Smart Sensor Architecture for Real-Time High-Resolution Range Finding

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Abstract

In this paper, a smart sensor architecture for real-time and high-resolution active range finding is presented. It realizes not only a high frame rate enough for real-time 3-D measurement, but also a high pixel resolution due to a small pixel circuit, and a high sub-pixel accuracy due to a gravity center calculation using an intensity profile. Simulation results show the ultimate frame rate is 32.6k fps (i.e. 31.8 range_map/sec) in a 1024 × 1024 pixel sensor. A 3-bit intensity profile allows a sub-pixel accuracy under 0.1 pixel. A 128×128 smart sensor has been developed and successfully tested. A 2-D image, a range map and a texture-mapped 3-D image have been acquired by the active range finding system using the fabricated sensor.

1. Introduction

In recent years, we often see 3-D computer graphics in movies and televisions, and handle them interactively using personal computers and video game machines. Real-time range finding system provides new attractive applications. 3-D measurement using triangulation-based light projection method allows high-accuracy range finding by simple calculation. It, however, requires thousands of images every second for real-time 3-D measurement. For example, a 1024 × 1024 range map in video rate requires 30k fps. It is difficult to realize real-time 3-D measurement by a standard readout architecture such as CCD. Even the high-speed CMOS APS using column-parallel ADCs [1] realizes 500 fps.

Some position sensors for the fast range finding are reported in [2, 3]. The sensor using pixel-parallel architecture [2] can acquire a 192×124 range map in video rate (i.e. 30 range_map/sec). It, however, has a large circuit for a frame memory and an ADC in pixel. It's difficult to realize a high pixel resolution. The sensor using a row-parallel winner-take-all (WTA) circuit [3] can acquire a 64×64 range map in 100 range_map/sec. Its pixel size can be smaller than [2] due to the row-parallel architecture. The pixel resolution, however, is limited by the precision of a current-mode WTA circuit. It's also difficult to realize a high frame rate enough for real-time range finding with a high pixel resolution.

In this paper, a smart sensor architecture for real-time high-resolution range finding is proposed. The architecture can realize not only high-speed position detection of the projected sheet light enough for real-time 3-D measurement, but also a high pixel resolution due to a 3-transistor pixel circuit. The present sensor can acquire both the position and the intensity profile of the projected light simultaneously. The intensity profile is used for a higher accurate range finding by a gravity center calculation than the conventional smart position sensors [2]-[5]. In addition, the sensor can acquire a 2-D image as well, so a texture-mapped 3-D image can be reproduced by the same sensor. A 128×128 smart image sensor has been developed and successfully tested.

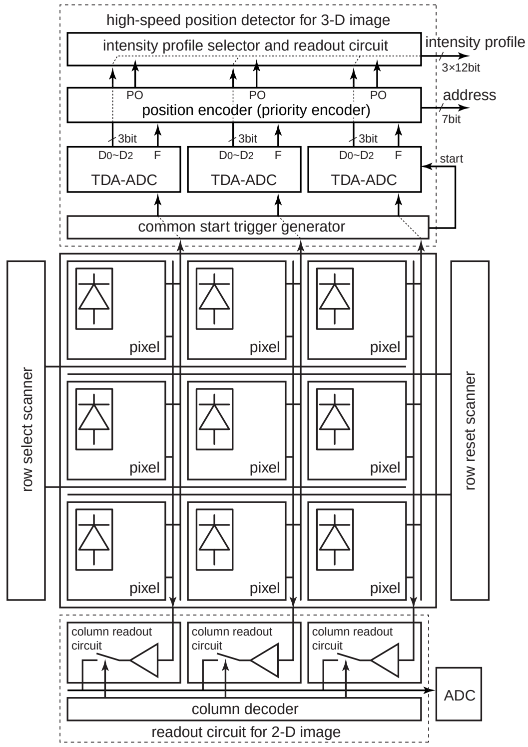

Figure 1. Block Diagram of Sensor Architecture

2. Sensor Architecture

Figure 1 shows a block diagram of the proposed sensor architecture. The sensor has a high-speed position detector for 3-D measurement, a pixel array, row select and reset scanners, and a readout circuit for 2-D image. The high-speed position detector consists of three pipelined modules as follows: time-domain approximate ADCs (TDA-ADCs) with a common trigger generator, a priority encoder composed of a priority decision circuit

