Real-time Crosstalk Mitigation Method Using On-Chip ISP in iToF System

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Abstract**—**We propose a real-time crosstalk mitigation method for iToF system by using on-chip ISP. We design the crosstalk mitigation block on the on-chip ISP to mitigate the crosstalk signal caused by a device cover glass. By considering temperature drift and exposure time of the sensor, the crosstalk is mitigated effectively in real time up to the frame rate of 30 fps. This paper also introduces a simple method of the crosstalk-pattern acquisition in the limited space. This pattern acquisition requires only two sets of images without any defacement of the cover glass, the iToF module, and the device components. Based on these methods, we achieve a depth offset of less than 1 %, which cannot be achieved without the use of the mitigation method in the presence of crosstalk.

I. Introduction

The indirect time-of-flight (iToF) sensor is a simple yet highly accurate sensor that has garnered significant attention in the extended reality (XR) and robotics applications. In these applications, for protection and aesthetic purposes, the sensor is concealed under a device cover glass. Considering the iToF's single module structure where the emitter and iToF sensor are co-located, there can exist a direct return of the emitted light to the sensor by the device cover glass, a phenomenon referred to as crosstalk.

Figure 1 shows the single module structure of the iToF sensor with the device cover glass. The emitted light passes through the cover glass and returns to the sensor by reflecting off an object. On the other hand, some portion of the emitted light reflects by the cover glass, which causes crosstalk. When these lights are overlapped, it behaves as multipath interference, which causes severe depth offset. And it is challenging to eliminate the interference signal from the overlapped signal [1]. Some physically reduce the crosstalk by manipulating the module structure (e.g., anti-reflective coating to the device cover glass or gaskets of the gap between the glass and module), but the crosstalk still remains due to the misalignment or variations of the module manufacturing [2].

In this paper, we propose a real-time crosstalk mitigation method in iToF sensor using on-chip image signal processor (ISP). We design the crosstalk mitigation block on the on-chip ISP to mitigate the crosstalk signal caused by the device cover glass. For real-time process, the block considers the effect of the temperature drift and sensor's exposure time, so it mitigates the crosstalk regardless of the environmental conditions. We also propose a simple crosstalk acquisition method in limited space without any defacement of the device. The result shows that our mitigation method achieves the depth offset to less than 1 %, which is 2.3-% point improvement compared to when the crosstalk mitigation is not used. We also observe that our crosstalk mitigation method is tolerable to the sensor's real-time driving environment of the exposure time and temperature.

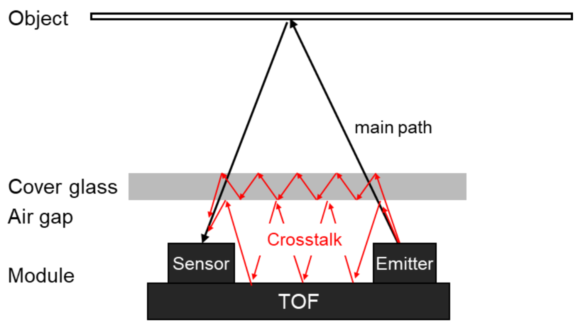


Figure 1. The module structure of the iToF sensor.

II. Real-time Crosstalk Mitigation

In 4-tap iToF systems, the modulated signal is a continuous and periodic signal with a period of $T=1/f_m$ (f_m: modulation frequency) having 50-% duty ratio. This signal is detected by sensor and stored in the four storage capacitors after division by four photo-gates. The photo-gates are controlled by sampling clocks having 25-% duty ratio. Here, the stored signals are referred to the cross-correlation or tap information and denoted as A_0, A_1, A_2, and A_3, respectively.

