PAPER

High-Sensitivity and Wide-Dynamic-Range Position Sensor Using Logarithmic-Response and Correlation Circuit

Yusuke OIKE[†a)], ***Student Member***, **Makoto IKEDA**[†], ***and*** **Kunihiro ASADA**[†], ***Regular Members***

SUMMARY We propose a high-sensitivity and wide-dynamic-range position sensor using logarithmic-response and correlation circuit. The 3-D measurement system using the proposed position sensor has advantages to applications, for example a walking robot and a recognition system on vehicles, which require both of availability in various backgrounds and safe light projection for human eyes. The position sensor with a 64×64 pixel array has been developed and successfully tested. We describe the sensitivity of position detection as SBR (Signal-to-Background Ratio). The minimum SBR of the sensor is -13.9 dB lower than standard sensors. High sensitivity under -10 dB SBR is realized in a dynamic range of 41.7 dB in terms of background illumination. Experimental results of position detection and 3-D measurement in a strong background illumination are also presented.

key words: *position sensor, high sensitivity, wide dynamic range, logarithmic response, correlation*

1. Introduction

3-D measurement system has a wide variety of application fields such as robot vision, computer vision and position adjustment. In 3-D measurement system using triangulation-based light projection method, a sensor detects the position of the projected light on the sensor plane. Some applications, for example a walking robot and a recognition system on vehicles, require both of availability in various backgrounds and safe light projection for human eyes.

Standard imagers and most of the smart position sensors [1]–[9] detect positions of peak intensity on the sensor plane to acquire the position of the projected light. Therefore these sensors require 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 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 suppress the background illumination and realize a high sensitivity of position detection. Sunlight has, however, distributed wavelengths with strong intensity, so that 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.

The position sensor of multiple light beams [10] can suppress uniform background illuminations, but it can't detect the position accurately in ununiform backgrounds due to LEPs (Lateral Effect Photodiode). Correlation technique [11] is one of solutions to the problems. The correlation sensor can suppress the background illumination to obtain a high sensitivity. Its dynamic range is, however, limited by the linear difference circuit due to the voltage signal saturation. It is not applicable for a strong contrast image in outdoor environment. The position sensor with electronic shutter [12] can prevent the saturation for the problem of [11]. 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 study, we have developed and tested a wide dynamic range photo detector using logarithmic-response and correlation circuit [13]. Wide-dynamic-range and high-sensitivity position detection can be simultaneously realized without saturation. In this paper, we present a position sensor with 64×64 proposed photo detectors. The position sensor realizes 3-D measurement system using very weak laser beam projection in various background illuminations.

In Sect. 2, the architecture of the proposed photo detector and the principle of its operation are described. In Sect. 3, chip implementation and specification of photo detectors and a position sensor are shown. In Sect. 4, the performance of the fabricated position sensor compared with the conventional sensors are discussed. In Sect. 5, experimental results in the system of position detection and 3-D measurement are described. Finally, conclusions are presented in Sect. 6.

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[†]The authors are with the Faculty of Engineering, and VLSI Design and Education Center (VDEC), the University of Tokyo, Tokyo, 113-8656 Japan.
a) E-mail: y-oike@silicon.u-tokyo.ac.jp

2. Chip Architecture

2.1 Pixel Circuit

Figure 1 illustrates the sensing scheme using logarithmic-response and correlation circuit. The photo detector receives the projected laser beam modulated by a pulse generator. The pixel consists of a photo detector with a logarithmic-response amplifier, a sample-and-hold circuit, a differential circuit, an analog multiplier for correlation and an integrator with a source follower output.

Figure 2 shows a schematic of the pixel. The logarithmic-response circuit realizes wide-dynamic-range photo detection. The photo current $I_{PD}(t)$ generates the voltage $V_{sig}(t)$ at the node sig as follows:

$$V_{sig}(t) = \alpha \log I_{PD}(t) \tag{1}$$

Here α stands for the characteristics of the pre-amplifier. At the sample-and-hold circuit, the signal ref_sw synchronized with $2f_0$ generates the voltage $V_{ref}(t)$ at the node ref when the modulation frequency of the projected light to be detected is f_0. $V_{ref}(t)$ is given by

$$V_{ref}(t) = V_{sig}\left(t - \frac{1}{2f_0}\right) \tag{2}$$

The differential voltage $\Delta V_{sig}(t)$ between $V_{sig}(t)$ and $V_{ref}(t)$ is multiplied by the external differential signal $\Delta V_{sync}(t)$ between V_{sync1} and V_{sync2} for correlation. V_{sync1} and V_{sync2} are synchronized with f_0. The timing diagram of the control signals is shown in Fig. 3. The output current $I_{out}(t)$ is integrated at the capacitance C_0 and results in the output voltage $V_{out}(t)$ as follows:

