A multi-aperture compressive time-of-flight CMOS imager for pixel-wise coarse histogram acquisition

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I. Introduction

ToF imagers can obtain depth maps based on traveling time of light between a subject and a source of short light pulse equipped with a camera. Fig. 1 shows schematic diagrams of two ToF imaging methods: direct and indirect methods. The direct method measures ToF from a histogram of photon arrival time[1], which builds a histogram with many bins from the received light. On the other hand, in the indirect method, photo electrons are accumulated with multiple time-windows. The depth map is obtained by calculating from the amount of accumulated electrons[2]. The direct method offers long range and high resolution, although complex signal processing circuitry and large memory are required. Most part of the circuits of indirect method imagers are almost the same as ordinary CMOS imagers, and much simpler than that for the direct method. However, it has a tradeoff between range and resolution.

In this paper, a new ToF CMOS imager based on compressive sampling is proposed, which has both benefits of direct and indirect ToF methods: histogram acquisition and simple circuits. Its feasibility is confirmed in simulation. Furthermore, by using multi-aperture optics and the compressive CMOS imager, depth imaging whose resolution and range are 0.75m and 24m, respectively, is realized as a preliminary experiment.

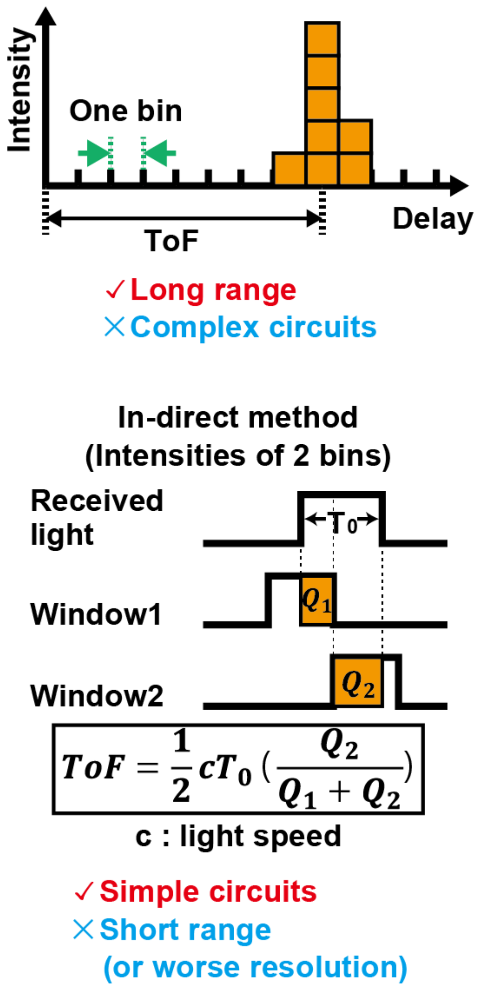

Figure 1: Comparison between direct and in-direct ToF range imaging methods.

II. Architecture

Compressive sampling (CS)[3] is a new high efficiency sampling scheme using sparsity. More frames than the captured frames can be reproduced after solving the inverse problem of the observation system. Fig. 2 shows a concept of CS. When signal $\mathbf{x}$ with N elements is observed, N samplings are needed in the conventional sampling theory. However, in CS, if the original signal $\mathbf{x}$ is K-sparse (K < N), only M samplings, where M is smaller than N and bigger than K, are required. K-sparse means only K elements have finite values and the others are zero. In sampling, M×N-element random observation matrix $\mathbf{A}$ is multiplied with $\mathbf{x}$, and the compressed signal $\mathbf{y}$ is obtained. After sampling, the original

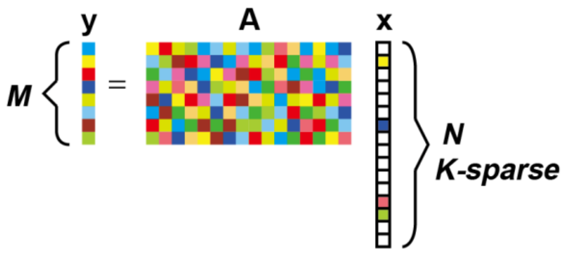

Figure 2: Concept of compressive sampling.

signal **x** is reconstructed from **y** and **A** by solving the inverse problem. The number of sampling is dependent on K in CS. Because ToF signal is very sparse, namely, it includes only one or a few pulses, it is very effective to temporally compress a ToF signal.

