Programmable Dynamic Range Extension up to 110 dB Based on Charge-Splitting Method with 4-Tap CMOS Image Sensor

Yu Feng[*1], Yusuke Tanihata[*2], Kamel Mars[*3,4], Keita Yasutomi[*4], Shoji Kawahito[*4], and Keiichiro Kagawa[*4]

[*1] Graduate School of Science and Technology, Shizuoka University, Hamamatsu, 432-8011, Japan

[*2] Graduate School of Integrated Science and Technology, Shizuoka University, Hamamatsu, 432-8011, Japan

[*3] Faculty of Science and Technology, Shizuoka Institute of Science and Technology, Fukuroi, 437-8555, Japan

[*4] Research Institute of Electronics, Shizuoka University, Hamamatsu, 432-8011, Japan

Email: kagawa@idl.rie.shizuoka.ac.jp

I. Introduction

High dynamic range (HDR) imaging has seen increasing demand in automotive, security, and other fields, driven by the need to capture scenes with an extended dynamic range (DR) without compromising image quality. This work presents an HDR imaging system using a 4-tap CMOS image sensor (CIS) that employs a charge-splitting method [1] to achieve HDR of up to 110 dB while effectively minimizing signal-to-noise ratio (SNR) degradation and motion artifacts. Unlike the lateral overflow capacitor method, our approach does not require large or high-density in-pixel capacitors. The system provides the ability to dynamically adjust the DR and optimize the SNR to meet different imaging requirements. In our previous study, the charge-splitting method with a 2-tap CIS was proposed to achieve adjustable HDR by varying the duty ratio of the transfer gates. In this work, the technique is extended to a 4-tap CIS [2] to further improve the DR and explore its use in vein pattern measurement.

II. Materials and Methods

A. Multitap CIS Pixel

The pixel structure of the 4-tap CIS utilized in the proposed system is depicted in Fig. 1(a), while Fig. 1(b) presents the demodulator diagram of the 4-tap pixel. The demodulator of the 4-tap pixel comprises a photodiode (PD), four taps, and a drain. Each tap consists of a transfer gate (G) paired with a floating diffusion (FD). During the exposure period, only one of the transfer gates is turned on at any given time, transferring the photogenerated charges to the corresponding FD or storage diode (SD) for temporary storage. The drain gate (GD) is used for the purpose of draining the photogenerated charges, thereby creating periods of insensitivity to light, such as during readout. In contrast to conventional CIS pixels, which output a single pixel value, the 4-tap CIS pixel reads each tap independently, generating four distinct pixel values upon readout. The 4-tap CIS is capable of capturing four images with different exposure times within a single frame because the transfer gates can be controlled independently.

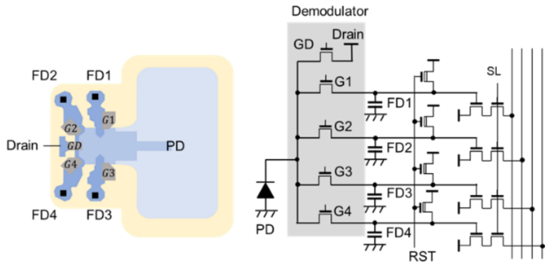

Fig. 1 (a) Conceptual diagram of the 4-tap CIS pixel, and (b) demodulator diagram of the 4-tap pixel. (Adapted from Ref. 2)

Table 1 summarizes the specifications and basic characteristics of the prototype 4-tap CIS. The sensor is fabricated using a 0.11 µm CIS process, resulting in a relatively large pixel size of 16.8 × 16.8 µm^2. This is the limit of the CIS process that is currently available for university research purposes.

Table 1 Specifications of the prototype 4-tap CIS

Parameter	Value
Technology	0.11 µm CIS process
Pixel count	648 (H) × 480 (V)
Pixel size	16.8 µm × 16.8 µm
Chip size	14.92 mm × 15.5 mm
Shortest time window	20 ns
ADC resolution	12 bits
Readout time	1.45 ms
Full well capacity	44k e^-
Conversion gain	10.0 µV/e^-
Quantum efficiency	18.6% @(940 nm)

B. Operation Principle of the HDR Camera System

Fig. 2 shows the timing diagrams for achieving HDR: (a) represents the conventional multi-exposure method, while (b) represents the proposed charge-splitting method. In the conventional multi-exposure method, each tap of the 4-tap CIS is assigned a different exposure time. This allows images with four different sensitivities to be captured simultaneously in a single frame. The readout time is 1.45 ms, resulting in a frame rate of 30.7 frames per second (fps), which is equivalent to the typical video rate. After readout, the four images are then combined into a single HDR image.

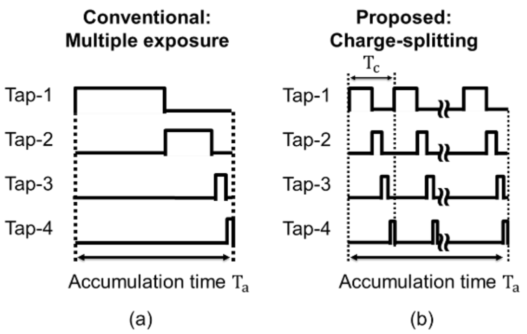

Fig. 2 (a) Timing diagram of the conventional multi-exposure method, and (b) Timing diagram of the proposed charge-splitting method.

