A Multi-Zone Light-Tracing Hybrid Time-of-Flight CMOS Image Sensor for Low Power Long-Range Outdoor Operations

Kamel Mars[1,2], Seiya Ageishi[2], Masashi Hakamata[2], Tomoaki Sakita[3], Daisuke Iguchi[3], Junichiro Hayakawa[3], Keita Yasutomi[2], Keiichiro Kagawa[2], Shoji Kawahito[2]

[1] : Shizuoka Institute of Science and Technology, Fukuroi, 437-0032 Japan

[2] : Research Institute of Electronics, Shizuoka University, Hamamatsu, 432-8011, Japan

[3] : FUJIFILM Business Innovation Corp., Kanagawa, 243-0494, Japan

E-mail: kamel@idl.rie.shizuoka.ac.jp **TEL**: +81-53-478-1341 **FAX**: +81-53-478-3251

I. Introduction

Various types of time-of-flight (ToF) imagers, employing either direct ToF (dToF) or indirect ToF (iToF), have recently been developed to perform effectively in outdoor environments with strong ambient light. The dToF imagers are well placed for long range applications while they still have difficulty having high depth-image resolution [1]-[3]. On the other hand, iToF imagers using short pulse (SP) are more effective for outdoor operation under strong background light due to the reduced in-pixel ambient light charge acquisition shot noise, while having a higher range-image resolution [4]-[7].

For extended range measurements, flash-type light sources require higher optical power, resulting in increased power consumption [8]-[11]. In contrast, scanning light sources offer an effective solution for reducing the required optical power to achieve specified precision, particularly in strong ambient light conditions, or for enhancing precision under limited optical power. The approach introduced in this paper focuses the light on a small region of the target scene for a shorter duration, minimizing the amount of ambient light charge to be collected.

II. Sensor Architecture and Operation

The proposed multi-zone light-tracing hybrid Time of Flight (LT-hToF) imaging technique combines both advantages of scanning light sources and hybrid ToF measurements where the ToF of a short pulse is measured by both direct ToF (dToF) and indirect ToF (iToF) which is very suitable for extended outdoor range measurement under strong ambient light conditions [11]-[16]. To do this, the

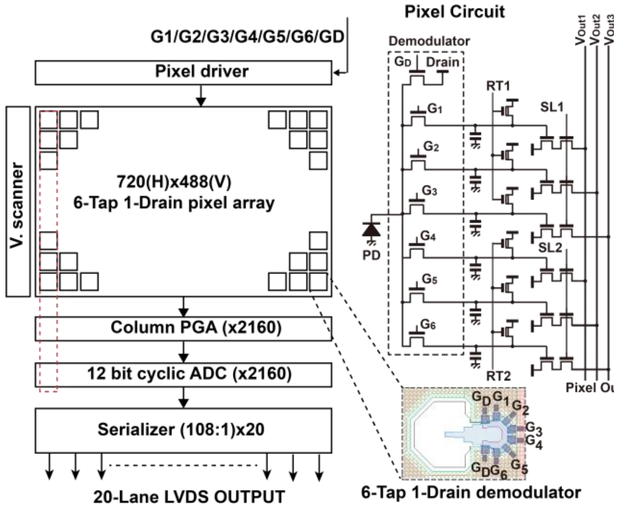

Figure 1: Prototype chip photograph (Left), Pixel circuit and demodulator diagram (Right).

designed hToF sensor has a function of activation and deactivation control of a set of pixel columns. The proposed sensor chip architecture and six taps and one drain pixel are depicted in Figure 1. The proposed technique is very suitable for outdoor extended range measurement under strong ambient light conditions with reduced light-source power.

The pixel of the hybrid ToF (hToF) sensor with 12.6µm pitch has a pinned photodiode with 6 taps and one drain, which are controlled by 6 transfer gates G1~G6 while the drain is controlled by a draining gate GD. The gate driver which delivers the gating clocks has a function that selects and scans pixel blocks to be driven while remaining non used pixel blocks are drained to avoid any unwanted light charge accumulation. In this architecture, every three outputs are readout simultaneously and the 6 output signals can be read out by performing the readout process twice. As illustrated in Figure 2, the proposed measurement method uses two non-overlapping subframes to implement multiple time window. A measurable range of 0 to 11TP (e.g., 24.75m (2.5m to

27.25m) for TP of 15ns, where TP is the light-pulse width) can be attained.