$$V_{out}(t) = \frac{1}{C_0}\int_{t-T}^{t} I_{out}(\tau)d\tau + V_0 \tag{3}$$

$$I_{out}(t) = I_b \tanh\frac{\kappa\Delta V_{sig}(t)}{2}\tanh\frac{\kappa\Delta V_{sync}(t)}{2} \tag{4}$$

$$\Delta V_{sig} = V_{sig} - V_{ref} \tag{5}$$

$$\Delta V_{sync} = V_{sync1} - V_{sync2} \tag{6}$$

where T is frame interval and κ is a gain factor of the multiplier. V_0 is an output bias voltage of the integrator. I_b is a bias current of the analog multiplier. V_{out} increases monotonously such as (a)–(d) in Fig. 4 when the incident light has the frequency f_0. On the other hand, V_{out} remains constant such as (e) in Fig. 4 when the incident light is a constant background illumination. In this simulation, the photo currents of (a)–(c)

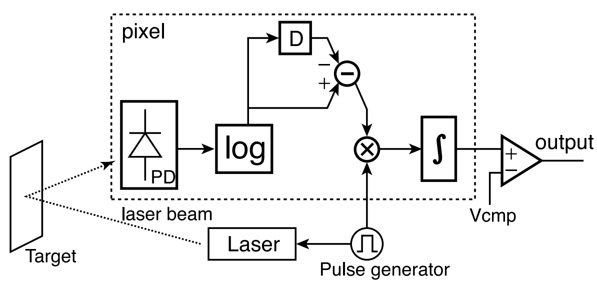


Fig. 1 Sensing scheme of the proposed photo detector.

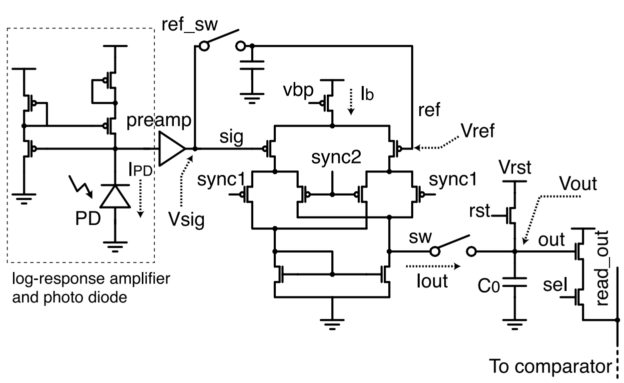


Fig. 2 Schematic of the proposed photo detector.

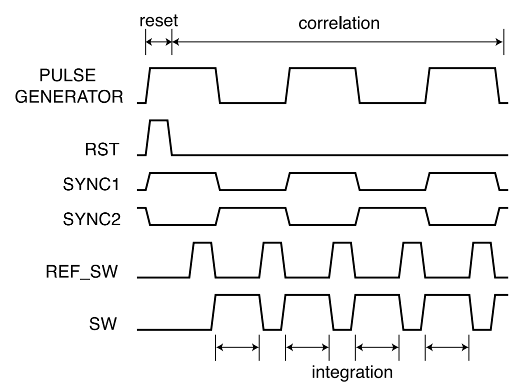


Fig. 3 Timing diagram of the control signals.

