A 120 × 110 Position Sensor With the Capability of Sensitive and Selective Light Detection in Wide Dynamic Range for Robust Active Range Finding

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***Abstract*—A 120 × 110 sensitive and light selective position sensor array with wide dynamic range is presented. The sensor can detect the position of a low-intensity light projected on nonuniform background illumination for a robust range finding system. It achieves −18-dB signal-to-background ratio (SBR) light detection in wide range of 48-dB background illumination due to a modulated light projection and correlation technique on the sensor plane. It also realizes selective light detection for multiple light projection systems. The range finder has been fabricated in 0.6-μm CMOS process and successfully tested. The range finding system achieves <1.5-mm range accuracy at 1000 mm using a low-intensity projected laser beam in a nonuniform target scene.**

***Index Terms*—CMOS image sensor, high selectivity, high sensitivity, position sensor, range finding, robust, wide dynamic range.**

I. Introduction

TRIANGULATION-BASED light projection is a typical technique for three–dimensional (3-D) measurement, which achieves high range accuracy with simple calculation in general. In the future, a 3-D measurement system will become part of a walking robot, a recognition system on vehicles, 3-D contents of multimedia, and so on. It, however, has a problem to realize such applications. A typical system configuration of a triangulation-based light projection method is shown in Fig. 1. A spot laser beam is projected on a target object and a image sensor acquires the position of the reflected beam on the sensor plane as shown in Fig. 1(a). Based on triangulation, the range data of the target object can be calculated by the angle of the projected beam and the beam position detected on the sensor plane. And then the range map is acquired by a spot beam projection with *X*-*Y* scanning. On the other hand, we can also get the range map using a sheet beam projection with *X* scanning in the same way as shown in Fig. 1(b). The system using a sheet beam projection can reduce the number of the frames of position detection for range finding, and so it achieves higher range finding rate. The conventional image sensors and range finders [1]–[9] detect a position of a projected light on the sensor plane by its intensity. Therefore, it is difficult for the active method to use illumination levels that are safe for human eyes but strong enough to be recognized against a nonuniform contrast background. A simple method for the suppression of background illumination is color filters mounted on the sensor. Sunlight has, however, distributed wavelengths with strong intensity so that the color filters are not enough for some applications. A high-sensitivity position sensor with the capability of electronic suppression of background illumination

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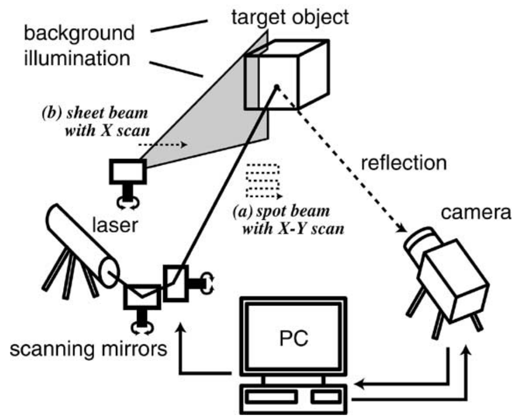


Fig. 1. Typical system configuration of triangulation-based light projection method. (a) Spot beam projection with *X*-*Y* scanning. (b) Sheet beam projection with *X* scanning.

is required in such situations. Correlation techniques provide a possible solution to the problem. The correlation sensor [10] can suppress background illumination to obtain selective light detection. Its dynamic range is, however, limited by the linear differece circuit due to voltage signal saturation. It is not applicable for a strong contrast image in outdoor environments.

Our proposed sensing scheme for projected light detection achieves high sensitivity and wide dynamic range in nonuniform background illumination [11]. In this paper, we present a 120 × 110 sensitive position sensor that has a high light selectivity in wide dynamic range. It can detect the position of a low-intensity light projection on a nonuniform background for robust range detection.