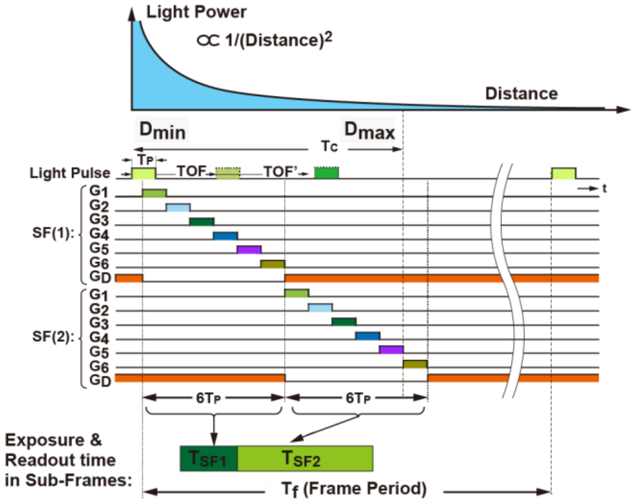

Figure 2: Gates timing chart with 2-subframes for outdoor measurement

For ToF measurement, 12-zones solid state self-scanning VCSEL is being used. The large size pixel array depicted in Figure 3 is divided into 12 regions of interest (ROI) and the exposure of each ROI region (i.e. Z(i,j)) is synchronized with the corresponding zone of the 12-zone laser source via a trigger signal in order to illuminate that corresponding specified area only. Every four horizontal ROIs are reset just before exposure and then readout simultaneously once the exposure is completed.

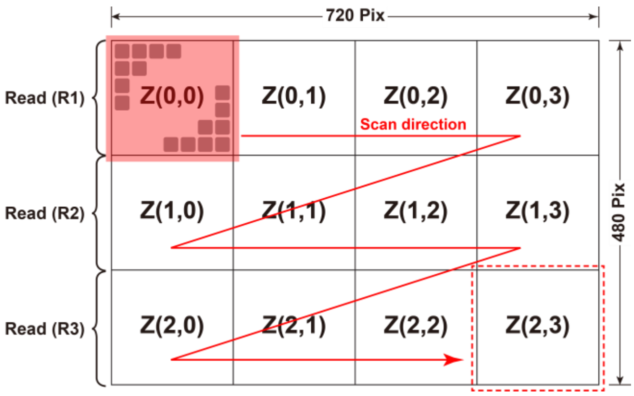

Figure 3: Pixel array ROI splitting and illumination scheme: 12zone 2-D scanning

The exposure time is carefully adjusted in each sub-frame to avoid pixel saturation in the near region and to get enough signal to be readout. With careful exposure adjustments and high-speed sensor architecture, a frame rate of 25fps is achieved.

The operation pattern described previously can achieve outdoor ToF measurement under strong ambient light while the required light average power is twelve times smaller than in the flash mode operation. Therefore, a low power consumption and more cost effective easy to use ToF camera system is achievable.

III. MEASURMENT RESULTS

In order to test the proposed measurement technique, a prototype image sensor has been designed and implemented using 0.11µm (4-Metal, 1poly) CMOS image sensor process technology. Table 1 shows a summary of specifications and basic characteristics of the fabricated chip.

Table 1: Prototype Sensor performances

Parameter	Value
Technology	0.11µm CMOS Image Sensor
Number of Pixels	720(H) x 488(V)
Pixel size	12.6µm x 12.6µm
Chip size	13.32mm x12.26mm
ADC resolution	12bits cyclic
Readout Time	3.945ms Full VGA frame at 12bit ADC
Conversion gain	34µV/e-

Multizone scanning VCSEL operation synchronized to multi-subframes, and short charge modulations were all successfully obtained. The VCSEL light source wavelength is 940nm. In this measurement, a pulse width of 10ns is being used to characterize the demodulation contrast. Figure 4(a) and Figure 4(b) shows the measured response curve of a single frame time-gaiting to the delay of the light pulse and the normalized response curve, respectively.