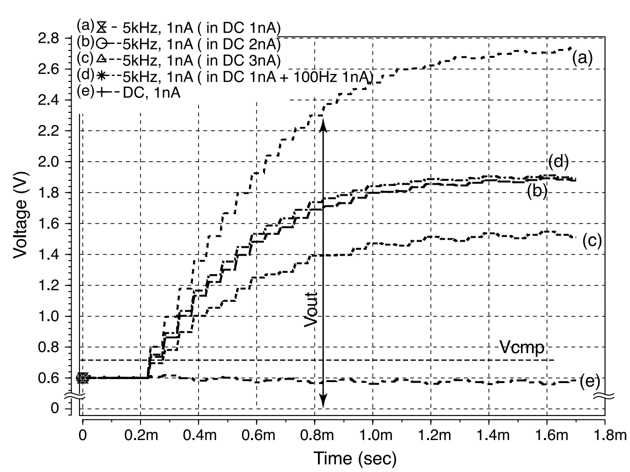


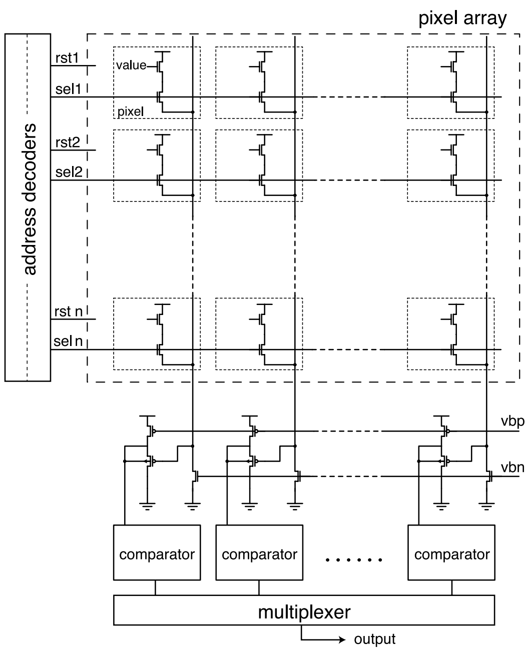
Fig. 4 Output voltages at the integration capacitance.

in Fig. 4 are 5 kHz 1 nAp-p pulse waves with 1 nA, 2 nA and 3 nA offset current, respectively. Figure 4(d) is 5 kHz 1 nAp-p and 100 Hz 1 nAp-p pulse wave with 1 nA offset current. Figure 4(e) is a constant current 1 nA. The correlation frequency is 5 kHz. V_{out} is compared to a reference voltage, V_{cmp}, to detect the laser signal position as follows:

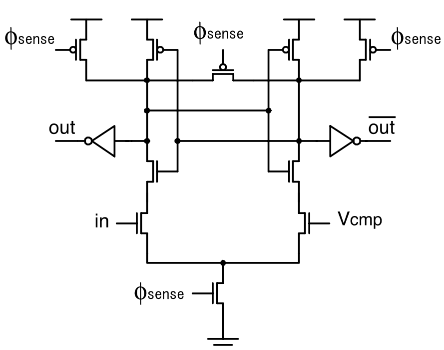
$$V_{out}(t) \geq V_{cmp} \tag{7}$$

2.2 Pixel Array Structure

Figure 5 is an array structure of the position sensor. It has an array of the proposed photo detectors, row address decoders for select and reset, column-parallel source follower circuits, column-parallel comparators and an output multiplexer. Pixel values on a row are read out at a time and compared with the external reference signal V_{cmp} in parallel.



(a)



(b)

Fig. 5 Array structure of the position sensor(a) and schematic of column-parallel comparator(b).

3. Chip Implementation

3.1 Preliminary Test

We designed and fabricated the proposed photo detector in 0.6 μm CMOS 3-Metal 2-Poly-Si process. Pixel size is 32 μm × 56 μm and a photo diode occupies about 23.5% of the pixel area. The photo diode is formed by an n^+-diffusion in a p-substrate. Figure 6 shows a microphotograph of the photo detectors. We confirmed the position detector can suppress background illuminations and detect a very weak laser beam in various background illuminations [13]. In the measurement system using the modulated laser beam projection, the minimum SBR (Signal-to-Background Ratio), which stands for the sensitivity of the position detection, is −10.9 dB. Table 1 shows the parameters of the photo detector.

3.2 64 × 64 Position Sensor

Based on the successful preliminary test results, we designed and fabricated a position sensor with a 64 × 64 proposed photo detector array in 0.5 μm CMOS 3-Metal 1-Poly-Si process. Figure 7 shows a mask layout of a pixel. Pixel size is 40 μm × 40 μm and a photo diode occupies 18.05% of the pixel area. The photo diode is formed by an n^+-diffusion in a p-substrate. The pixel has 24 transistors including transistor capacitances. Figure 8 shows a microphotograph of the fabricated position sensor and Table 2 shows parameters of the position sensor.

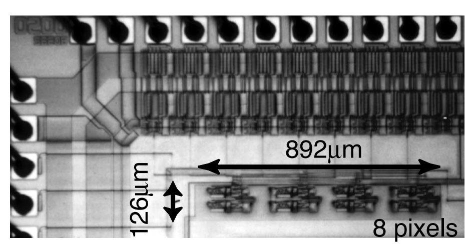


Fig. 6 Microphotograph of the photo detector.

Table 1 Parameters of the photo detector.