II. Circuit Configuration

A. Pixel Circuit and Sensing Scheme

The basic idea [11] of a sensing scheme for projected light detection, shown in Fig. 2(a), achieves both high sensitivity and wide dynamic range in nonuniform background illumination. In addition, selective light detection is realized for a multiple-light-projection system as implemented in the circuit of Fig. 2(b). The pixel consists of a photo diode, a current-mode suppression circuit with low-pass filters, a bias circuit for the low-pass filters, a logarithmic I–V converter, two integrators for correlation, and two source follower circuits for readout. The transistor size (W/L) is also shown by micrometers (μm) in Fig. 2. The size of coupled or cascaded transistors is omitted in Fig. 2 since they are the same size. The operation of the system uses a projected light source with detection based on the modulation frequency. A current-mode suppression circuit for constant illumination provides adaptive removal of background illumination and avoids saturation difficulties. A logarithmic

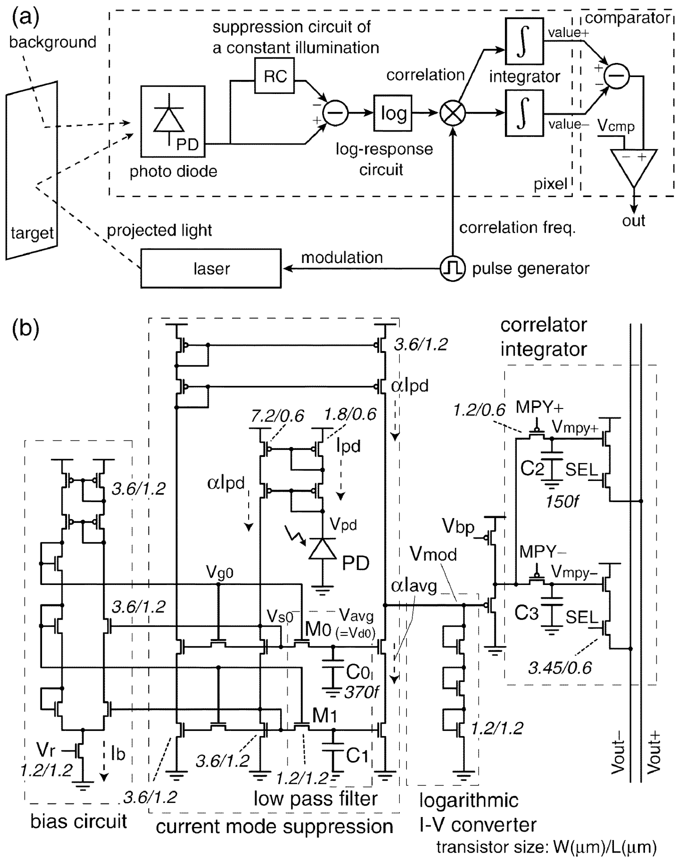


Fig. 2. Sensing scheme. (a) Basic idea. (b) Circuit implementation.

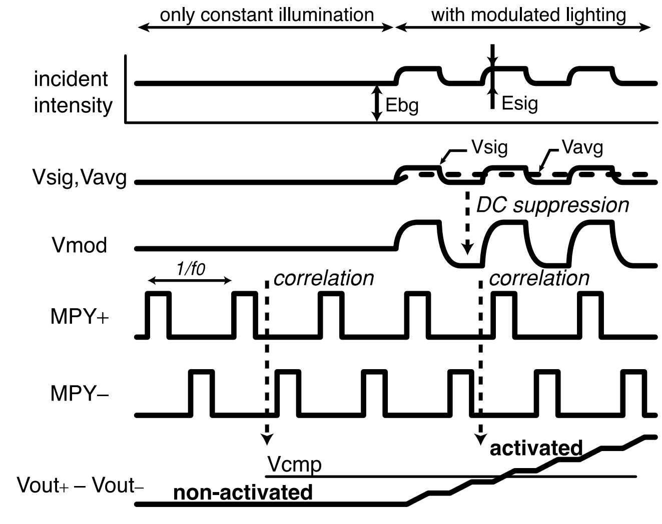


Fig. 3. Pixel circuit operation.

response circuit limits the level of the ac component of output current. A correlation circuit multiplies the alternating signal by a global external signal of the correlation frequency. Light can be detected selectively by the correlation signal when multiple lights of various modulation frequencies are projected on the scene. Integration of the correlation permits detection of extremely weak modulation signals. In addition, the pixel-parallel sensing scheme achieves quick detection for high-speed range finding.

