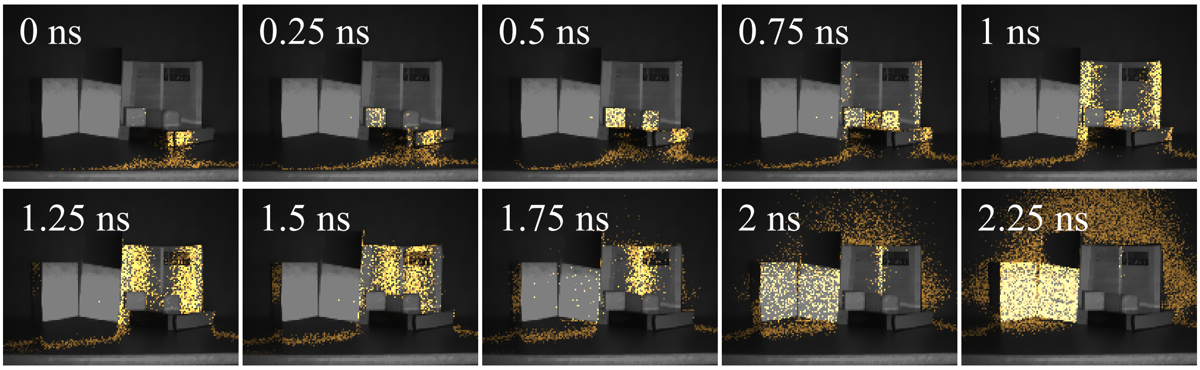
(a) Scene



(b) Estimation of PSF



(c) Temporal PSFs



(d) Transient images. PSFs depicted as orange are superposed on a long exposure photo.

Figure 3: Estimated temporal PSFs. (a) Scene including a mirror and translucent objects. (b) Comparison with observation and recovered results with and without a non-negative constraint. Non-negativity contributes to the stability. (c) PSFs of different translucent objects. Different shapes of PSFs are recovered. (d) Recovered PSFs for all pixels, known as transient images. Light propagation of the scene is thus visualized.

3 Material Classification from ToF Distortions[2]

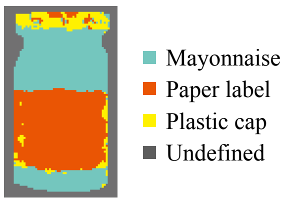
The ToF camera can also be used for material classification. The proposed method is based on an important observation that a depth measurement made by a ToF camera is distorted for objects with certain materials, especially translucent materials. We show that this distortion is due to the variation of the time-domain impulse responses across materials and to the measurement mechanism of the ToF camera. Specifically, we reveal that the amount of distortion varies according to the modulation frequency of the ToF camera, the object material, and the distance between the camera and object. Our method uses the depth distortion of ToF measurements as a feature for classification and allows material classification of a scene.

Figure 4 shows a real example of depth distortion. (b) shows the restored shape of the mayonnaise bottle in (a) obtained using a Kinect device. We see the shape is distorted at the mayonnaise part while the shape is measured correctly at the label part. This depth distortion is used as a clue for material estimation as in (c). If materials become known, the distorted depth can be recovered as in (d).

Figure 5 shows the depth distortions when using a Kinect device for three different materials. The differ-