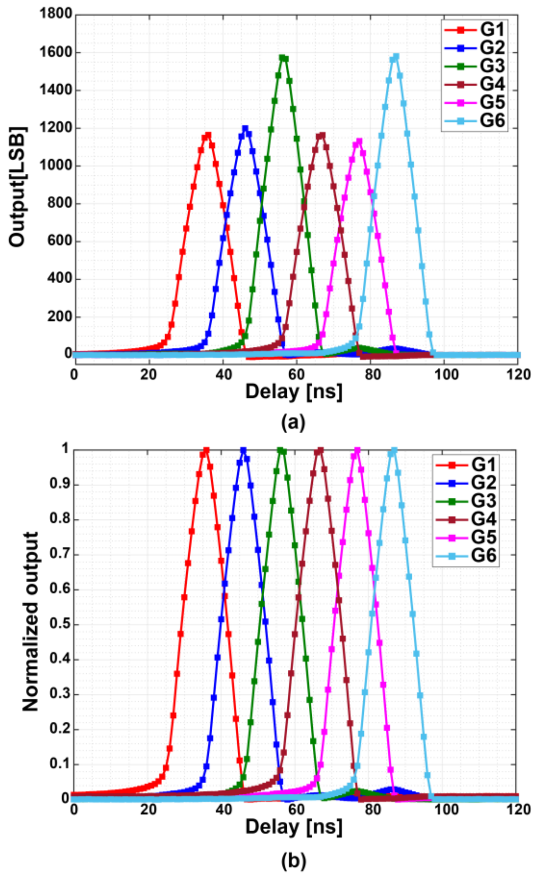

Figure 4: 6-TAPs Pixel response to the light pulse delay: 1-subframe curve (a) and normalized response (b)

For TOF range and image measurement a pulse width of 15ns is used. Figure 5 shows the measured distance, linearity and depth noise for outdoor operations. A 3x3 median filter is used for reducing noise while maintaining image resolution.

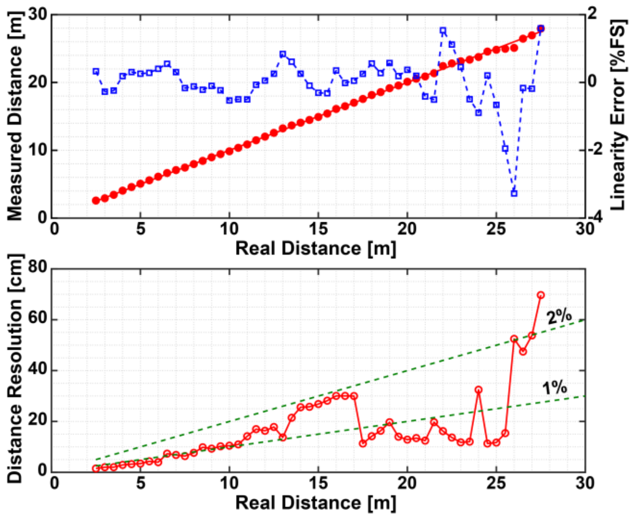

Figure 5: 3-subframes gates timing chart for indoor measurement

The whole measurement process is performed under an ambient light of over 100klux measured with an illuminance meter fixed near the camera system. Up to 27.5m range have been successfully measured. The maximum non-linearity is less than 4%, and the maximum depth noise is less than 1% at 25m distance range and less than 2% at 27m distance range. Figure 6 shows an image of the outdoor depth measurement setup. A total of 11 bords (10 small and one large board) are place at 2.5 m interval starting at 2.5m away from the camera system. Figure 7 shows 6-taps and two subframes modulated light IR images captured under 100klx ambient light and 25fps. This image shows that the last board placed at 27.5m is

Figure 6: Outdoor environment setup for TOF depth image measurement

illuminated and therefore TOF range measurement can be successfully achieved. Figure 8 shows the captured outdoor depth image (27.5m, 100klux). The light power of the 12-zone scanning VCSEL light source used for these measurements is 200mW (average) and 4W(peak). Theoretically, achieving the same range measurement performance using flash illumination requires 12 times more power in scenes where ambient light shot noise is the dominant noise component.