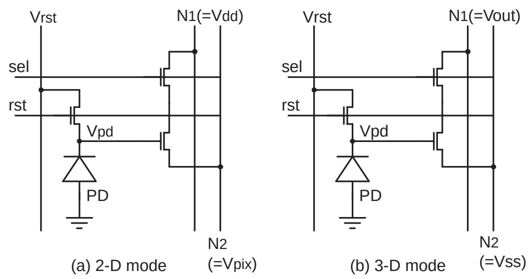

Figure 2. Pixel Configurations

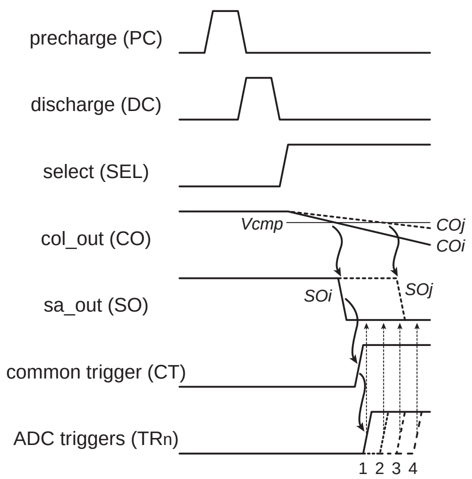

Figure 3. Timing Diagram of TDA-ADC.

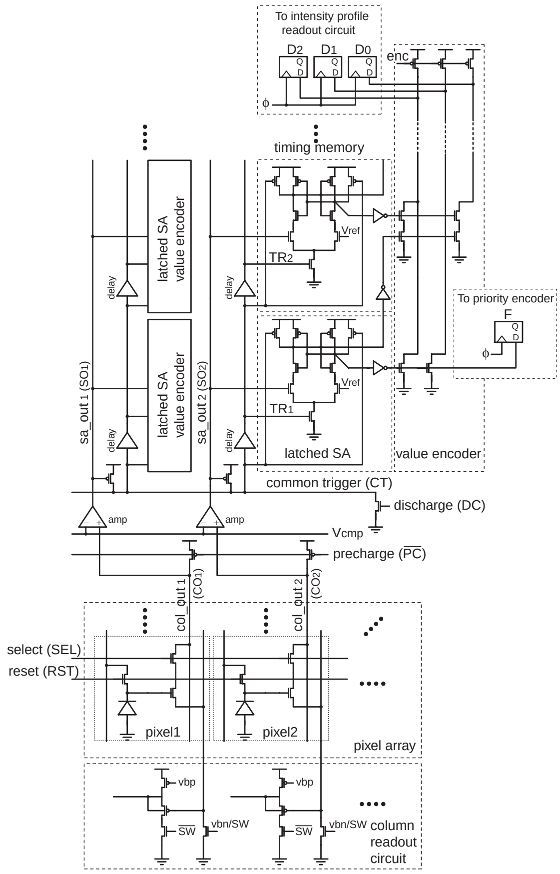

Figure 4. Structure of Time-Domain Approximate ADC

and an address encoder, and an intensity profile readout circuit. The readout circuit for 2-D image consists of column-parallel source follower buffers, a multiplexer with a column selector, and an ADC.

2.1. Pixel Circuit

In the present architecture, a pixel circuit can be the same as the 3-transistor CMOS APS [6]. This pixel structure realizes a small pixel area and a high pixel resolution in general. The pixel circuit in the architecture has two operation modes as follows. (1) In 2-D mode, the node N_1 is fixed to the supply voltage V_{dd}, and the node N_2 leads to the readout source follower circuit as shown in Fig. 2 (a). (2) In 3-D mode, the node N_1 is employed for the output of the dynamic circuit, and the node N_2 is connected to the ground V_{ss} as shown in Fig. 2 (b). After the node N_1 is charged to a precharge voltage V_{pc} and the pixel is selected, the output voltage V_{out} at N_1 begins to decrease depending on the pixel value V_{pd}. The pixel values are detected as discharging times. Namely N_1 associated with pixels of a strong incident light is decreasing more slowly.

