40.4: High Performance Photo Detector for Modulated Lighting

– High Sensitivity, High Selectivity, High Suppression of Background, and Wide Dynamic Range –

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Abstract

A new sensing scheme for high-sensitivity and wide-dynamic-range position detection is presented. A correlation circuit and a current-mode suppression circuit of a constant illumination allow high sensitivity, high selectivity, and high suppression of a background illumination. A logarithmic-response circuit is employed to avoid saturation for wide dynamic range. The photo detector can quickly detect the modulated light by the pixel-parallel sensing. It has advantages to applications which require both of availability in various backgrounds and a safe light projection for human eyes. The photo detectors have been developed and successfully tested. The high sensitivity under -18 dB signal-to-background ratio (SBR) is realized in over 47.2 dB dynamic range. The minimum SBR is -22.8 dB and the maximum frame rate is 2000 fps. In addition, the photo detector shows high selectivity in a multiple light system due to the suppression of orthogonally modulated lights.

Keywords

photo detector, modulated lighting, high sensitivity, wide dynamic range, high selectivity

INTRODUCTION

Some applications of 3-D measurement using triangulation-based light projection method, such as a walking robot and a recognition system on vehicles, require both of availability in various backgrounds and a safe light projection for human eyes. Standard imagers and most of the smart position sensors [1]–[7] detect the positions of peak intensity on the sensor plane to acquire the position of the projected light in the 3-D measurement system. Therefore these sensors require a strong light projection when a target object is placed in a non-ideal environment such as a strong background illumination. A possible method to realize the suppression of the background illumination is the interframe difference method, where the difference signals between subsequent two frames are used to detect the projected light. This method is, however, not suitable for a quick detection because it takes at least a frame interval time. Color filters mounted on the sensors can suppress the background illumination and realize a high sensitivity of position detection. 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 a capability of electronic suppression of background illumination is required in such situations.

Correlation technique is one of solutions to the problems. The correlation sensor [8] can suppress a background illumination to obtain high sensitivity. Its dynamic range is, however, limited by the linear difference circuit due to voltage signal saturation. It is not applicable for a strong contrast image in outdoor environment. The range finder with an electronic shutter [9] can prevent the saturation for the problem of [8]. Its dynamic range is decided by the limit of the shutter interval and an extremely short shutter intervals decreases SNR. In addition, it is difficult to adjust an optimal shutter interval autonomously, especially in ununiform backgrounds.

In this paper, a new sensing scheme for high-sensitivity and wide-dynamic-range position detection is presented. For wide dynamic range, a logarithmic-response circuit is employed to overcome the saturation problem of [8], [9]. A correlation circuit and a current-mode suppression circuit of a constant illumination realize higher sensitivity than the conventional sensors [8]–[10]. The photo detector can quickly detect the modulated light by the pixel-parallel sensing. In addition, it also realizes high selectivity due to the suppression of orthogonally modulated lights. The photo detectors have been developed and successfully tested.

PHOTO DETECTOR ARCHITECTURE

The architecture of the proposed photo detector is described in this section. The proposed sensing scheme, its circuit realization, and the principle of its operation are shown.

New Sensing Scheme

Fig.1 illustrates the proposed sensing scheme for high-sensitivity and wide-dynamic-range position detection. In the range finding system, a laser beam modulated by a pulse generator is projected on a target object. The photo detector receives the reflection of the projected laser beam and a background illumination. The photo current generated by the incident light is inputted to a low-pass filter. The output current of the low-pass filter is subtracted from the original photo current. The subtraction is realized using the current mode circuit instead of the voltage mode circuit [8], [9] to avoid saturation. The output current is alternating when the incident light includes a modulated light. It is suppressed by

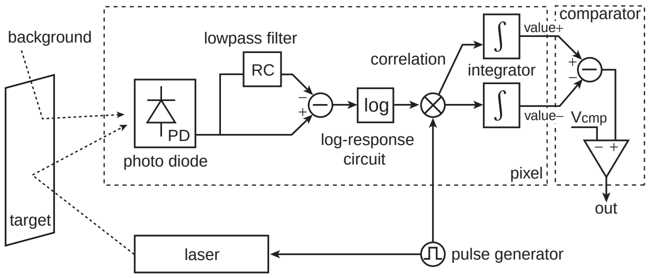

Figure 1. Proposed sensing scheme.