Fig. 3 shows a timing diagram of the sensing scheme. Here f_0 is a correlation frequency. When the incident light is modulated, two components of photo current I_{pd} are a constant current I_{dc} due to background illumination and an alternating current I_{ac} due to the modulated light projection. The average current I_{avg} generated by a low-pass filter is subtracted from the original photo current in the current-mode suppression circuit. Here, the time constant of the low-pass filter is designed at 1.2 ms in a typical situation, though it can be adjusted by the external bias voltage V_r. The output current I_{mod} is converted to the voltage V_{mod} and correlated by the external signals, $MPY+$ and $MPY-$, synchronized with the correlation frequency. The integrator output voltages are now read. When the incident light contains background illumination, that is, the photo current is constant, I_{mod} is dc and the difference voltage between $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ is zero. Alternatively, the difference voltage is acquired only when the incident light contains the correlation frequency. The pixel is activated when the difference voltage exeeds the reference voltage V_{cmp}.

B. Sensor Structure and Operation

Fig. 4 shows a sensor structure with our photo detectors. It consists a pixel array, a row-select address decoder, row buffers of correlation signals, column-parallel subtraction circuits, and comparators with a column-select decoder. Both of the output voltages, $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$, are read out into the subtraction circuit. The difference voltage between $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ is compared with the reference voltage V_{cmp} at the column-parallel comparators. All pixels of a selected row are decided to be activated or not in parallel. Fig. 4 also shows its timing diagram. After a pixel is selected, its output voltages, $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$, are sampled on each node of C_{dif} by ϕ_1. When ϕ_2 is ON, the voltage V_+ at the node of C_{dif} is given by

$$V_+ = V_{\mathrm{out}+} - V_{\mathrm{out}-} + V_o \tag{1}$$

where V_o is an offset voltage for adjusting to the input range of the comparator. The reference voltage V_{cmp} of the comparator is given by

$$V_{\mathrm{cmp}} = V_{\mathrm{ref}} + V_o. \tag{2}$$

The voltage V_+ is compared with V_{cmp} at a latch sense amplifier when ϕ_3 is ON. The pixel will be activated when the difference voltage exceeds the threshold voltage V_{ref}. When the incident light of the selected pixel contains a modulated light synchronized with the correlation frequency, the difference voltage becomes large as shown in *case1* of Fig. 4. Alternatively, the difference voltage is zero or small as shown in *case2* when the incident light does not contain the correlation frequency.

The variation in characteristics of two readout ways for $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ causes the offset between the output voltages, V_+ and V_-. And the comparator requires a large margin of threshold level. That is, V_{cmp} should become higher, and then a large difference voltage of $V_{\mathrm{out}+}$ and $V_{\mathrm{out}-}$ is required. It means that the variation is a possible reason to decrease the sensitivity of our sensing scheme. It is suppressed by the threshold margin at column-parallel comparators to detected activated pixels with a correlative incident light. On the other hand, the uniformity

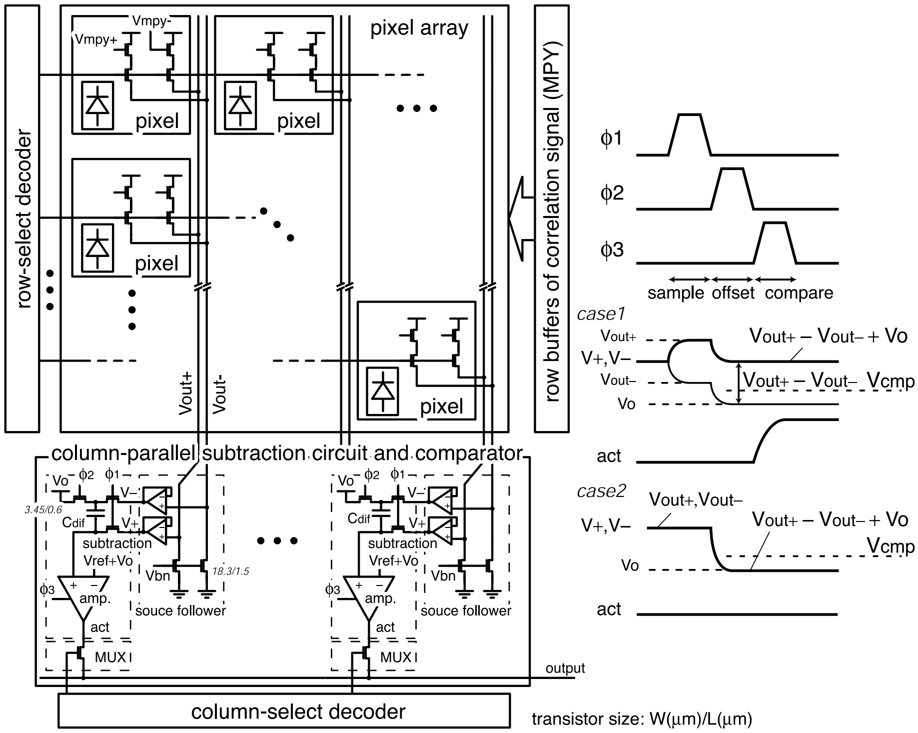


Fig. 4. Array structure and timing diagram of the position sensor.

