High-speed three dimensional measurement by coding of exposure time and TOF with a multi-aperture imaging system

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Abstract A three-dimensional measurement scheme based on time-of-flight method using multi-aperture image capturing system, which can give temporally coded exposure for each aperture individually by programming shutter pattern for each block of pixel array is proposed. The measurement frequency is enhanced on the basis of compressive sensing technology by capturing multiple temporally coded images simultaneously. The results of preliminary experiments are presented to confirm measurement of the phase of a light signal modulated at a higher frequency than the frame rate of the image sensor.

Keywords: multi-aperture, TOF, compressive sampling

1. Introduction

Recently, three-dimensional (3-D) measurements have performed by various methods. In 3-D measurement method with a conventional image capturing device, measurement frequency is limited to video frame rate because of data transmission rate from the imaging device to processor or storage device. The purpose of this research is the development of a 3-D measurement method based on time-of-flight (TOF) method to improve measurement frequency using high-speed image sensor device, which has developed in Shizuoka University[1]. We construct a multi-aperture image capturing system, and apply shutter patterns vary for respective image blocks to detect a modulated light signal for TOF. We performed preliminary experiment to confirm measurement of the phase of a light signal modulated at a higher frequency than the frame rate of the image sensor.

2. The principle of measurement

Structure of multi-aperture camera used in this research is illustrated in Fig1. The pixels on an image sensor are divided to some blocks and the capturing timing is controlled individually for each block. Moreover, lens is equipped for each block, to implement multi-aperture structure, so that we can get multiple images with different capturing timings on single capturing.

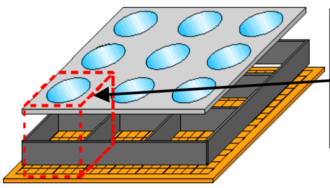

Fig1. Multi-aperture image capturing system

The pixel structure of the image sensor is illustrated in Fig2. Each pixel has one photo detector (PD) and two charge-storage parts (floating diffusion, FD). Charge current generated by photo detector can be switched to both parts by turning each gate ON or OFF according to binary control signal. Therefore, it can be possible to temporally modulate shutter pattern at very high-speed rate. Electric shutter pattern can be defined by binary signal of 128bit for each block. We can achieve temporally coded exposure individually for every block on a single capturing in order to obtain temporal information at higher frequency than frame rate.

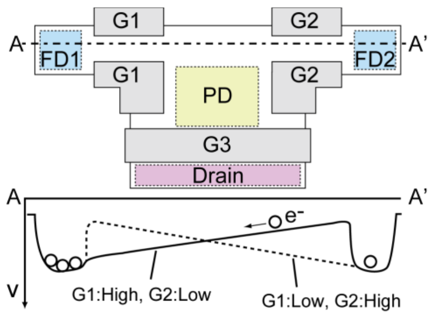

Fig2. Structure of pixel in image sensor.

TOF method is used as the principle of 3-D measurement. It can acquire distance from a measured object by projecting temporally modulated light onto the object and measuring the traveling time of reflected light from the object to a detector. The output image from this image capturing system can be considered as superposition of images captured for the duration of “1” in the shutter control signal while exposure time. Therefore, sets of output images can be expressed as linear equations of images captured during very short exposure time corresponding to 1 bit of the shutter control signal. When the shatter pattern is designed in consideration for solving the equations we can obtain images temporally resolved from the captured image by resolving inverse problem on the basis of compressive sensing technique [2], so that it becomes possible to capture images at a frequency over the frame rate of the image sensor.

3. Experiment results

As a preliminary experiment for TOF, we confirmed that a phase change of modulated light at a higher frequency than the frame rate of the image sensor can be measured by entering laser beam, whose amplitude was modulated by sine wave, to multi-aperture image capturing system. We used a laser diode with 658 nm wavelength as a light source, which was drove by electric current modulated by sine wave at 1 MHz frequency. The multi-aperture image capturing system and a function generator were synchronized so that sine wave was output on the timing of trigger produced when camera starts an exposure. Laser light emitted to a retro reflective sheet and reflected light was detected by multi-aperture image capturing system. Relation between light modulation and four shutter patterns applied to four apertures respectively is illustrated in Fig3. The shutter patterns are periodic at 1 MHz frequency and 1/4 duty ratio whose phases are shifted by 1/4 period for every aperture.