The total DR (DR_{total}) can be calculated using the following equation:

$$DR_{total} = DR_{base} + DR_{ext} \quad (1)$$

The base DR of the 4-tap CIS (i.e. the DR of tap-1), DR_{base}, is expressed as follows as long as the read noise is larger than a couple of electrons:

$$DR_{base} = 20\log_{10}(I_{sat}/I_{noise}) \quad (2)$$

where I_{sat} represents the saturation light intensity level and I_{noise} represents the equivalent light intensity of the noise floor (dark noise). Meanwhile, DR_{ext} is the DR extension resulting from the addition of the other three taps. The total DR extension can be expressed as:

$$DR_{ext} = \sum \log_{10}(t_n/t_{n+1}) \ \ (n = 1, 2, 3) \quad (3)$$

where t_n/t_{n+1} is the exposure time scaling factor between two adjacent taps. In this work, the exposure time scaling factor between two adjacent taps is 10, resulting in a DR extension of 20 dB per additional tap. For the 4-tap CIS, a total DR extension of 60 dB is expected.

In the proposed charge-splitting method, the accumulation time T_a (= 31.1 ms) is divided into 100 cycles, each with a cycle length T_c of 311 µs. Within each cycle, taps 1-4 operate with duty cycles D_n of 90%, 9%, 0.9%, and 0.09%, respectively. The total effective exposure time of each tap, denoted as $T_a \times D_n$, remains the same as in the conventional multi-exposure method; therefore, the DR should remain the same as in the multi-exposure method.

In the proposed method, the unit exposure times at each tap are 100 times shorter in comparison to the conventional method, resulting in a substantially reduced time difference between images at each tap. When capturing a moving object, the perceived difference in object motion is significantly minimized compared to the conventional multi-exposure method, resulting in fewer motion artifacts.

C. SFDI and NLOS

In this work, we implemented the proposed system for HDR vein pattern imaging using spatial frequency domain imaging (SFDI) and non-line-ofsight imaging (NLOS). Fig. 3 shows the conceptual diagrams of these two techniques. SFDI is a wide-field, diffuse optical technique that quantitatively measures the optical properties of shallow and superficial tissue (a few millimeters). NLOS, on the other hand, is based on point measurements and focuses on the optical properties of deeper tissues (a few centimeters). Since the reflectances for NLOS and SFDI differ significantly in intensity, simultaneous imaging of both modalities requires a motion artifact-free HDR system. To address this, we employed the proposed 4-tap CIS-based system that simultaneously captures high- and low-intensity reflectances, allowing accurate imaging over varying tissue depths.

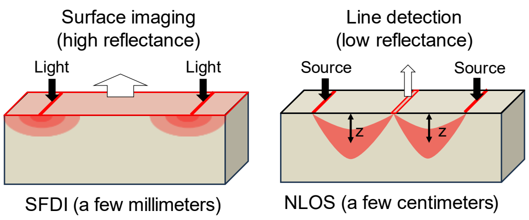

Fig. 3 Conceptual diagrams of SFDI and NLOS

III. HDR Measurement

Fig. 4 shows the average pixel values of the four taps under different light intensities. The saturation and dark noise pixel values are 3598 LSB and 6.3 LSB, respectively.

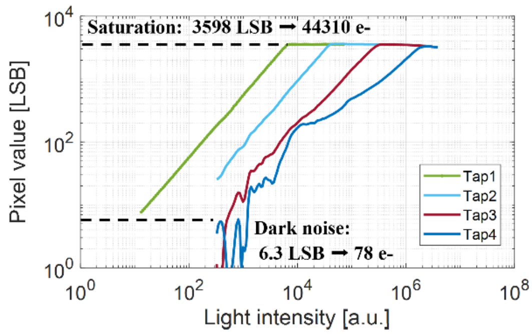

Fig. 4 The Light intensity vs. pixel value curve for the four taps.

Fig. 5 shows the average SNR across the four taps as a function of incident light intensity. The base DR of the CIS (DR of tap-1) is measured to be 55.9 dB, while the combined extended DR of taps 2-4 is 53.5 dB, resulting in a total DR of 110.1 dB. The maximum SNR achieved is 45.4 dB, with SNR transitions above 33 dB, ensuring high SNR while significantly extending the DR.

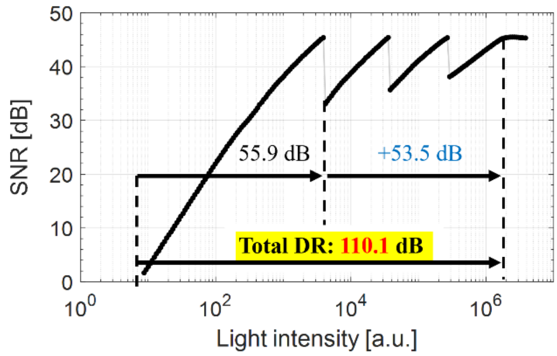

Fig. 5 Light intensity vs. SNR curve of the synthesized signal.