2.2. Time-Domain Approximate ADC

In the present architecture, the pixels of a strong incident light are quickly detected by time-domain approximate ADCs (TDA-ADCs). Figure 3 shows a timing diagram of the TDA-ADC and Figure 4 shows the structure of the TDA-ADC. The TDA-ADC consists of a precharge circuit, an amplifier, a common trigger generator, delay circuits, latched sense amplifiers (SAs) for a timing memory, and a pixel value encoder. The TDA-ADC employs the speed of decreasing voltages at the output lines CO_n for a threshold logic and an approximate analog-to-digital conversion. The threshold intensity of the projected light detection can be decided adaptively by the common trigger generator. In addition, both the position and the intensity profile of the projected light can be acquired.

The output voltages of each column CO_n are precharged to V_{pc} by the signal PC. The common trigger line CT is, then, discharged by the signal DC. Pixels of a row line are selected by SEL and the output voltages at CO_n begin to decrease according to each pixel value. SO_n is thrown OFF when the voltage at CO_n is below the reference voltage V_{cmp}. The common trigger line CT is thrown ON by the first-arrival signal of SO_n, that is, the trigger is initiated by the weakest intensity. CT propagates through delay circuits, so that the trigger signals TR_n for the latched SAs are thrown ON one after another. The latched SAs sample and hold SO_n in each timing with TR_n. The intensity values of detected pixels in a timing memory are encoded and transferred to a intensity profile readout circuit. The result of the first latched SA is transferred to a priority encoder for position detection.

2.3. Position Encoder

The present architecture has a priority encoder to search the position of the detected pixels and to encode

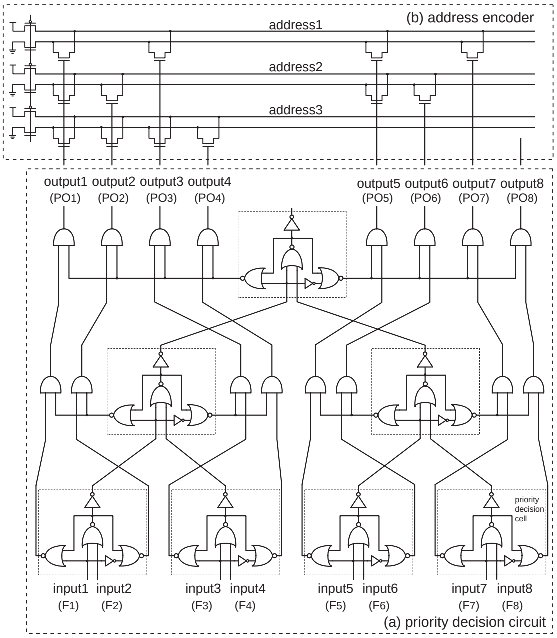

Figure 5. Schematic of Priority Decision Circuit.

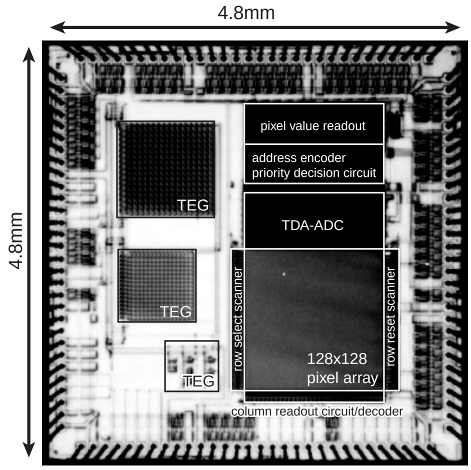

Figure 6. Microphotograph of the Fabricated Sensor.

Table 1. Parameters of the Fabricated Sensor.