Process	0.6 μm CMOS 3-metal 2-poly-Si
Chip size	3.9 mm × 3.9 mm
Pixel size	32.0 μm × 56.0 μm
Fill-factor	23.5%
Num. of transistor	18 transistors and 2 capacitors
Frame interval	5 ms (at f_0=1 kHz)
Minimum SBR	−10.9 dB

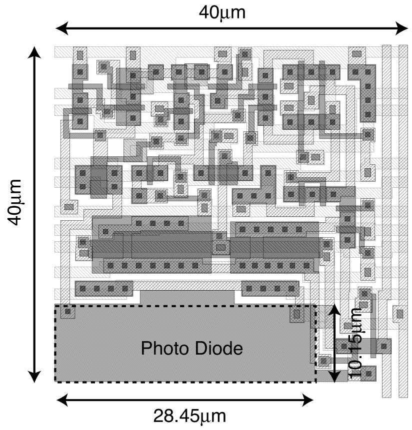


Fig. 7 Mask layout of a pixel.

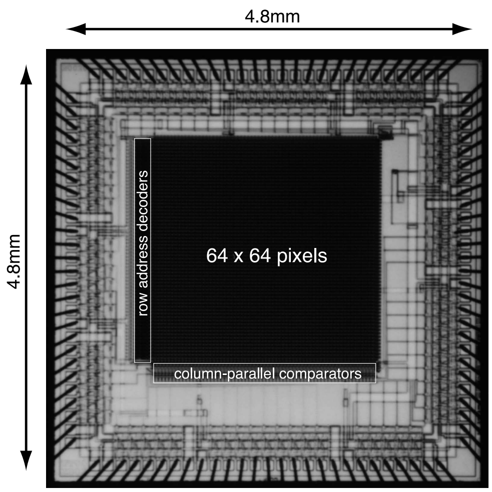


Fig. 8 Microphotograph of the position sensor.

Table 2 Parameters of the position sensor.

Process	0.5 μm CMOS 3-metal 1-poly-Si
Chip size	4.8 mm × 4.8 mm
Num. of pixels	64 × 64 pixels
Pixel size	40.0 μm × 40.0 μm
Photo diode size	10.15 μm × 28.45 μm
Fill-factor	18.05%
Num. of transistor	24 transistors

4. Performance Evaluation

4.1 Experimental Results

Figure 9 shows the output voltage, V_{out}, and the suppression ratio at various input signal frequencies. The frequency f_0 for correlation is 1 kHz and the frame interval, T, is 10 ms. The input signals with a frequency not equal to f_0 are suppressed. Especially, the suppression ratios of even harmonics of f_0 are less than 0.05. Therefore a set of frequencies such as 1 kHz, 2 kHz, 4 kHz and 8 kHz can be used in a multiple light projection system. Odd harmonics of f_0 can't be fully suppressed due to the rectangular modulation.

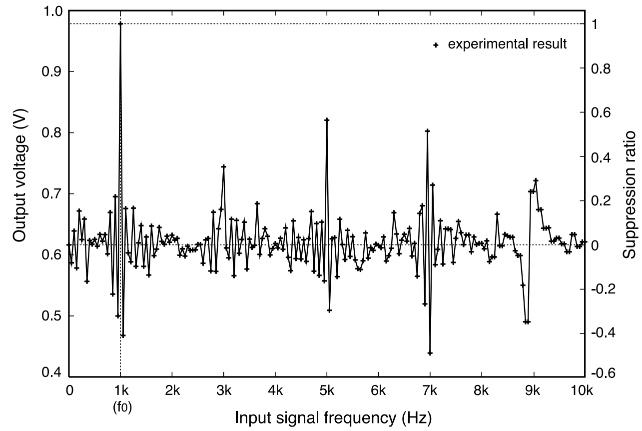


Fig. 9 Output voltage and suppression ratio at various input signal frequencies.

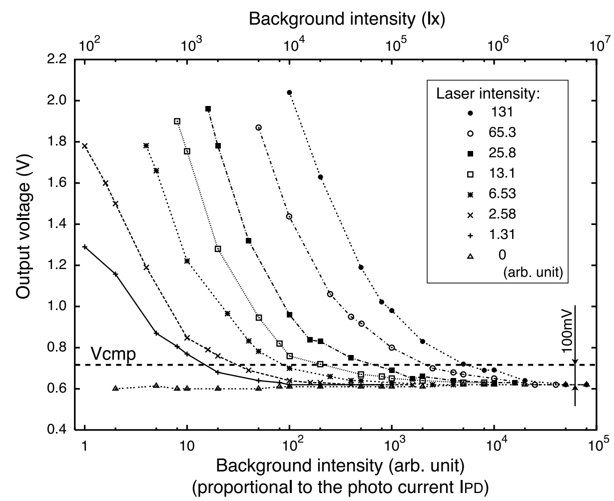


Fig. 10 Output voltages at various intensities of laser beam and background.

