Digital hologram generation for a real 3D object using by a depth camera

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Abstract. We introduce a digital hologram generation of a real 3D object captured by a depth camera. The depth camera is employing a time multiplexed concept for color and depth image acquisition in a single chip sensor. The 3D information, point cloud, corresponding to the real scene, is extracted from taken image pairs, a gray texture and a depth map by a depth camera. The extracted point cloud is used to generate a digital hologram as input information. The experimental results are satisfactory.

1. Introduction

Holography is a unique technology that can express 3D information almost perfectly in human-friendly way. Optical holography has developed into digital holography which creates interference pattern of object using digital technology and displays it through spatial light modulator.

In general, a 3D computer graphic model is being used to generate a digital hologram as the input information because the 3D information of an object can be extracted from a 3D model easily. Also there are many available methods to find the depth information including a stereo camera, depth camera of TOF (time of flight) method, 3D scanner, and Kinect of Microsoft.

In this paper, we introduce a digital hologram generation method of a real 3D object captured by a depth camera. The depth camera is a 3D image sensor based on the Time of Flight (TOF) principle using photon gating techniques. The basic feature incorporates real time depth imaging by capturing the shape of a light-pulse front as it is reflected from a three dimensional object. The depth camera is capable of producing RGB and D signals, where depth map D stands for the distance to each pixel. The taken RGB texture can be regarded as the intensities of the observable real object surface at the corresponding view point. However, it is still challenging to implement a single image sensor that can simultaneously acquire color and depth images. We present a 2nd-generation 2D/3D imager based on the pinned photodiode pixel structure. The time-division readout architecture for both image types (color and depth) is maintained. A complete redesign of the imager makes pixels smaller and more sensitive than before.

The taken image set, the color texture, and the depth map are mapped to a 3D coordinate system, and are represented to a 3D point cloud in which each point is consisted with 3D coordinate values and color intensities. This extracted 3D information from a real object is used to generate a digital hologram.
2. TOF camera to obtain both color and depth images in a single sensor\textsuperscript{5,6}

A 3D image sensor is presented employing a time multiplexed concept for color and depth image acquisition in a single chip to generate a real-time 3D image of an arbitrary scene. Fig. 1 shows the conceptual diagram of a time multiplexing architecture for obtaining color and depth images. There is no dedicated pixel for each image, but all the pixels have the same structure for both images that can be alternatively captured by switching operation mode. Because the conventional color filter is transparent to near infrared (NIR), there is no problem for using NIR emitting source in TOF depth cameras.

Fig. 1. Conceptual diagram of a time multiplexing architecture

The sensor can operate in two alternate readout modes for color and depth images in each frame using a time-division scheme shown in Fig. 2. The IR cut or pass filter is adjusted to the next image’s mode during a filter change time between both operation modes, and all the transfer gates are simultaneously activated to reset photodiodes.

Fig. 2. Timing diagram for obtaining color and depth images
Fig. 3(a) shows a color image from the prototype sensor under typical room illumination (about 1000lux) with gain 2. The reason why the lower image is brighter than the upper is that half of pixels have small size of FD nodes for a test. Fig. 3(b) is a depth image of the same object and three flat panels located on 1.2m, 1.5m and 1.9m from the sensor are clearly distinguished by 8-bit gray level. Any image processing algorithms for the improvement of image quality are not applied to both images.

Fig. 4 shows the measured depth and accuracy of a flat white board between 1m and 3m per every 0.25m distance. The integration time is 50ms and the modulation frequency is 10MHz. The depth below 1m is distorted by pixel saturation so that the sensor cannot work properly under this condition. After calibration, the non-linearity error is about 0.8% and the depth accuracy, which means temporal non-uniformity, is lower than 62mm at 3m distance measured from small FD pixel showing better performance. Table 1 summarizes the prototype sensor characteristics and measurement environments.