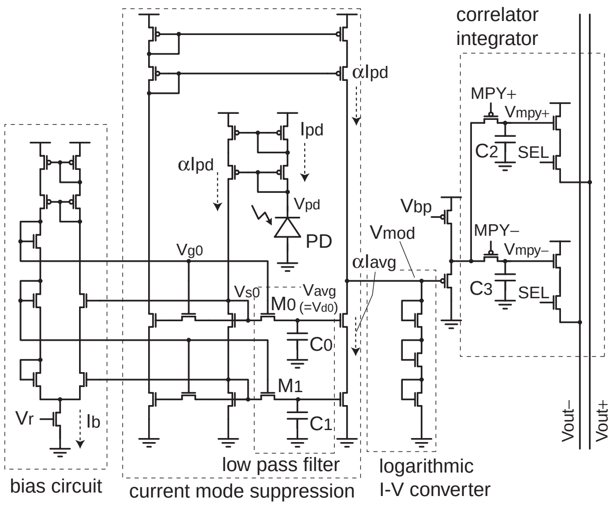

Figure 2. Schematic of the photo detector.

a logarithmic-response circuit and correlated with the correlation frequency. The marked difference voltage between the outputs of each integrator is acquired only when the incident light has the correlation frequency. The low-pass filter and the current mode subtraction circuit realize a suppression of a constant illumination adaptively. The logarithmic-response circuit and the correlation circuit are dedicated to wide-dynamic-range and high-sensitivity photo detection.

Pixel Circuit Realization

Fig.2 shows a schematic of the pixel. The photo current I_{pd} is generated in proportion to the incident intensity. The photo current is copied as the current αI_{pd}, where α is a gain of the current copier circuit. Its average current αI_{avg} is generated by a low-pass filter and it is subtracted from αI_{pd}. The low-pass filter consists of two biased transistors (M_0 and M_1) and two capacitors (C_0 and C_1). The biased transistors are used for a resistor of the low-pass filter as a simple version of the HRES circuit [11]. The drain-source current I_{M0} of the transistor M_0 is controlled by the gate voltage V_{g0}. The bias circuit keeps the gate-source voltage V_q constant in each pixel for a constant resistance. The saturation current of the biased transistor M_0 is half the current of the bias current I_b controlled by V_r.

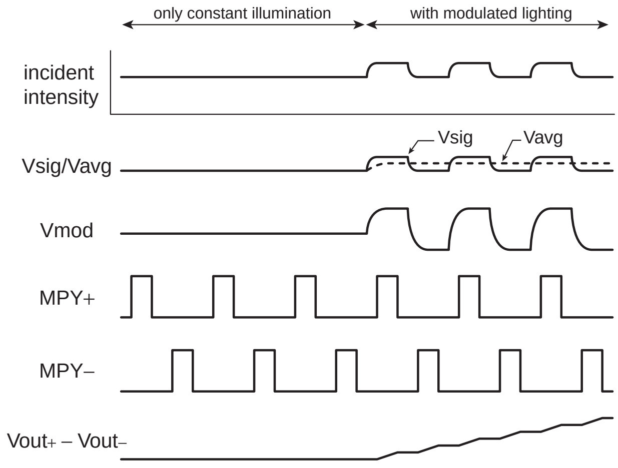

Figure 3. Timing diagram of the sensing scheme.