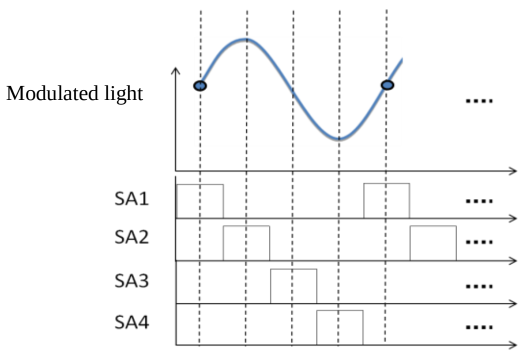

Fig3. Programmed shutter patterns

The image sensor used in this experiment has pixel size of 11.2 μm × 11.2 μm, 9 blocks consisting of 64 × 52 pixels,. The image sensor has two FD regions for charging photo-induced carrier. Because the images stored respective FD regions are captured with complementary shutter patterns, each other. This complementary pixel value was used for normalization. The images captured in four apertures, which has different shutter patterns, were obtained at the timing shifted by quarter of the period of light modulation. In this experiment, with knowledge of pixels corresponding to same distance, calculation was by norm. The phase φ of light modulation is obtained by a phase shift method from intensities I_1, I_2, I_3, I_4 of equivalent position in four captured images using the following equation,

$$\varphi = \tan^{-1}\left(\frac{I_3 - I_1}{I_2 - I_0}\right) \qquad (1)$$

The measured results at four timing of three kinds of modulated light, whose initial phases are 0 rad, π/2 rad, and π rad, respectively, and sine curves fit to the measured values are shown in Fig. 4. Moreover, the measured values of each phase are shown in Fig. 5. The error between the measured value and the ideal value for phase shifts π/2 rad and π rad was 3% and 9%, respectively. We considered that the errors are due to higher order components in light modulation. From these results, we confirmed that phase shift of modulated light faster than the frame rate of the image sensor can be measured by the multi-aperture image capturing system. In measuring the distance, the distance image can be obtained by a measurement of phase varying according to the time of flight of the light reflected from a measured object.

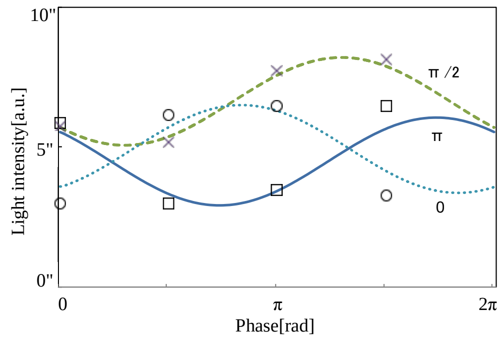

Fig4. Measured intensity of modulated light with four different phase shifts and sine curves fit to measured values.

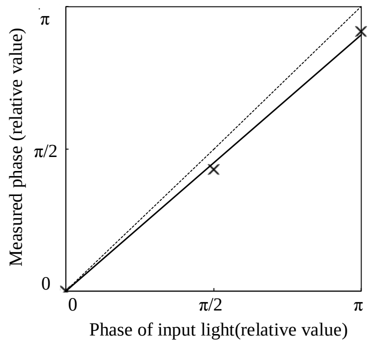

Fig5. Measured results of relative phase shift.

4. Conclusion

We confirmed the principle of the elemental technology, which is required to implement high speed 3-D measurement. The measurement method by the multi-aperture image capturing system proposed in this work enables a new sequential acquisition of the distance image at high frame rate, and can be applied to fast phenomenon, which is difficult to be measured by conventional measurement methods.

The reported work is preliminary experiment for proof of principle of the proposed method. The result of this work confirms the basic concept of the proposed approach. In order to obtain sufficient result by utilizing the full ability of the image sensor, continuous research is required to improve the response speed of the image sensor and the frequency of light modulation, and the investigation for appropriate shutter pattern.

References

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