![Fig. 3. (a) Color image and (b) depth image from the sensor](image)

![Fig. 4 Measurement data of a depth](image)
Table 1  Prototype sensor characteristics

| Sensor | Process | 0.11μm 1P4M CMOS |
|--------|---------|------------------|
| Fill factor | 38.5% |
| Die size | 9.7×6.2mm² |

| System | Emitter | LED with 850nm wavelength (SFH4259) |
|--------|---------|-----------------------------------|
| Lens | Focal length – 16mm, F# – 1.6 |
| Supply voltage | 3.3V |

| Color | Pixel size | 3.65μm (2.5Tr/Pixel) |
|-------|------------|----------------------|
| Resolution | 2000×1096 (Effective: 1920×1080) |
| Frame rate | 30fps (Single color mode) |

| Depth | Pixel size | 14.6μm (4×4 binning) |
|-------|------------|----------------------|
| Resolution | 500×274 (Effective: 480×270) |
| Frame rate | 11fps (Single depth mode, int. time 40ms) |
| Modulation frequency | 20MHz |
| Measured range | 0.75m ~ 4.5m (Setup limit) |
| Non-linearity | 0.93% |
| Depth error | 10mm ~ 38mm (with different int. times) |

3. Experiment

By using the taken image pair which is composed with a color texture and its corresponding depth image, the 3D information can be extracted. The depth image is two-dimensional gray scale image. The intensity of the depth image is used as the depth information, and expressed by a gray scale. The depth range of the camera is dependent to the system initialization, whose parameter value is initialized by a user. Therefore, since we know the depth range and the field of view of the depth camera, the coordinate values on the three dimensional coordinate system can be extracted from the taken depth image. The taken gray image has scene information. Therefore, two-dimensional coordinate values on the coordinate system and intensity of the real object can be extracted. Accordingly, the necessary 3D information, coordinate (x, y, z) and real object intensity (A), corresponding to the real scene can be extracted as shown in Fig. 5. The extracted information is used to generate a digital hologram.

A digital hologram can be obtained by using the Rayleigh-Sommerfeld(RS) integral since such an approach gives exact complex light disturbance over a plane at a certain distance from an interesting object \(^7,8\). The complex function form of the RS integral in \((\xi, \eta)\) plane is

\[
S(\xi, \eta) = \sum_{p=1}^{N} \frac{A}{r_p} \exp(jkr_p) 
\]

where \(N\) is the number of object points. \(A = \alpha_p \exp(\phi_p)\) is the complex constant, where \(\alpha_p\) and \(\phi_p\) are the amplitude and the phase of the \(p^{th}\) object point in a point cloud, respectively. The wave number \(k\) is \(2\pi/\lambda\) where \(\lambda\) is the free-space wavelength of the coherent light. The distance \(r_p\)
between the $p^{th}$ object point and the point $(\zeta, \eta)$ on the hologram is $\sqrt{(\zeta - x_p)^2 + (\eta - y_p)^2 + z_p^2}$.

The RS integral treats the propagating light from a point as a spherical wave, and the desired complex amplitude distribution on a hologram plane can be exactly determined.

The taken color image and its corresponding depth image is shown in Fig. 5. A point cloud which has 3D information is extracted from the image pair. The extracted point cloud is utilized to generate digital hologram. The number of the points in the point cloud is about 20,000 due to the used camera resolution. The generated digital hologram by the R-S integral and its numerical reconstruction are shown in Fig. 6. In addition, the optical reconstruction is shown in Fig. 7. As shown in Fig. 6 and 7, even it is only red channel, the quality of the numerical reconstruction and the optical reconstruction are acceptable. The experimental environment is shown in Table 2.

![Fig. 5. The utilized input images: (a) color image, (b) depth image](image1)

![Fig. 6. (a) the generated digital hologram and (b) its numerical reconstruction](image2)

![Fig. 7. Optical reconstruction for the red color information](image3)
Table 2. Experimental environment

| Digital hologram generation | Resolution of hologram | 1920 x 1080 pixels |
|-----------------------------|------------------------|--------------------|
|                             | Pixel interval         | 7um                |
|                             | Object distance        | 500mm              |
| Display system              | Wavelength             | 633nm              |
|                             | Resolution of SLM      | 1920 x 1080 pixels |

4. Conclusion

Color image and depth map of an object have been necessary to create a real 3D image. We presented a time-of-flight (TOF) 3D image sensor for acquiring a depth image as well as a normal 2D image. In this work, we propose an improved 3D pixel architecture to obtain both color and depth images in a single sensor. It will be necessary to conduct further research on a depth camera and hologram generation methods for the high quality digital hologram of a real object.

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