Process	0.6 μm CMOS 3-metal 2-poly-Si
Sensor size	3.32 mm $\times$ 1.88 mm
# pixels	128 $\times$ 128 pixels
Pixel size	12.0 μm $\times$ 12.0 μm
# trans. / pixel	3 transistors
Fill factor	29.54 %

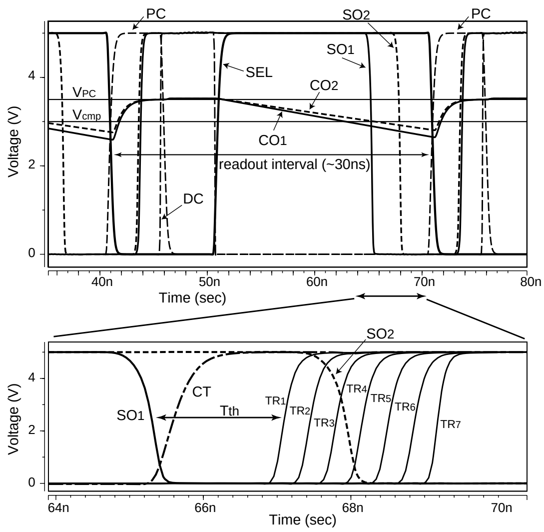

Figure 7. Simulated Wave Forms.

its address quickly. The priority encoder consists of a priority decision circuit and an address encoder as shown in Fig. 5. The priority decision circuit can detect only a prior active input (i.e. the left edge of the detected pixels), and the output corresponding to the prior active input is thrown ON. After encoding, the prior active input can be masked by the output of the priority decision circuit sequentially in order to acquire the address of the next peak of intensity.

2.4. Intensity Profile Readout Circuit

After an address encoding of the detected pixels, the intensities of them are read out in order to acquire the intensity profile of the peak. A 3-bit intensity profile allows high sub-pixel accuracy under 0.1 pixel. In general, the position detection using a binary image realizes no more than 0.5 pixel accuracy. The accuracy of measured range data is improved proportionally to the sub-pixel accuracy.

3. Chip Implementation

We designed and fabricated a smart sensor using the present architecture in 0.6 μm CMOS process[1]. Figure 6 shows a microphotograph of the fabricated smart sensor. The sensor has a 128 $\times$ 128 pixel array, 3-bit TDA-ADCs, a 128-input priority encoder, a 3$\times$12-bit-parallel intensity profile readout circuit, select and reset scanners, and a column-parallel readout circuit. The pixel has a photo diode and 3 transistors, and its area is 12 μm $\times$ 12 μm with 29.5% fill factor. The photo diode is formed by an n^+-diffusion in a p-substrate. Table 1 shows the parameters of the fabricated sensor.

[1]The sensor in this study has been designed with CAD tools of Avant! Corp. and Cadence Design Systems Inc., and fabricated through VLSI Design and Education Center (VDEC), University of Tokyo in collaboration with Rohm Corp. and Toppan Printing Corp.

4. Performance Evaluation

4.1. Frame Rate

Figure 7 shows the simulated wave forms of the TDA-ADC. After a row line is selected by SEL, the output CO_1 and CO_2, which are precharged to V_{pc}, begin to decrease. In this simulation, the pixel values are 2.4 V and 2.2 V. The present sensor can read one row line in 30 ns. The delay time of the priority encoder is 7.2 ns, and the readout time of the intensity profile is 4.3 ns. The ultimate frame rate of the sensor is 260k fps (i.e. 2034 range_map/sec). The present architecture is capable of acquiring a 1024$\times$1024 range map in 31.8 range_map/sec.

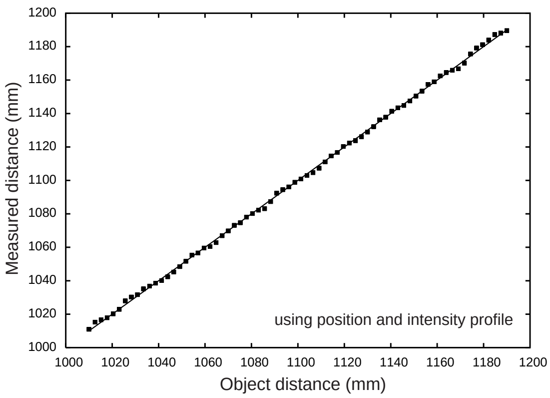

Figure 8. Linearity of Measured Range Data.