Fig. 3 shows a schematic diagram of the proposed ToF imaging method. In CS, a signal is measured with multiple observation matrices. Therefore, multiple temporal random binary shutter patterns are used for CS-ToF. To implement CS-ToF, there are a variety of system configurations. For example, when a wider point spread function than a pixel is used in a single-aperture system, we can use an array of sub-pixels to cover the point-spread function, so that a different shutter pattern can be assigned to each sub-pixel. Another option is a multi-aperture imaging system, in which a different shutter pattern is applied to each aperture. In this paper, the multi-aperture optics shown in Fig. 3(a) is adopted for its simple sensor implementation. Note that signal compression is achieved at each pixel in time, but not in space.

When the pixel values for the same subjective point are picked up, they become a compressed histogram as shown in Fig. 3(b). After solving the inverse problem from the shutter patterns and compressed images, they become the histogram identical to that obtained by the direct method. The time resolution of the reconstructed frames is defined by the minimum shutter pattern pulse. The number of bins is determined by the number of apertures and compression ratio. Compression ratio is defined as the number of compressed frames (apertures) divided by that for the reproduced frames. In Ref. [4], compression ratio of 47% is realized. However, the ToF signal is much sparser than the observed signals in Ref. [4]. Therefore, compression ratio can reduce. Although the histogram by the proposed method is coarser than that by the direct method, it has benefits such as capability of histogram-based signal processing, extended measurement range without any scanning of time windows, and applicability of charge modulation pixels for the direct method.

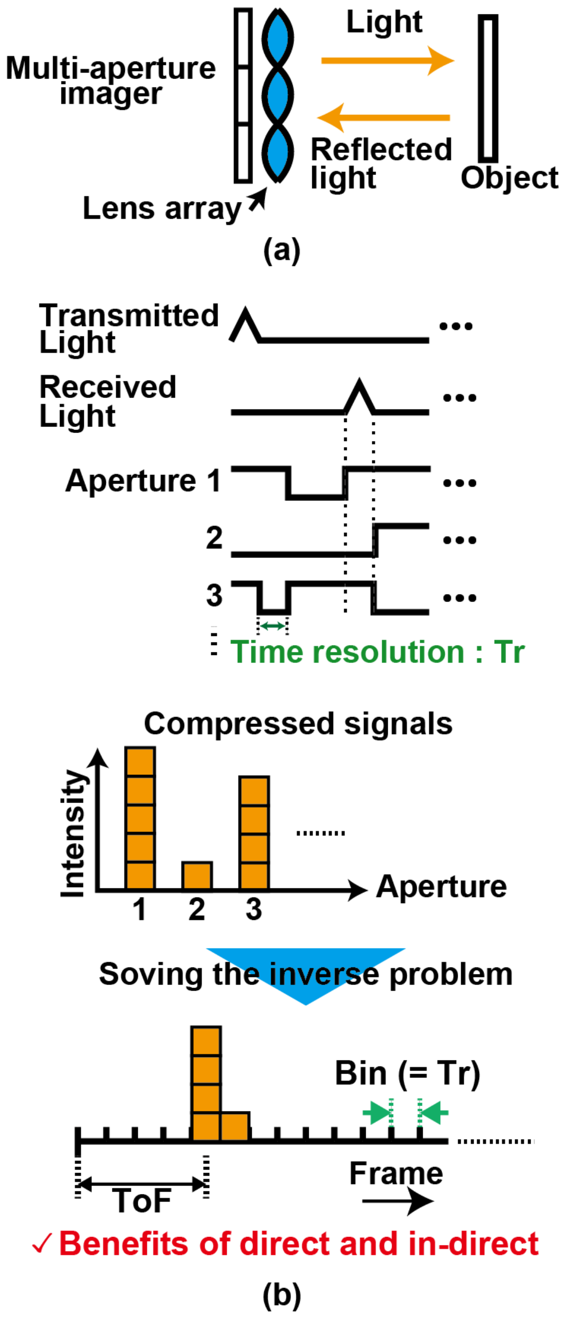

Figure 3: Proposed ToF method using multi-aperture and compressive sampling. (a) The multi-aperture compressive ToF imaging system, (b) a flow of the proposed method.