Fig.3 shows a timing diagram of the sensing scheme. When the incident light includes a modulated light, the photo current has a constant current I_{dc} by a background illumination and an alternating current I_{ac} by a modulated light.

$$I_{pd} = I_{dc} + I_{ac} \tag{1}$$

The low-pass filter generates the average current αI_{avg} as follows:

$$\alpha I_{avg} = \alpha\overline{I_{pd}} = \alpha(I_{dc} + \overline{I_{ac}}) \tag{2}$$

The constant current I_{dc} is suppressed adaptively by the current mode suppression circuit. The output current I_{mod} of the suppression circuit is given by

$$I_{mod} = \alpha I_{pd} - \alpha I_{avg} = \alpha(I_{ac} - \overline{I_{ac}}) \tag{3}$$

The current I_{mod} is converted to the voltage V_{mod} by a logarithmic-response circuit.

$$V_{mod} = \beta \log(I_0 + I_{mod}) \tag{4}$$

where β is a gain factor of the logarithmic-response circuit and I_0 is an offset current. The output is divided into two capacitors C_2 and C_3 by the external signals $MPY+$ and $MPY-$ synchronized with the correlation frequency. The voltages V_{mpy+} and V_{mpy-} at C_2 and C_3 are read out as V_{out+} and V_{out-} by a source follower circuit respectively.

When the incident light is only a background illumination, the photo current is constant and I_{mod} is zero. In this case, the difference voltage between V_{out+} and V_{out-} is zero and the pixel is decided not to be activated. On the other hand, the marked difference between V_{out+} and V_{out-} is acquired only when the incident light has the frequency synchronized with the correlation frequency. The pixel is decided to be activated when the difference voltage is over the reference voltage V_{cmp} of the comparator as follows:

$$V_{out+} - V_{out-} \geq V_{cmp} \tag{5}$$

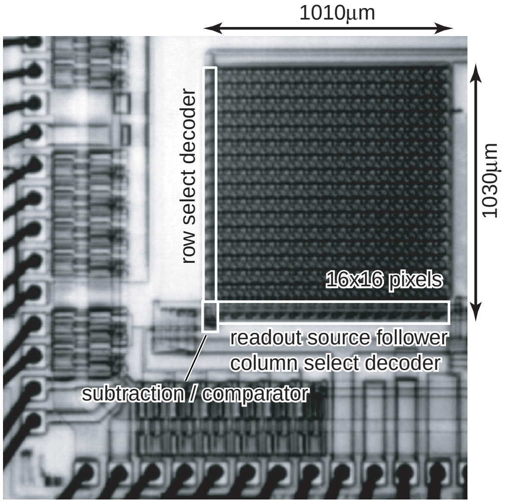

Figure 4. Microphotograph of the fabricated chip.

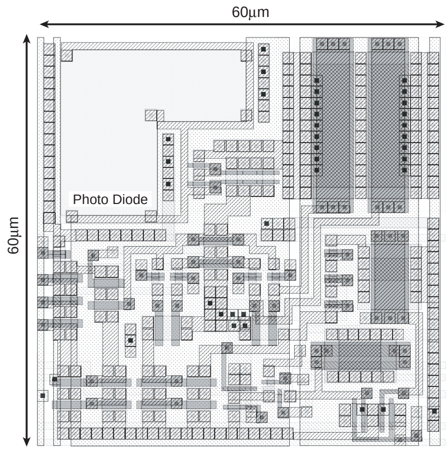

Figure 5. Pixel layout.

Table 1. Specification of the photo detectors.

Process	0.6 μm CMOS 3-metal 2-poly-Si
Chip size	4.8 mm × 4.8 mm
Num. of pixels	16 × 16 pixels
Pixel size	60.0 μm × 60.0 μm
Fill-factor	13.5 %
# trans./pixel	43 trans. (including MOS capacitors)

CHIP IMPLEMENTATION

The presented photo detectors have been designed and fabricated in 0.6 μm CMOS process. Fig.4 shows a microphotograph of the fabricated photo detectors. The chip has a 16 × 16 pixel array. Fig.5 shows a layout of the photo detector. The pixel area is 60 μm × 60 μm with 13.5% fill factor. The photo diode is formed by an n^+-diffusion in a p-substrate. The pixel has 43 transistors including 4 MOS capacitors. The specification of the fabricated chip is shown in Table 1.