Figs. 6 (a) and 6 (b) compare captured single-frame images (30.7 fps) of a rotating chopper blade in an HDR scene, using both the conventional method and the proposed charge-splitting method. The scene features a dimly lit left side and a right side directly illuminated by an LED. A chopper blade rotates clockwise at 600 RPM on the right. Fig. 6(c) shows synthesized RGB images of the two methods using images from taps 2–4.

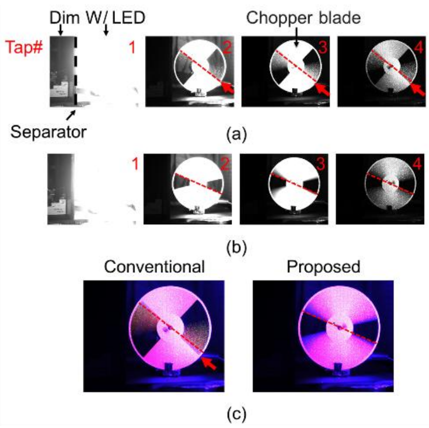

Fig. 6 Captured frames of an HDR scene from each tap using: (a) the conventional method, (b) the proposed charge-splitting method, and (c) synthesized RGB images of the two methods.

In the conventional method, the blade edge position (red arrow) deviates from the ideal position (dashed line) due to motion artifacts. This discrepancy becomes more pronounced in the synthesized RGB images, highlighting the greater error induced by motion artifacts in the results of the conventional method. In contrast, the proposed method maintains alignment with the ideal position, demonstrating superior effectiveness in mitigating motion artifacts.

IV. Vein Pattern Measurement

Fig. 7 shows the multi-line laser scanning vein imaging system, which simultaneously acquires NLOS and SFDI images for both deep and superficial tissues, respectively [3]. The multi-line light emitted from the laser is scanned across the measurement area in 32 steps using a galvanometer mirror, and 32 images are captured for each tap. Fig. 8(a) shows the raw images captured at taps 1 and 2 for each scanning step. Fig. 8(b) shows the reproduced NLOS image, while Fig. 8(c) shows the reproduced SFDI images at different spatial frequencies.

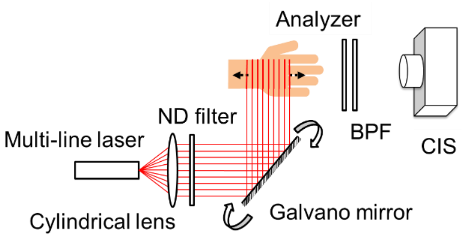

Fig. 7 The multi-line scanning vein imaging system

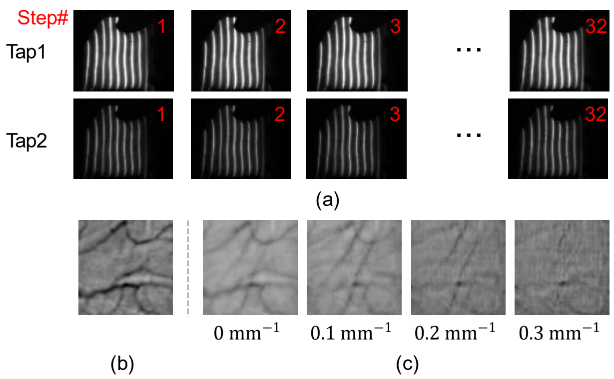

Fig. 8 (a) Raw images obtained from each scanning step at tap 1 and 2, (b) reproduced NLOS image, and (c) reproduced SFDI images.

The NLOS image, derived from the tap-1 images, is denoised and edge-enhanced using a bilateral filter, an unsharp filter, and a frequency filter. Vein patterns are then sharpened by deconvolution using a Wiener filter. Additionally, reflectance images corresponding to multiple spatial frequencies were acquired using HDR images combining taps 1 and 2 images for this experiment. The vein patterns are clearly visible in the NLOS images, while the SFDI images show more vein structure at low spatial frequencies and highlight the skin surface structure at higher spatial frequencies.

V. Conclusion

In this work, we presented an HDR camera system based on the charge-splitting method with integrated motion artifact mitigation using a 4-tap CMOS image sensor. The proposed system achieved an adjustable DR from 55.9 to 110.1 dB while maintaining a high SNR, with SNR transitions consistently above 33 dB. Measurement results demonstrate that the charge-splitting method drastically reduces motion artifacts. Additionally, the system simultaneously captured NLOS and SFDI images, enabling depth-resolved quantification and visualization of vein patterns in superficial and deep tissues.

Acknowledgement

This work was supported in part by JSPS KAKENHI Grant Number 24H00313. The authors are grateful to Prof. Hiruyuki Suzuki from Gunma University for the collaboration on the vein imaging experiments.

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