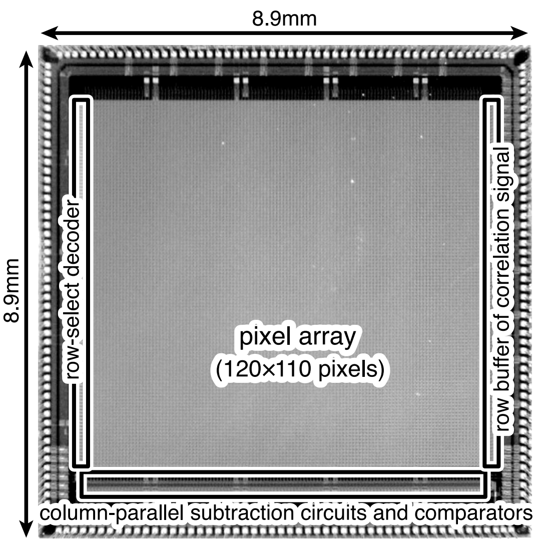
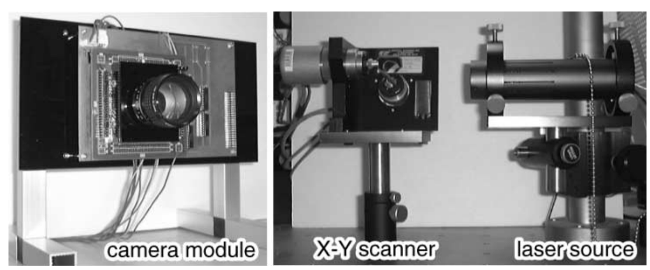


Fig. 5. Die microphotograph.



(a) (b)

Fig. 6. Our measurement system. (a) Camera module with the present sensor. (b) Spot beam source with *X-Y* scanning mirrors.

of the circuits over the array hardly influences the performance since the suppression of background illumination and the correlation of a incident light are carried out in pixel parallel.

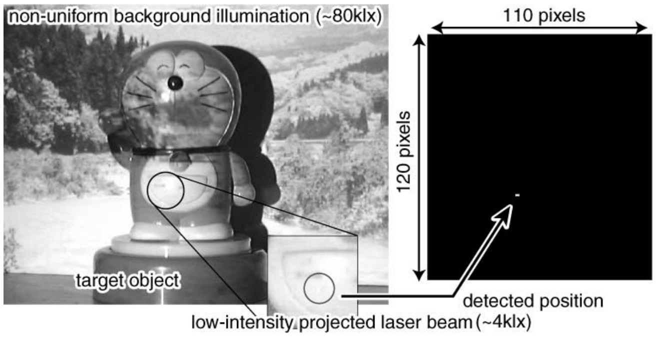
III. Chip Implementation

The position sensor with 120×110 pixels has been designed and fabricated in 0.6-μm two-poly-Si three-metal CMOS process. Fig. 5 shows a chip microphotograph of the fabricated position sensor. The pixel area is 60 μm $\times$ 60 μm with 13.5% fill factor. The photo diode is formed by an n^+-diffusion in a p-substrate.

IV. Experimental Results

For performance evaluation, the measurement system of the fabricated sensor has been constructed with a laser pointer (wavelength 635 nm), a pulse generator for modulated lighting, a light projector for nonuniform background illumination, and a luxmeter. Fig. 6 shows a camera module with the present sensor and a spot beam source with *X-Y* scanning mirrors in our measurement system.

Fig. 7 shows a measurement result of the detection of a low-intensity light source against strong and nonuniform background illumination. The modulated laser beam corresponding to 4 klx is projected on a target object. the maximum intensity of the background illumination is 80 klx. In this measurement, the correlation frequency is set at 8 kHz and the correlation operation lasts 0.7 ms. The distance between the range finder and the target object is $\sim$600 mm. The range finder detects the position of the projected laser beam clearly, as shown in Fig. 7(b). Its light detection has a tolerance not only to nonuniform background illumination but also to target colors.