Figure 10 shows the output voltages at various laser beam and background intensities. To evaluate the sensitivity of position detection, the intensities of the projected light and the background illumination are measured by photo current I_{PD} generated by each incident light. The illuminance corresponding to the background photo current is shown in Figs. 10 and 11 (in the upper axis) for reference. The output voltage remains constant when the input signal is a constant background illumination, so that the reference voltage of comparators V_{cmp} can be fixed. Here V_{cmp} is 100 mV more than the offset voltage V_0. The input signal can be detected when the output voltage is more than V_{cmp}. The minimum laser intensity to be detected at each background intensity is shown by (a) in Fig. 11. The measurement system is composed of the fabricated sensor, a laser pointer (wavelength 635 nm), a pulse generator, a light projector for background illumination, and

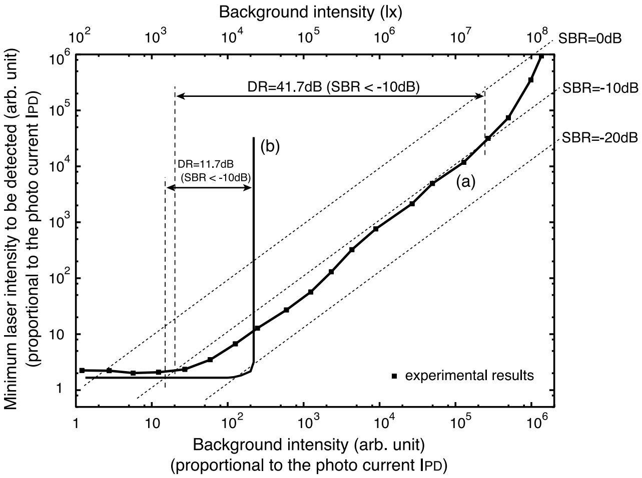


Fig. 11 Dynamic range and sensitivity of : (a) the fabricated position sensor, (b) the conventional correlation sensor [11].

Table 3 Performance parameters of the position sensor.

Power supply	3.3 V
Minimum SBR	−13.9 dB
DR (Dynamic Range)	41.7 dB (at −10 dB SBR)
Depth resolution	14.6 mm at 1418.0 mm
Chip power	400 mW at 200 fps
Max. frame rate	2000 fps (at f_0=10 kHz)

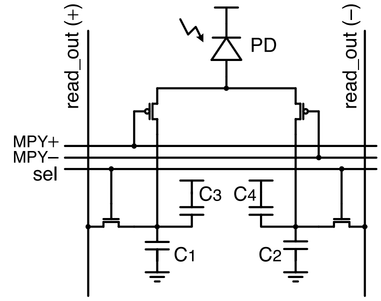


Fig. 12 Schematic of the conventional correlation pixel [11].

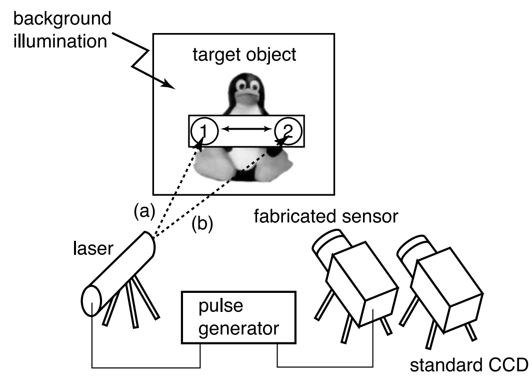


Fig. 13 Measurement system of the position detection in various background illuminations.

a luxmeter. In this measurement system, the modulation frequency is 1 kHz and the frame interval is 10 ms. This experimental result shows that the position sensor can suppress the background illumination. In other words, the projected laser beam can be weaker than the background illumination. In addition, it shows that the high-sensitivity position detection can be available without saturation in a wide range of background illumination. For example, the laser beam intensity can be equivalent to about 3×10^3 lx in outdoor environment, where the background intensity is about 1×10^5 lx in summer season. It can be equivalent to about 126 lx in a room, where the background intensity is about 1×10^3 lx. The minimum SBR is −13.9 dB. High sensitivity under −10 dB SBR is realized in dynamic range of 41.7 dB in terms of background illumination. Performance parameters of the proposed position sensor are summarized in Table 3.