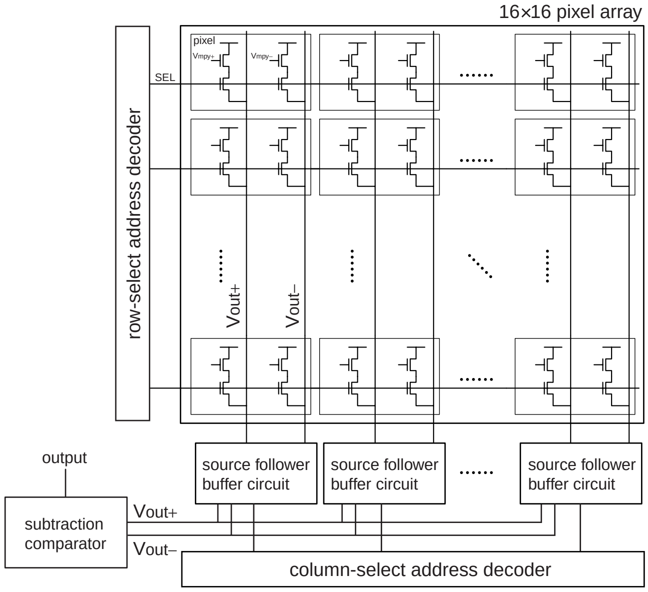

Figure 6. Array structure of the position sensor.

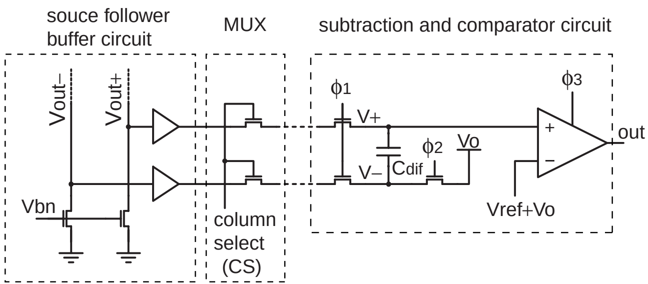

Figure 7: Schematic of the subtraction and comparator circuit.

Pixel Array Structure

Fig.6 is an array structure of the position sensor. It has an array of the present photo detectors, a row-select address decoder, a column-parallel source follower buffer circuit, a column-select address decoder, and a subtraction and comparator circuit. The row-select and column-select address decoder are select one pixel. Both of the output voltages V_{out+} and V_{out-} are read out to the subtraction and comparator circuit by a column-parallel source follower buffer circuit. At the comparator circuit, the difference voltage between V_{out+} and V_{out-} is compared with the reference voltage V_{cmp} and the selected pixel is decided to be activated or not.

Subtraction and Comparator Circuit

Fig.7 shows a schematic of the subtraction and comparator circuit and Fig.8 shows its timing diagram. A pixel is selected by the column-select address decoder and its output voltages V_{out+} and V_{out-} are sampled at each node of C_{dif} by ϕ_1. When ϕ_2 is thrown ON, the voltage V_+ at the node of

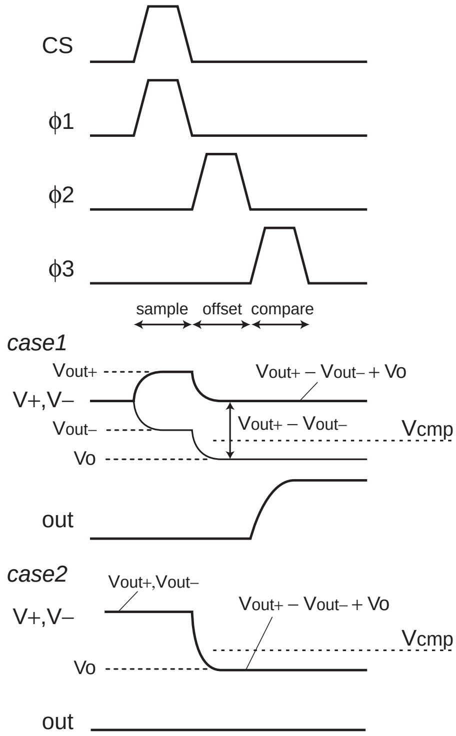

Figure 8: Timing diagram of the subtraction and comparator circuit.