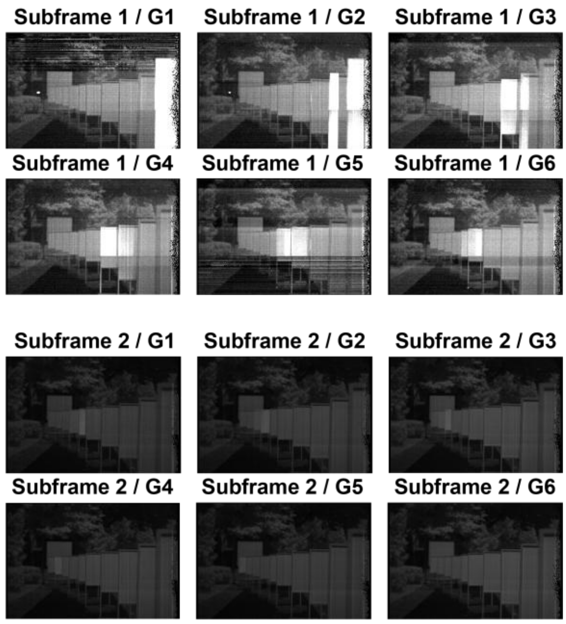

Figure 7: 6-TAPs and two subframes modulated light IR images

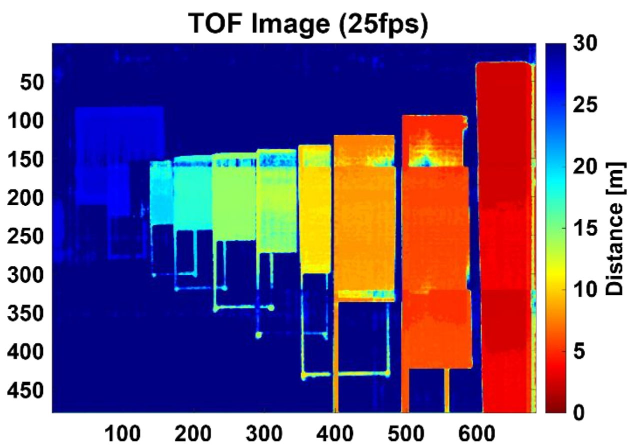

Figure 8: Captured TOF range image at 25fps under 100klux

IV. CONCLUSION

In this paper, a multi-zone light-tracing hybrid time-of-flight CMOS image sensor for low power long-range outdoor operations has been presented. In this approach, a VGA pixel array with 6-TAPs pixel and 2-sumbframes range shifting in combination whit short pulse and a 12-zone synchronized self-scanning solid state VCSEL light source were used. Up to 27.5m range have been successfully measured under an ambient light of over 100klux. The maximum non-linearity achieved is less than 4%, and the maximum depth noise is less than 1% at 25m distance range and less than 2% at 27m distance range. Additionally, ToF range image under the same strong ambient light condition was successfully obtained enabling outdoor ToF measurements with 12times lower light power when compared to ToF measurement using flash illumination mode.

ACKNOWLEDGMENT

This work was partly supported by Adaptable and Seamless Technology Transfer Program through Target-driven R&D (A-STEP) from Japan Science and Technology Agency (JST) Grant Number JPMJTR211A. It was also partly supported by A JSPS KAKENHI Grand Number 24H00313. The authors also appreciate DB HiTek for the prototype chip fabrication.

REFERENCES

[1] H. Seo et al., "Direct TOF Scanning LiDAR Sensor With Two-Step Multievent Histogramming TDC and Embedded Interference Filter," in IEEE Journal of Solid-State Circuits, vol. 56, no. 4, pp. 1022-1035, April 2021.