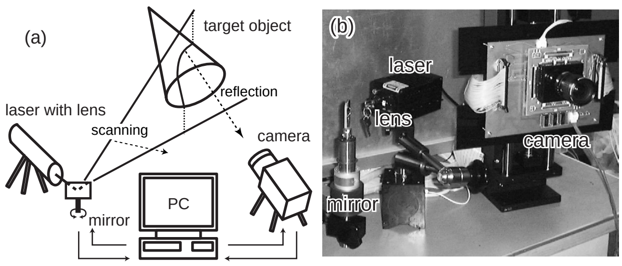

Figure 9. 3-D Measurement System.

4.2. Sub-Pixel Accuracy

Figure 8 shows measured distances using the positions and the intensity profile. The position of the projected light is calculated by a gravity center calculation using the intensity profile. The standard deviation of measured error is 1.18 mm and the maximum error is 2.64 mm at a distance of 1000 mm – 1200 mm by a gravity center calculation using an intensity profile. On the other hand, the standard deviation is 2.58 mm and the maximum error is 7.61 mm without an intensity profile, that is, based on a binary image. The present sensor can realize higher accuracy than the conventional position sensors[2]-[5].

5. Application to 3-D Measurement

Figure 9 (a) illustrates the measurement system based on triangulation using the present smart sensor. The 3-D measurement system is composed of the camera using the fabricated sensor, a laser (wavelength 665 nm) with a rod lens for beam extension, a scanning mirror, and a PC with a digital I/O board and ADC/DAC boards. Figure 9 (b) shows a photograph of the measurement system.

A range data can be calculated from the positions of the projected laser beam on the sensor plane and both positions of the sensor and the projected light source. Figure 10 (a) shows an acquired 2-D image by the present sensor. Figure 10 (b) shows the range data calculated and calibrated by the measurement results in 3-D mode. The present sensor can acquire both a 2-D image and a range map, and a texture-mapped 3-D image can be reproduced as shown in Fig. 10 (c). In the active 3-D measurement system, the whole range data of a target object can not be obtained because of a dead angle of a camera and a laser projector in general. 3-D measurement system using a couple of cameras and projectors can acquire an all-direction 3-D image.

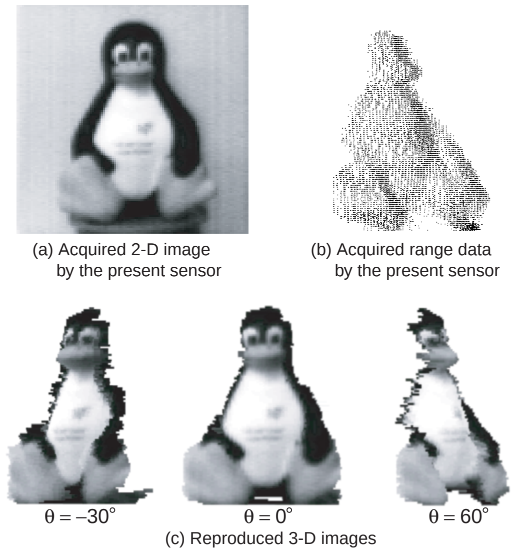

Figure 10. Acquired and Reproduced Images.

6. Conclusions

A smart sensor architecture for real-time and high-resolution active range finding has been proposed. It realizes not only a high frame rate enough for real-time 3-D measurement, but also a high pixel resolution due to a small pixel circuit, and a high sub-pixel accuracy due to a gravity center calculation using an intensity profile. The present sensor can acquire a 2-D image as well, so a texture-mapped 3-D image can be reproduced by the same sensor. A 128×128 smart sensor has been developed and successfully tested. The ultimate frame rate is 260k fps (i.e. 2034 range_map/sec) in a 128×128 pixel sensor. The standard deviation of measured error is 1.18 mm and the maximum error is 2.64 mm at a distance of 1000 mm – 1200 mm. A 2-D image, a range map and a texture-mapped 3-D image have been acquired by the 3-D measurement system using the fabricated sensor.

7. References

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