4.2 Comparison

Figure 12 shows the pixel circuit of the conventional correlation sensor [11]. The photo current $I_{PD}(t)$ is divided into the capacitance C_1, C_2, C_3 and C_4. When the photo current is divided perfectly in ideal operation, the divided currents, I_{D+} and I_{D-}, are given by

$$I_{D+} = I_{bg} + I_{laser} \quad (8)$$
$$I_{D-} = I_{bg} \quad (9)$$

where I_{bg} is the photo current caused by the background illumination and I_{laser} is the photo current caused by the projected light. The dynamic range of the conventional correlation pixel is limited by the voltage signal saturation as follows:

$$V_{out+} = \frac{1}{C_0}\int_{t-T}^{t} I_{bg}(\tau) + I_{laser}(\tau)d\tau \leq V_{DD} \quad (10)$$

where $C_0 = C_1 + C_3 = C_2 + C_4$. Frame interval T is decided by the frequency of the projected light. The voltage signals at the capacitances are saturated when I_{PD} increases in strong background illuminations. The minimum intensity of the projected laser beam is decided by the inequality as follows:

$$\Delta V_{out} = \frac{1}{C_0}\int_{t-T}^{t} I_{laser}(\tau)d\tau \geq \Delta V_{cmp} \quad (11)$$

where $\Delta V_{out} = V_{out+} - V_{out-}$ and ΔV_{cmp} is the offset voltage of a comparator. The SBR of the conventional correlation sensor is decided by inequality (10) and (11). The minimum laser beam intensity in ideal operation, which means perfectly divided photo current and no transistor switching noise, is shown by Fig. 11. The conventional sensor realizes −10 dB SBR at most in 13 dB of background illumination range. V_{DD} is 5.0 V and ΔV_{cmp} is 50 mV here.

5. Application to 3-D Measurement

Figure 13 illustrates a measurement system of the po-

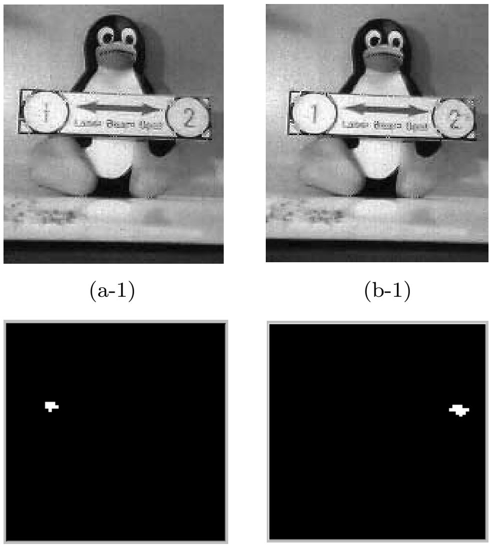


Fig. 14 Experimental results of the position detection in various background illumination: (a) laser beam is projected at Circle 1, (b) at Circle 2. (a-1) and (b-1) are acquired by a standard CCD. (a-2) and (b-2) are acquired by the fabricated sensor.

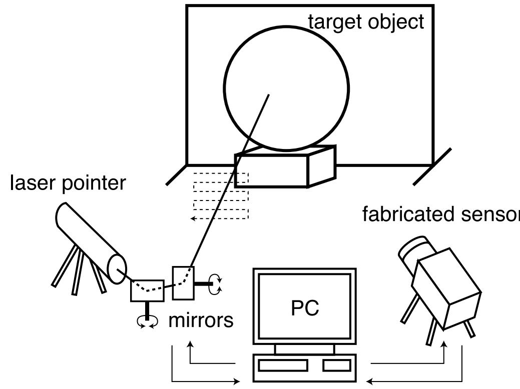


Fig. 15 Block diagram of 3-D measurement system.