III. Simulation

The feasibility of the proposed method is confirmed by simulation. In the simulation, 150 images are prepared as original ToF images. The resolution of one image is 64×108 pixels, and only one frame of the images has a finite value and the other images are dark. Fig. 4(a) shows an example of the original image histogram. In this histogram, only frame-50 has a finite value. The images are compressed to 15 apertures with 150-bit random shutter patterns with a 50% duty ratio as shown in Fig. 4(b). Thus, the compression ratio is 10%. The compressed images include photon shot noise and 1-electron-RMS sensor noise. After compression, the time-resolved images are reconstructed by solving the inverse problem as shown in Fig. 4(c). In this simulation, the light pulse position is scanned from frame-1 to frame-150, and peak signal to noise ratio (PSNR) is calculated for every light position to figure out the average, because PSNR changes depending on the position of the bright frame. The average PSNR is as high as 59.5dB, which means smaller compression ratio if there is no background light.

IV. Sensor

To realize the proposed method, a multi-aperture (MA) CMOS imager fabricated in 0.11-μm CMOS imager process [4] is used. The chip block diagram is shown in Fig. 5. The MA imager is composed of 5×3 apertures. An aperture consists of 64×108 pixels and an aperture driver. The pixels uses electric field charge modulation (LEFM)[5] for high-speed charge modulation and accumulation. Shutter patterns are configured to every aperture driver before capturing through a clock controller and an addressing module. Every aperture driver has a 128-bit memory to memorize a shutter pattern and a repetition count from 1 to infinity.

V. Experiment result

To confirm the proposed method, ToF image compression and decompression are demonstrated with the MA CMOS imager[4]. In this experiment, an 88-ps 635nm pulse laser is used and a small light spot on a diffusive white board is captured. The measured time resolution, which corresponds to one bin after reproduction, is 5ns (equivalent to 0.75m).

The imager captures 15 compressed images at the same time, and 32 images are reconstructed by solving the inverse problem with TVAL3[6]. Fig. 6(a) shows the original and the reproduced images for 0.3m and 1.05m. As shown in Fig. 6(b), the histograms based on the reproduced images for a pixel on the light spot are successfully produced. In this preliminary demonstration, the compression ratio is about 47%, and the depth range is 24m.

VI. Conclusion

A new ToF imaging method based on multi-aperture optics and compressive sampling in the time domain is proposed. The benefits are simple circuits based on indirect ToF pixels, full histogram acquisition, and capability of long range measurement. The feasibility of the method in compression ratio of 10% is confirmed in simulation. In the preliminary experiments, pixel-wise histograms with 32 bins are successfully reproduced. The resolution is 0.75m and the calculated range is 24m.