(a) (b)

Fig. 7. High sensitive position detection in nonuniform target scene. (a) Measurement environment. (b) Captured image.

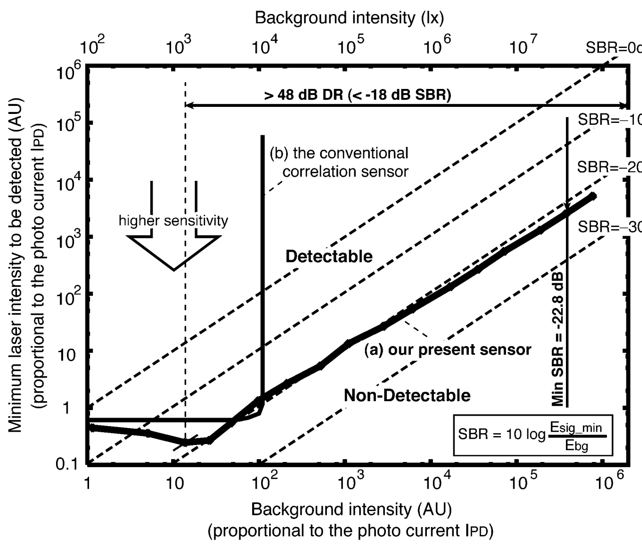


Fig. 8. Sensitivity and dynamic range.

The range data of a target object can be acquired by triangulation when the projected laser beam is scanning on a target object and the sensor detects the position of the projected laser beam on the sensor plane. We show its sensitivity, dynamic range, selectivity, range accuracy, and reproduced range maps.

A. Sensitivity and Dynamic Range

Fig. 8 shows the relationship between the background intensity E_{bg} and the minimum detectable intensity $E_{\mathrm{sig\_min}}$ of the projected light. In the measurement of sensitivity and dynamic range, the modulation frequency is 1 kHz and the frame interval is 5 ms. To evaluate the sensitivity of the light detection, the intensities of the projected light and the background illumination are measured by the photo current I_{pd} generated by each incident light. It is because the projected laser beam has only 635-ns wavelength, which is relatively sensitive for the photo detector, and the background light has distributed wavelengths. The illuminance corresponding to the background photo current is shown in Fig. 8 (in the upper axis) for reference.

The experimental results of the present sensor is shown by (a) in Fig. 8. The present sensor enables to use a low-intensity projected light due to suppression of background illumination. The minimum signal-to-background ratio (SBR), which stands for the sensitivity of the light detection, is -22.8 dB. SBR is defined as follows:

$$\mathrm{SBR} = 10 \log \frac{E_{\mathrm{sig\_min}}}{E_{\mathrm{bg}}}. \tag{3}$$

In addition, the high-sensitivity light detection is available without saturation in wide range of background illumination. The high sensitivity under -18-dB SBR is achieved in >48-dB range of background illumination. For example, the projected light intensity can be equivalent to $\sim 1.2 \times 10^3$ lx in outdoor environment, where the background intensity is $\sim 1.1 \times 10^5$ lx in summer season. On the other hand, it can be equivalent to $\sim$ 22 lx in a room, where the background intensity is $\sim 1.0 \times 10^3$ lx in general.

Fig. 8 shows that the sensitivity becomes worse under low-level irradiance conditions due to the current mirror speed and mismatch, hence, a higher intensity level of the projected beam is required to keep the correlation speed and signal-to-noise ratio under such a situation. The maximum dynamic range is limited by our test equipment. According to a circuit simulation, the limiting factor of dynamic range is a saturation problem of the logarithmic-response photo detector. In other words, the reverse bias voltage at a photo diode becomes low due to a strong incident light so that the photo diode cannot get the photo current in proportion to the incident light.

For comparison, the capability of the conventional correlation sensor [10] is shown by (b) in Fig. 8. The present position sensor is more applicable to wide variety of applications than the conventional correlation sensor with a saturation problem as shown in Fig. 8. The performance is achieved by a current-mode dc suppression circuit to avoid a saturation problem and a correlation circuit to accumulate a small signal swing from a logarithmic-response circuit.