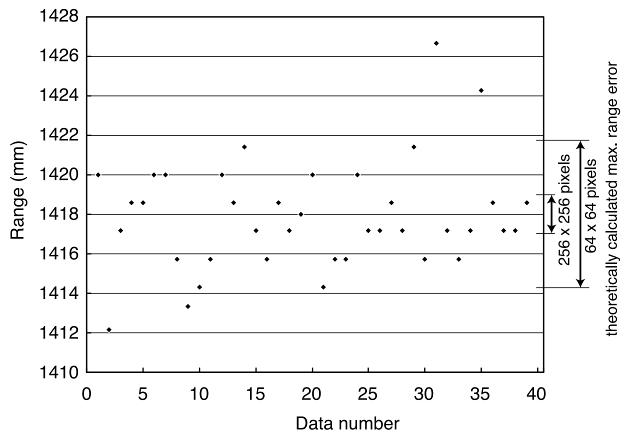
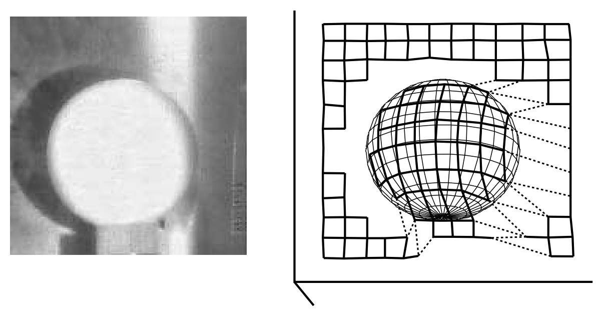


Fig. 16 Measurement result of a flat panel.



(a) (b)

Fig. 17 Measurement result of a sphere object: (a) a target sphere-shaped object, (b) a reproduced wire frame.

sition detection in a strong background illumination. The system is composed of a laser pointer, the fabricated position sensor with a lens mounted on a test board, a pulse generator, a target object and a standard CCD camera. The laser intensity corresponds to 4 klx and the maximum background illumination on the target object is about 60 klx. Figure 14(a-1) and Fig. 14(b-1) are acquired by the CCD camera. Figure 14(a-2) and Fig. 14(b-2) show laser beam positions detected by the present camera. In Fig. 14(a-1) and Fig. 14(a-2) the laser beam is projected at Circle 1, where the background illumination is almost maximum of 60 klx, while in Fig. 14(b-1) and Fig. 14(b-2) the laser beam is projected at Circle 2, where the background illumination is much lower compared to Circle 1. Note that CCD images shown in Fig. 14(a-1) is difficult even for human eyes to detect the laser beam position due to the strong background illumination, though we can vaguely detect the beam position in Fig. 14(b-1). On the other hand, the fabricated sensor can detect the laser beam position clearly such as Figs. 14(a-2) and (b-2).

Figure 15 illustrates a 3-D measurement system based on triangulation. The 3-D measurement system is composed of the fabricated sensor, a laser with mirrors and a PC with digital I/O boards. The sensor acquires the positions of the scanning laser spot. 3-D range map can be calculated from the positions of the projected laser beam on the acquired images and both positions of the sensor and the projected light source. Figure 16 shows an accuracy of 3-D measurement. A flat panel is measured at a distance of 1418.0 mm from the sensor. The maximum error of measured range is 14.6 mm, which corresponds to about 1%. The theoretically calculated maximum range error in the measurement system based on triangulation method is shown in Fig. 16, where the sensor has 64×64 pixels and 256×256 pixels. Figure 17 shows a sphere-shaped target object and a reproduced wire frame. In this measurement, maximum background illumination on the target object is 28 klx and the laser intensity is 1.6 klx. The projected laser beam scans the target object and the position sensor needs to acquire 12×12 frames to obtain Fig. 17(b). In Fig. 17, several points are not measured because these are placed at invisible positions from the laser and the position sensor. A couple of sensors and lasers are required to acquire an all-direction wire frame.

6. Conclusions

A high-sensitivity and wide-dynamic-range position sensor using logarithmic-response and correlation circuit has been developed in 0.5 μm CMOS process and successfully tested. The fabricated sensor has a 64×64 pixel array. The sensor can acquire the position of the projected light in strong background illuminations. The minimum SBR is -13.9 dB less than standard imagers. The sensor can realize less than -10 dB SBR in a wide dynamic range of 41.7 dB of background illumination. Multiple light projection systems are also realized using a frequency set to be detected independently. We showed the position detection capability and the 3-D measurement system using the fabricated sensor in a strong background illumination. The proposed sensor has advantages to applications which require both of availability in various backgrounds and safe light projection for human eyes.