C_{dif} is given by

$$V_+ = V_{out+} - V_{out-} + V_o \quad (6)$$

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

$$V_{cmp} = V_{ref} + V_o \quad (7)$$

The comparator is realized by a latched sense amplifier. The voltage V_+ is compared with V_{cmp} when ϕ_3 is thrown ON. The pixel is decided to be activated when the difference voltage between V_{out+} and V_{out-} is over the threshold voltage V_{ref}.

$$V_{out+} - V_{out-} \geq V_{ref} \quad (8)$$

When the incident light of the selected pixel includes a modulated light synchronized with the correlation frequency, the difference voltage becomes large as shown in *case*1 of Fig.8. On the other hand, the difference voltage is zero or small as shown in *case*2 of Fig.8 when the incident light does not include the correlation frequency.

EXPERIMENTAL RESULTS

For performance evaluation, the measurement system of the fabricated sensor has been constructed as shown in Fig.9. It consists of the fabricated sensor with a lens mounted on a test board, a laser pointer (wavelength 635 nm), a pulse generator, a light projector for background illumination, and a luxmeter. Fig.10 shows a photograph of the camera on a test board. The sensitivity, the dynamic range, the selectivity and the maximum frame rate of the present sensor are evaluated by the measurement system. The range data of a target object can be acquired by a 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.

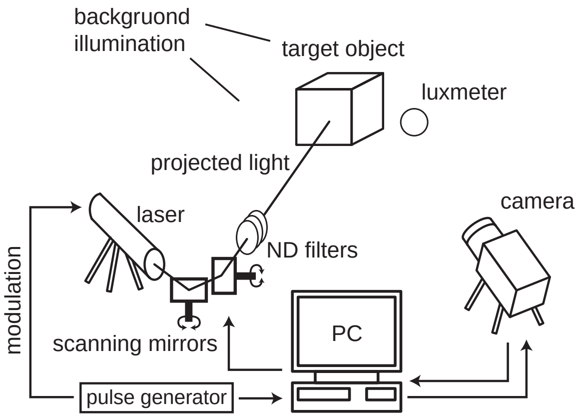

Figure 9. Measurement system structure.

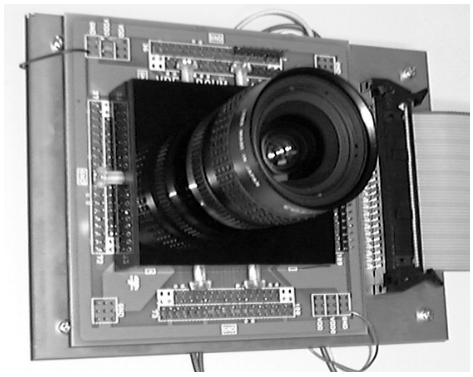

Figure 10. Photograph of the sensor on a test board.

Sensitivity and Dynamic Range

Fig.11 shows the relationship between the background intensity and the minimum projected light intensity to be detected. In the measurement of the sensitivity and the dynamic range, the modulation frequency is 1 kHz and the frame interval is 5 ms. To evaluate the sensitivity of the position detection, the intensities of the projected light and the background illumination are measured by the photo current I_{pd} generated by each incident light. The illuminance corresponding to the background photo current is shown in Fig.11 (in the upper axis) for reference.