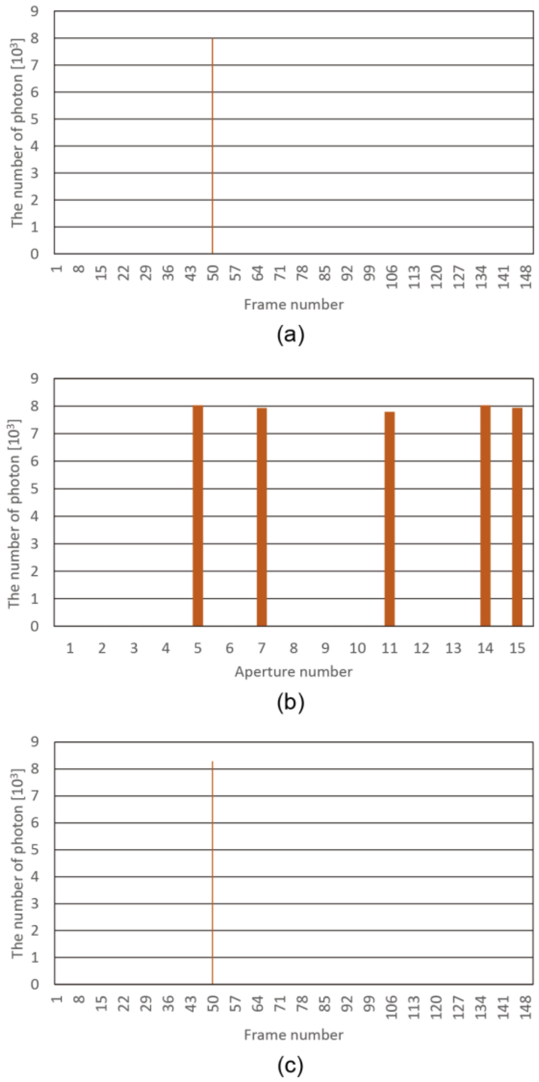

Figure 4: Simulation results of the CS ToF imaging. (a) Histogram of one pixel in prepared original 150 images, (b) compressed histogram, (c) reconstructed histogram.

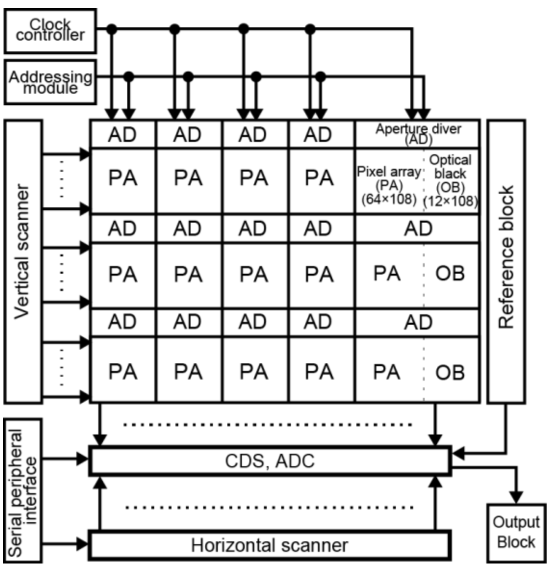

Figure 5: Block diagram of the MA CMOS imager.

VII. Acknowledgment

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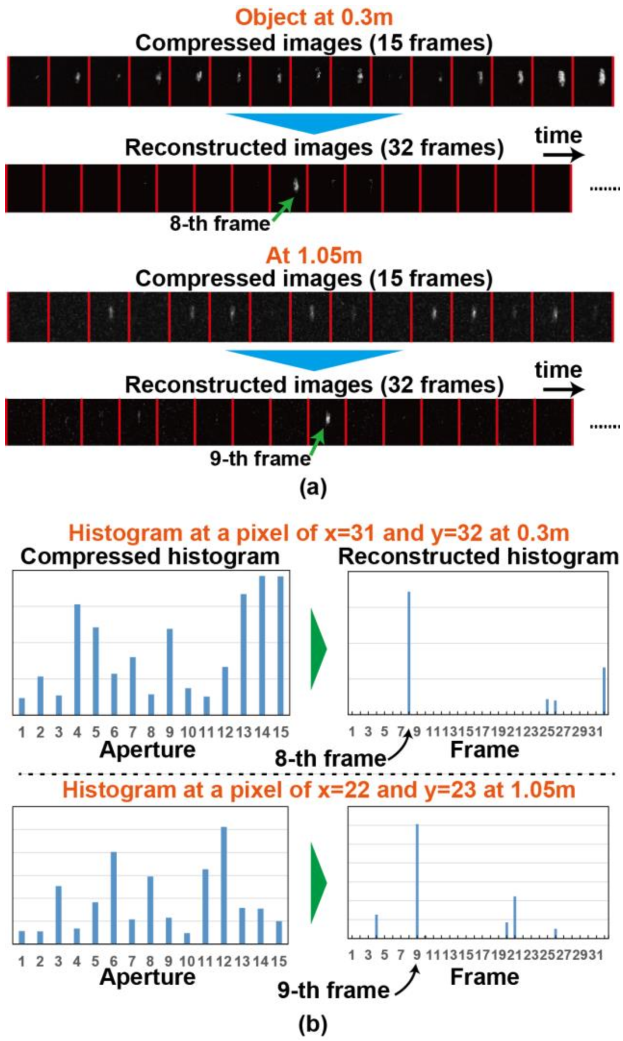

Figure 6: Experimental results. (a) Compressed images and reconstructed images for the distance of 0.3m and 1.05m and (b) compressed and reconstructed histograms of a pixel at (x, y)=(31, 32) and (22, 23).