Figure 2 shows the block diagram of the depth calculation process of the 4-tap iToF system with our proposed the real-time crosstalk mitigation block. These blocks are implemented by using the 4-tap iToF sensor having on-chip ISP [3]. First, we calculate in-

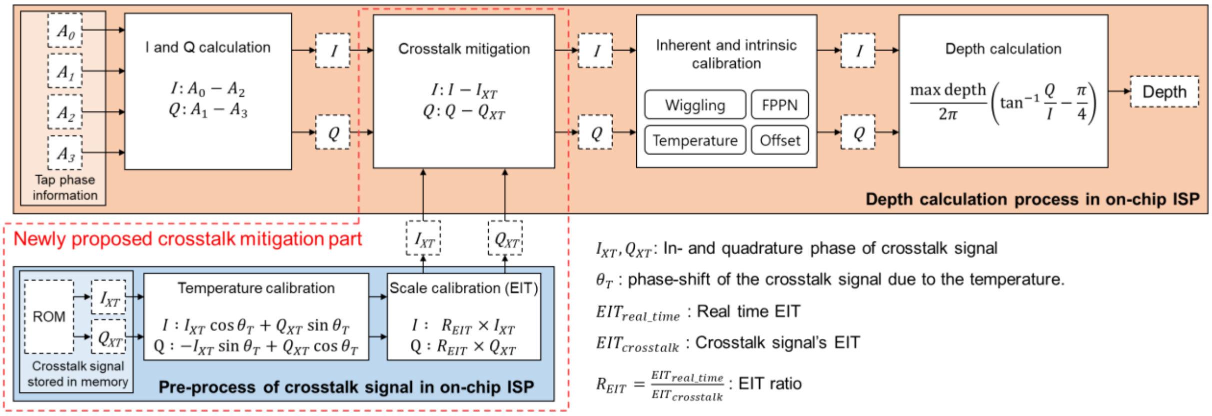


Figure 2. The block diagram of the real-time depth calculation process of 4-tap iToF system implemented in on-chip ISP including the proposed crosstalk mitigation.

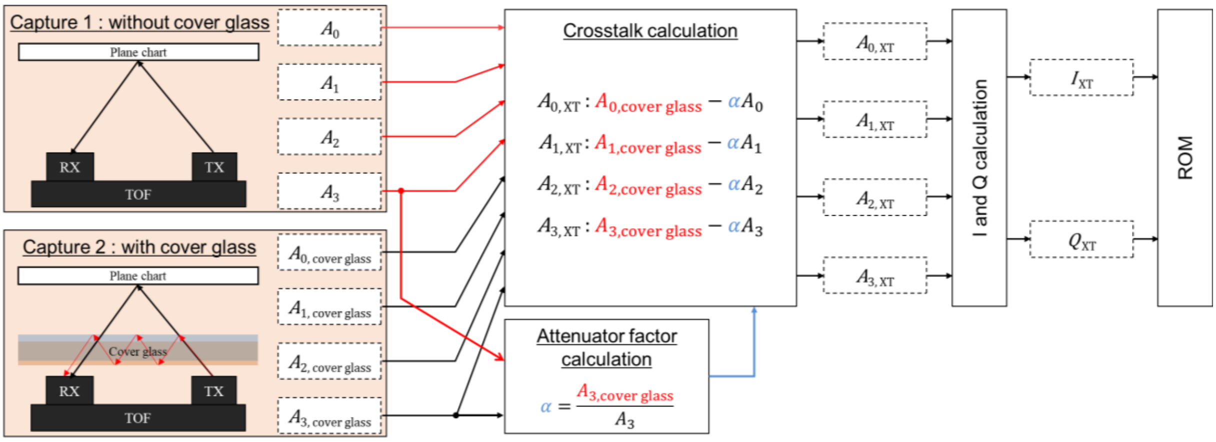


Figure 3. The block diagram of crosstalk acquisition method.