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References

[1] A. Gruss, L.R. Carley, and T. Kanade, "Integrated sensor and range-finding analog signal processor," IEEE J. Solid-State Circuits, vol.26, pp.184–191, 1991.
[2] M. Baba, T. Konishi, Y. Hori, and K. Otani, "A new position sensor for high-speed measurement of multiple points," IEEE Proc. Instrumentation and Measurement Technology Conference, pp.642–647, 1996.
[3] M. de Bakker, P.W. Verbeek, E. Nieuwkoop, and G.K. Steenvoorden, "A smart range image sensor," Proc. European Solid-State Circuits Conference, pp.208–211, 1998.
[4] V. Brajovic and T. Kanade, "Computational sensor for visual tracking with attention," IEEE J. Solid-State Circuits, vol.33, pp.1199–1207, 1998.
[5] T. Nezuka, M. Hoshino, M. Ikeda, and K. Asada, "A smart position sensor for 3-D measurement," Proc. Asia South-Pacific Design Automation Conference, pp.21–22, 2001.
[6] S. Yoshimura, T. Sugiyama, K. Yonemoto, and K. Ueda, "A 48 kframe/s CMOS image sensor for real-time 3-D sensing and motion detection," ISSCC Dig. Tech. Papers, pp.94–95, 2001.
[7] V. Brajovic, K. Mori, and N. Jankovic, "100 frames/s CMOS range image sensor," ISSCC Dig. Tech. Papers, pp.256–257, 2001.
[8] S. Decker, R. McGrath, K. Brehmer, and C. Sodini, "A 256 × 256 CMOS imaging array with wide dynamic range pixels and column-parallel digital output," ISSCC Dig. Tech. Papers, pp.176–177, 1998.
[9] M. Schanz, C. Nita. B.J. Hosticka, and R.K. Wertheimer, "A high-dynamic-range CMOS image sensor for automotive applications," IEEE J. Solid-State Circuits, vol.35, pp.932–938, 2000.
[10] C. Narayanan, A.B. Buckman, and I. Busch-Vishniac, "Position detection of multiple light beams using phase detection," IEEE Trans. Instrum. & Meas., vol.43, pp.830–836, 1994.
[11] A. Kimachi and S. Ando, "Time-domain correlation image sensor: First CMOS realization and evaluation," Transducers '99, pp.958–961, 1999.
[12] R. Jeremias, W. Brockherde, G. Doemens, B. Hosticka, L. Listl, and P. Mengel, "A CMOS photosensor array for 3D imaging using pulsed laser," ISSCC Dig. Tech. Papers, pp.252–253, 2001.
[13] Y. Oike, M. Ikeda, and K. Asada, "Wide dynamic range photo detector for smart position sensor using log-response and correlation circuit," Ext. Abst. the 2001 Int. Conf. SSDM, pp.282–283, 2001.

Yusuke Oike was born in Tokyo, Japan on July 4, 1977. He received the B.S. and M.S. degrees in electronic engineering from University of Tokyo, Tokyo, Japan, in 2000 and 2002, respectively. Presently, he is working towards the Ph.D. degree in the Department of Electronic Engineering of University of Tokyo. His current research interests include architecture and design of smart image sensors, mixed-signal circuits and functional memories. He is a student member of the Institute of Electrical and Electronics Engineering (IEEE).

Makoto Ikeda received the B.S., M.S., and Ph.D. in electronics engineering from the University of Tokyo, Tokyo, Japan, in 1991, 1993, and 1996, respectively. He joined EE department of University of Tokyo as a faculty member in 1996, and is currently an associate professor at VLSI Design and Education Center, University of Tokyo. His interests are in architecture and design of Content Addressed Memories and its applications. He is a member of Institute of Electrical and Electronics Engineers (IEEE), Information Processing Society of Japan (IPSJ).

Kunihiro Asada was born in Fukui, Japan, on June 16th, 1952. He received the B.S., M.S., and Ph.D. in electronic engineering from University of Tokyo in 1975, 1977, and 1980, respectively. In 1980 he joined the Faculty of Engineering, University of Tokyo, and became a lecturer, an associate professor and a professor in 1981, 1985 and 1995, respectively. From 1985 to 1986 he stayed in Edinburgh University as a visiting scholar supported by the British Council. From 1990 to 1992 he served as the first Editor of English version of IEICE (Institute of Electronics, Information and Communication Engineers of Japan) Transactions on Electronics. In 1996 he established VDEC (VLSI Design and Education Center) with his colleagues in University of Tokyo. It is a center supported by the Government to promote education and research of VLSI design in all the universities and colleges in Japan. He is currently in charge of the head of VDEC. His research interest is design and evaluation of integrated systems and component devices. He has published more than 390 technical papers in journals and conference proceedings. He has received best paper awards from IEEJ (Institute of Electrical Engineers of Japan), IEICE and ICMTS1998/IEEE and so on. He is a member of IEEE and IEEJ. He is currently Chair of IEEE/SSCS Japan Chapter.