The experimental results of the present sensor is shown by (a) in Fig.11. The present sensor can suppress the background illumination. In other word, the projected light can be weaker than the background illumination. The minimum SBR (Signal-to-Background Ratio), which stands for

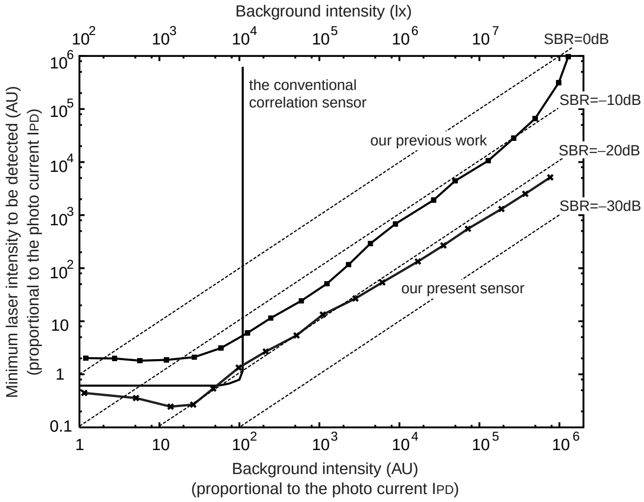

Figure 11. Sensitivity and dynamic range.

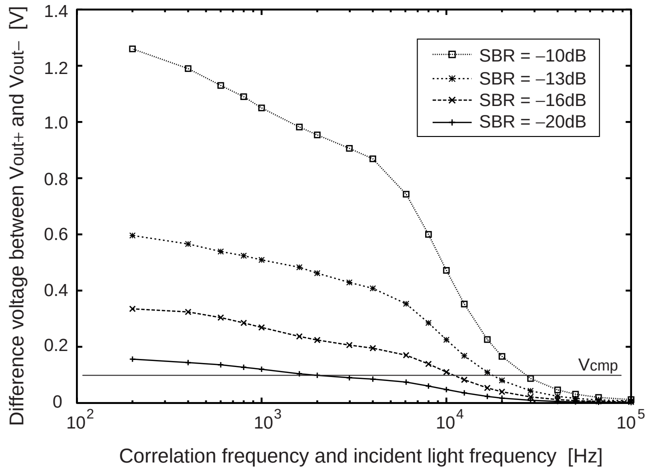

Figure 13: Relationship between the correlation frequency and the sensitivity.

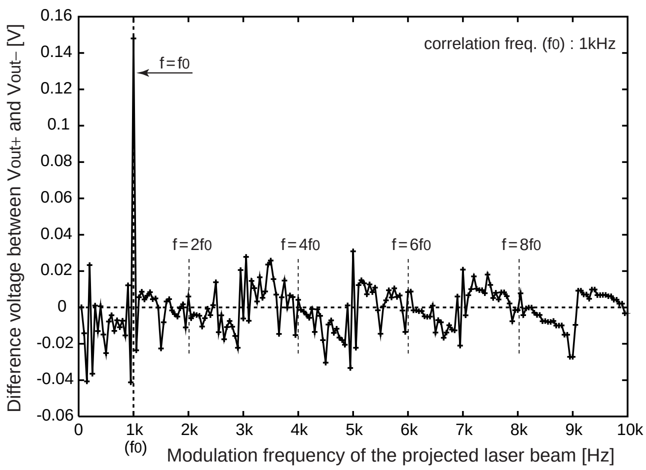

Figure 12: Difference voltage of the correlation outputs at various input signal frequencies.

the sensitivity of the position detection, is -22.8 dB. In addition, the high-sensitivity position detection can be available without saturation in a wide range of background illumination. The high sensitivity under -18 dB is realized in dynamic range of 47.2 dB in terms of background illumination. For example, the projected light intensity can be equivalent to about 1.2×10^3 lx in outdoor environment, where the background intensity is about 1.1×10^5 lx in summer season. It can be equivalent to about 22 lx in a room, where the background intensity is about 1.0×10^3 lx in general.

For comparison, the capabilities of our previous work [10] and the conventional correlation sensor [8] are shown by (b) and (c) in Fig.11 respectively. The present sensor has advantages of both high sensitivity and wide dynamic range.

Selectivity in Modulated Light

Fig.12 shows the difference voltage of the correlation outputs, which is $V_{out+} - V_{out-}$, at various input signal frequencies. In this measurement, the correlation frequency f_0 is 1 kHz and the frame interval is 5 ms. The input signals without the correlation frequency f_0 are suppressed. Especially, the suppression ratios of even harmonics of f_0 are less than 0.05. Therefore the input signals of each even-harmonics frequency can be detected independently. A set of frequencies such as 1 kHz, 2 kHz, 4 kHz and 8 kHz can be used in a multiple light projection system. The present sensing scheme has high selectivity in terms of each modulated lighting.