In our measurement, the noise level caused by various reasons such as transistor mismatch has been evaluated by the threshold adjustment of a column-parallel comparator under a constant incident illumination since our sensor provides only a binary image based on correlation. The correlation output of a column-parallel subtract circuit is theoretically the same level of V_o, which is shown in Fig. 4. That is, the noise level can be acquired by the threshold adjustment as the offset voltage from V_o. The average noise level of the present sensor was 42.3 mV. The standard deviation of the noise levels was 15.7 mV. In the range finding, the threshold voltage is set to the total voltage of V_o, the average noise level and a threshold margin. The fluctuation of the noise level can be suppressed by the threshold margin of 100 mV to detect the activated pixels.

In general, the range finding based on a light projection method suffers from reflectance variations of a target surface. However, the damage to our system is less than the conventional systems since our sensor can keep the SBR to detect the projected beam in wide range. That is, it is because the reflectivity variations often influence both the ambient light and the projected beam though it depends on the spectrum of their wavelengths.

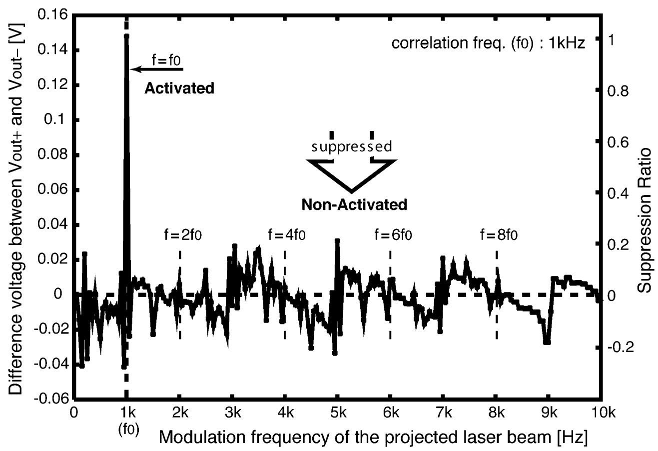


Fig. 9. Selectivity in other ambient light.

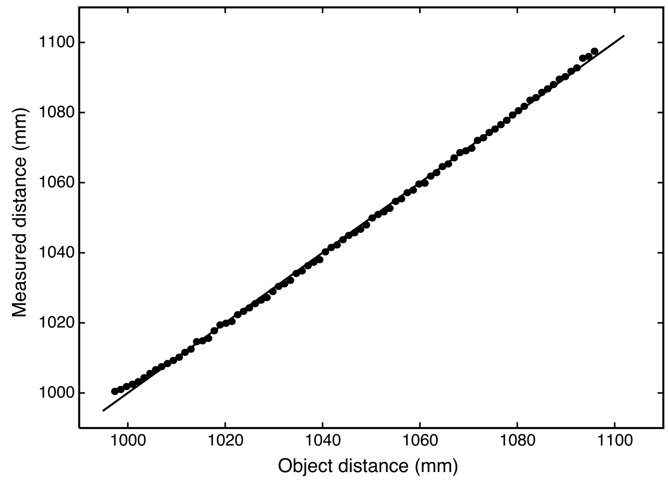


Fig. 10. Linearity of the measured range data.

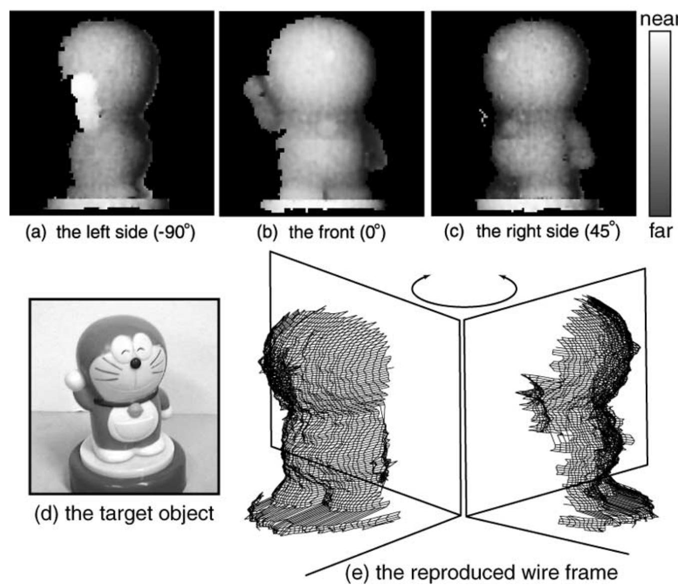


Fig. 11. Measured range maps.