(a) Mayonnaise bottle

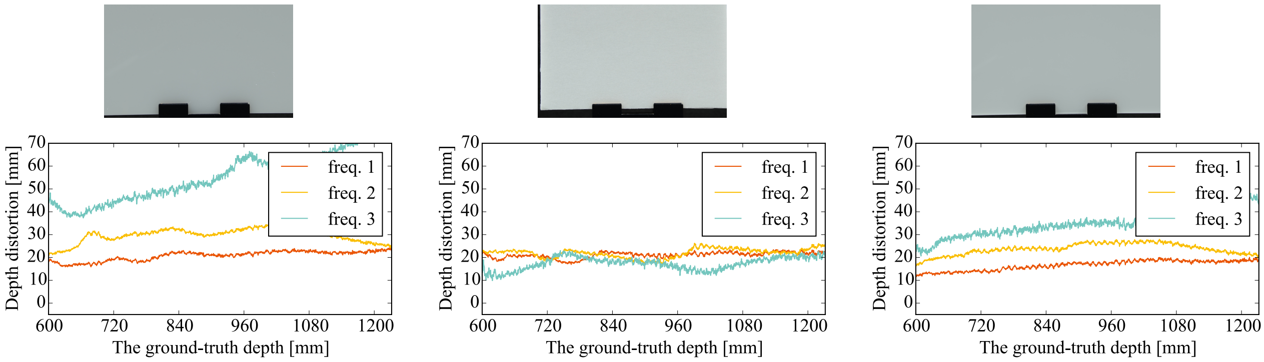
(b) Distorted depth



(c) Material classification

(d) Corrected depth

Figure 4: Depth distortion of a ToF camera. (a) A mayonnaise bottle is measured using a Kinect device. (b) 3-D view of the measured depth. There is a gap in depth between the mayonnaise and label regions. We use this depth distortion for material classification. (c) Material segmentation result. The material label is assigned for each pixel. (d) Application of material classification to depth correction. Depths are corrected according to the segmentation result and the distortion database. Depth gaps among materials are corrected and the 3-D shape is faithfully recovered.



(a) Acrylic board (b) Polystyrene board (c) Diffusion glass

Figure 5: Depth distortions measured using a Kinect device for three objects. The ground truth depth is obtained via a linear translation stage. The top row shows photographs of the target objects. Measurements of the second and third rows are different in terms of the surface orientation. Depth distortion at each frequency varies along with the actual depth and material. Depth distortion is similar for the same material regardless of the surface orientation but largely different for different materials. This frequency- and depth-dependent depth distortion is our important observation for material classification.

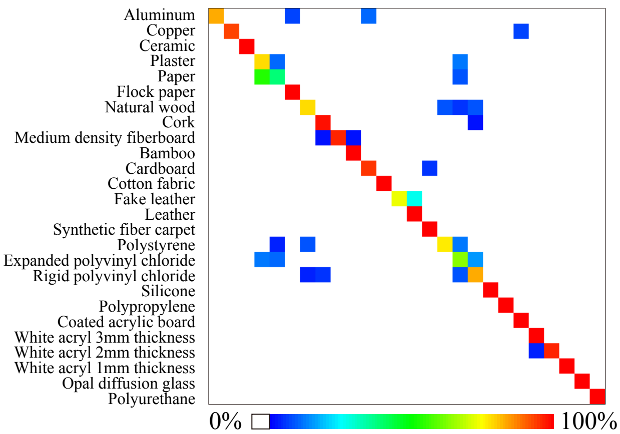


Figure 6: Confusion matrix. Higher values of confusion are indicated red and appear on the diagonal. The overall accuracy is 90.5%.

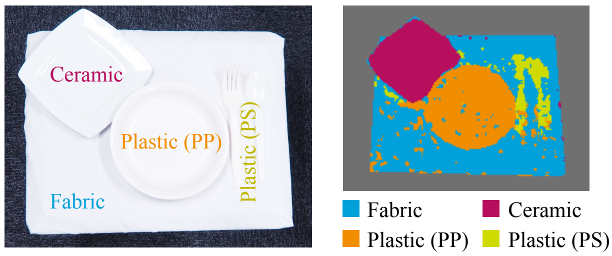


Figure 7: Left: Material segmentation results for a white scene. All utensils are white and classification is thus difficult using only with an RGB image. Right: The result of material classification. Although there is estimation error due to the pixel-wise processing and there being only one depth variation, the scene is much more interpretable than in the RGB image.

ence in materials appears as depth distortion. We see that depth distortion depends on not only the actual depth but also the frequency of modulation.

We classified 26 different materials, including metal, wood, plastic, and fabric. Figure 6 shows the confusion matrix. Higher values of confusion are indicated red and appears on the diagonal. The overall accuracy is 90.5%.

Figure 7 shows the material segmentation results for a white scene. It is difficult to classify the material by eye or using a normal RGB camera because all materials are white. However, pixels are independently segmented for each material without using shape information.

4 Conclusion

This paper introduced an unusual use of the ToF camera. Depth sensing is of course important for understanding a scene but the light transport also has rich optical information of the scene. We are attempting to develop new functions of the ToF camera so that it becomes a new tool in the field of computer vision.

Acknowledgment

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References

[1] K. Kitano, T. Okamoto, K. Tanaka, T. Aoto, H. Kubo, T. Funatomi, Y. Mukaigawa, “Recovering Temporal PSF using ToF Camera with Delayed Light Emission”, IPSJ Transactions on Computer Vision and Applications, June 2017.

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