Frame Rate

Fig.13 shows the relationship between the correlation frequency and the sensitivity. X-axis is a correlation frequency. The modulated light frequency is the same as the correlation frequency in this measurement. Y-axis is a difference voltage between V_{out+} and V_{out-}. The background illumination is 22 klx and the projected light intensity is varied in order to measure the difference voltage at various sensitivities, such as -10 dB, -13 dB, -16 dB and -20 dB SBR. The gain of correlation decreases by a high correlation frequency due to the parasitic capacitance of the photo diode. The correlation frequency can be 10 kHz at -16 dB SBR and the correlation interval is 0.5 ms in this situation, that is, the maximum frame rate is 2000 fps at -16 dB SBR.

3-D Measurement Results

Fig.14 shows a measured range data of a target cube. The range data are calculated by a triangulation using the position of the scanning laser beam on the sensor plane. In the range finding, the projected laser beam is equivalent to 4.0 klx and the background illumination is about 80 klx, i.e., -13 dB SBR. The correlation frequency is 8 kHz and the correlation time is about 0.7 ms. The range data of the cube in

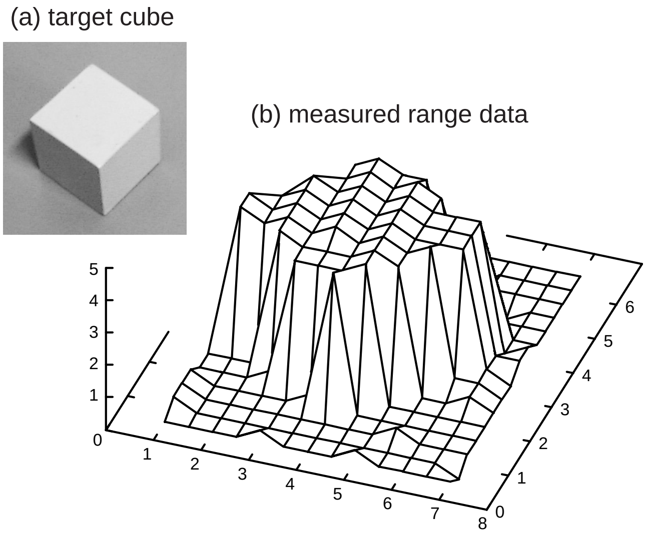

Figure 14. Measured range data.

Fig.14 are acquired in about 300 ms. The acquired range map is still rough due to a small pixel array, but a large pixel array will allow a high accurate range finding. In a high pixel resolution, the pixel-parallel correlation becomes important to be realize a high-speed range finding. The range finding is realized using a weak laser beam projection in a strong background illumination. The range finding system using the present sensor has advantages to applications which require both of availability in various backgrounds and a safe light projection for human eyes.

CONCLUSIONS

A new sensing scheme for high-sensitivity and wide-dynamic-range position detection has been proposed. A correlation circuit and a current-mode suppression circuit of a constant illumination realize high sensitivity, high selectivity, and high suppression of a background illumination. A logarithmic-response circuit is employed to avoid saturation for wide dynamic range. The photo detector can quickly detect the modulated light by the pixel-parallel sensing. The present photo detectors have been developed and successfully tested. Measurement results show the high sensitivity under -18 dB SBR is realized in dynamic range of over 47.2 dB in terms of background illumination. The minimum SBR is -22.8 dB and the maximum frame rate is 2000 fps at -16 dB SBR. In addition, the photo detector shows a high selectivity in a multiple light system due to the suppression of orthogonally modulated lights. The present sensor has been applied to the triangulation-based 3-D measurement system and the range data of a target cube has been acquired successfully using a weak projected light in a strong background illumination. The present sensor has advantages to applications which require both of availability in various backgrounds and a safe light projection for human eyes.

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