B. Selectivity in Other Ambient Light

The correlation technique suppresses another projected light with a modulation frequency f_1, which is not equal to a correlation frequency f_0. Fig. 9 shows the difference voltage of the correlation outputs, which is $V_{\text{out}+} - V_{\text{out}-}$, at various incident light frequencies. In this measurement, the correlation frequency f_0 is 1 kHz and the frame interval is 5 ms. The measurement result shows that the suppression ratio is < -7 dB. Especially, the suppression ratios of even harmonics of f_0 are < -13 dB. Thus, the projected light of even-harmonics frequencies can be ideally separated in a multiple-light-projection system. Such a separation of concurrently projected lights is important for a triangulation-based range finding to reduce a dead angle, where an object is illuminated by multiple light sources from different directions.

C. Frame Rate

The present position sensor has a tradeoff between its sensitivity and frame rate. The gain of correlation decreases by a high correlation frequency due to parasitic capacitances of a photo diode. That is, the time constant of the photo diode with a logarithmic-response circuit is a limiting factor of the present sensor. The correlation frequency can be 10 kHz at -16-dB SBR and the correlation interval is 0.5 ms in this situation. That is, a possible frame rate of the position sensor is 2000 fps (frames per second) at -16-dB SBR. The achievable frame rate at -22.8 dB, which is the minimum SBR of the present sensor, is 400 fps using 2-kHz correlation frequency. The frame rate at -18-dB SBR, which can be kept in the 48-dB range of background illumination, is 1200 fps using 6-kHz correlation frequency.

D. Range Accuracy

Fig. 10 shows the range accuracy of the range finder. The target object of a flat panel is placed at a distance from 1000 to 1100 mm. The maximum error of the measured range over the full area is 3.2 mm and the standard deviation of range error is 0.89 mm. In the effective area of 110×100 pixels, the maximum measurement error is 1.5 mm and the standard deviation of range error is 0.60 mm. The range finding system has an accuracy of 0.3% at a distance of 1000 mm.

E. Range Finding Results

The 120×110-point range data of a target object is acquired by *X-Y* scanning of a spot laser beam. In the condition of -13-dB SBR, the range maps in Fig. 11(a)–(c) are acquired. The brightness of the range map represents the distance from the range finder to the target. The wire frame of the target object in Fig. 11(d) can be reproduced from the range data as shown in Fig. 11(e). The specification of the position sensor and its range finding system is summarized in Table I. In our measurement system using a spot beam projection with *X-Y* scanning, the range finding takes about 66 s. It can be about 0.5 s due to few frames per range map if we can use a sheet beam projection with *X* scanning. In addition, our sensor has a possibility of higher range finding by means of a higher sensitivity photo diode customized for image sensors because

TABLE I
SPECIFICATION OF THE RANGE FINDER

Process	0.6 μm CMOS 3-metal 2-poly-Si
Chip size	8.9 mm × 8.9 mm
Num. of pixels	120 × 110 pixels
Pixel size	60.0 μm × 60.0 μm
Fill factor	13.5 %
# trans./pixel	43 trans. (inc. 4 MOS capacitors)
Power supply	5.0 V
Sensitivity (SBR)	-22.8 dB SBR
Dynamic range	> 48 dB (< -18 dB SBR)
Selectivity	-13 dB suppression ratio (for even harmonics of f_0)
Light detection rate	2000 fps (at -16 dB SBR)
Depth resolution	1.5 mm at 1000 mm
Power dissipation	250 mW

the performance of correlation speed is limited by the photo diode using a standard CMOS process.

V. CONCLUSION

A 120×110 position sensor for robust range finding has been presented. It has the capability of sensitive and selective light detection in wide dynamic range to utilize a low light levels that is safe for human eyes in a nonuniform contrast target scene. The present sensor achieves highly sensitive light detection of -18-dB SBR in 48-dB background illumination. It also realizes high selectivity to detect only a target projected light in other ambient lights due to -13-dB suppression to even harmonics of a correlation frequency. It has a tradeoff between sensitivity and frame rate, however, its possible frame rate is 2000 fps at -16-dB SBR. In the range finding system, the maximum error of range data is 1.5 mm at a distance of 1000 mm. The present range finder has advantages to future application fields which require safe light projection for human eyes in various measurement environments.

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