[2] B. Kim, S. Park, J. -H. Chun, J. Choi and S. -J. Kim, "7.2 A 48×40 13.5mm Depth Resolution Flash LiDAR Sensor with In-Pixel Zoom Histogramming Time-to-Digital Converter," in IEEE ISSCC Dig. Tech. Papers, Feb. 2021, pp. 108–110.

[3] O. Kumagai et al., "A 189 × 600 back-illuminated stacked SPAD direct time-of-flight depth sensor for automotive LiDAR systems," in IEEE ISSCC Dig. Tech. Papers, Feb. 2021, pp. 110–111.

[4] C. S. Bamji et al., "1Mpixel 65nm 320MHz demodulated TOF image sensor with 3.5um global shutter pixels and analog binning," in IEEE ISSCC Dig. Tech. Papers, Feb. 2018, pp. 94–95.

[5] M.-S. Keel et al., "A 4-tap 3.5μm 1.2Mpixel indirect time-of- flight CMOS image sensor with peak current mitigation and multi-user interference cancellation," in IEEE ISSCC Dig. Tech. Papers, Feb. 2021, pp. 105–106.

[6] D. Kim et al., "Indirect time-of-flight CMOS image sensor with on-chip background light cancelling and pseudo-four-tap/two-tap hybrid imaging for motion artifact suppression," IEEE J. Solid-State Circuit, vol. 55, no. 11, pp. 2849–2865, Nov. 2020.

[7] Y. Ebiko et al., "Low power consumption and high resolution 1280x960 gate assisted photonic demodulator pixel for indirect time of flight," in Int. Electron Device Meeting Tech. Dig., Dec. 2020, pp. 721–724.

[8] K. Hatakeyama et al., "A hybrid indirect ToF image sensor for long-range 3D depth measurement under high ambient light conditions," in Proc. IEEE Symp. VLSI Technol. Circuits, Jun. 2022, pp. 46–47.

[9] S. Kawahito, K. Yasutomi and K. Mars, "Hybrid Time-of-Flight Image Sensors for Middle-Range Outdoor Applications," in IEEE Open Journal of the Solid-State Circuits Society, vol. 2, pp. 38-49, 2022

[10] K. Mars, et al., "A 648 x 484-Pixel 4-Tap Hybrid Time-of-Flight Image Sensor with 8 and 12 Phase Demodulation for Long-Range Indoor and Outdoor Operations" In Proceedings of the 2023 International Image Sensor Workshop, Scotland, UK, 21–25 May 2023.

[11] C. Bamji et al., "A Review of Indirect Time-of-Flight Technologies," in IEEE Transactions on Electron Devices, vol. 69, no. 6, pp. 2779-2793, June 2022

[12] Morsy A, Vrijsen J, Coosemans J, Bruneel T, Kuijk M. Noise Analysis for Correlation-Assisted Direct Time-of-Flight. Sensors. 2025; 25(3):771

[13] Kim, J.e. Indirect Time-of-Flight CMOS Image Sensor With On-Chip Background Light Cancelling and Pseudo-Four-Tap/Two-Tap Hybrid Imaging for Motion Artifact Suppression. IEEE J. Solid-State Circuits 2020, 55, 2849–286

[14] Keel, M.S.; Jin, e. A VGA Indirect Time-of-Flight CMOS Image Sensor with 4-Tap 7-μm Global-Shutter Pixel and Fixed-Pattern Phase Noise Self-Compensation. IEEE J. Solid-State Circuits 2020, 55, 889–897

[15] S. Dabidian, S. Tafaghodi Jami, Z. Kavehvash and A. Fotowat-Ahmady, "Direct time-of-flight (d-ToF) pulsed LiDAR sensor with simultaneous noise and interference suppression", IEEE Sensors J., vol. 24, no. 17, pp. 27578-27586, Sep. 2024.

[16] A. Morsy et al. "An In-Pixel Ambient Suppression Method for Direct Time of Flight," in IEEE Sensors Letters, vol. 8, no. 10, pp. 1-4, Oct. 2024, Art no. 5504404