phase (I) and quadrature-phase (Q) signal by using four tap information (where $I = A_0$ - A_2 and $Q = A_1$ - A_3). Second, we subtract the crosstalk signals, I_{XT} and Q_{XT}, from the received signal. It should be noted that the crosstalk mitigation block is performed in advance of the calibration blocks, since the crosstalk signal deteriorates the calibration performance. This crosstalk signal is predefined signal stored in the sensor's memory by using our crosstalk acquisition method. According to the sensor's real-time driving environment, we compensate for the exposure integration time (EIT) and temperature effects on the crosstalk signal. This is because they change the crosstalk amount and its phase shift, respectively. Then, we calibrate the inherent and intrinsic characteristics of the iToF system [4]. Finally, we calculate the depth by using IQ signals. The depth can be calculated by using the IQ signal after calibrations as follows,

$$\frac{d_{max}}{2\pi}\left(\tan^{-1}\frac{I}{Q} - \frac{\pi}{4}\right) \quad (1)$$

where d_{max} is the maximum distance.

III. Crosstalk Acquisition Method

Ideally, in order to capture only the crosstalk signal due to the device cover glass, we require a wide and empty space in which light cannot be reflected and returned. However, it practically difficult to find such a large enough space. We propose a simple method of acquiring the crosstalk pattern in a limited space. As shown in Figure 3, we place a plane chart at a fixed distance of over $d_{max}/4$ (in the case of 4-tap iToF system) and capture the plane chart twice according to the presence or absence of the device cover glass. When there is no the device cover glass, the captured images (A_0, A_1, A_2, and A_3) have only the plane-chart information. However, when there is the device cover glass, the captured images ($A_{0,\text{cover glass}}$, $A_{1,\text{cover glass}}$, $A_{2,\text{cover glass}}$, and $A_{3,\text{cover glass}}$) have both the plane-chart and crosstalk-pattern information. In addition, the chart information passing through the device cover glass will be attenuated by the glass having a transmittance of less than 100 %. The attenuation factor is expressed as the square of the glass's transmittance since the emitted light passes through the cover glass twice. Then as in the crosstalk calculation block of Figure 3, we can obtain the crosstalk pattern ($A_{0,\text{XT}}$, $A_{1,\text{XT}}$, $A_{2,\text{XT}}$, and $A_{3,\text{XT}}$) by subtracting the first images from the with-cover-glass images in consideration of the attenuation factor.

The attenuation factor, α, is calculated by using a crosstalk-free tap. Practically, there is at least one non-interference tap because duty ratio of the modulation signal is 50 %. Here, we name this tap as crosstalk-free tap. For example, the crosstalk signal caused by the

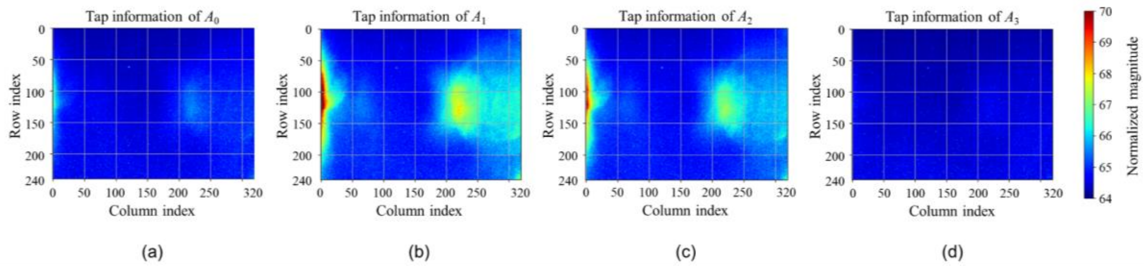


Figure 4. The tap information of the crosstalk captured in a wide and empty space: (a) A_0, (b) A_1, (c) A_2, and (d) A_3.

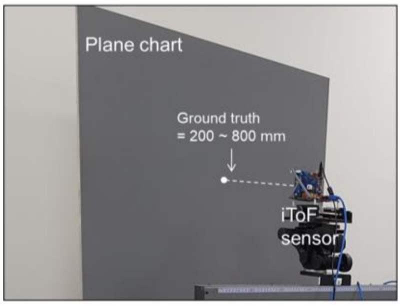


Figure 5. Implementation setup.

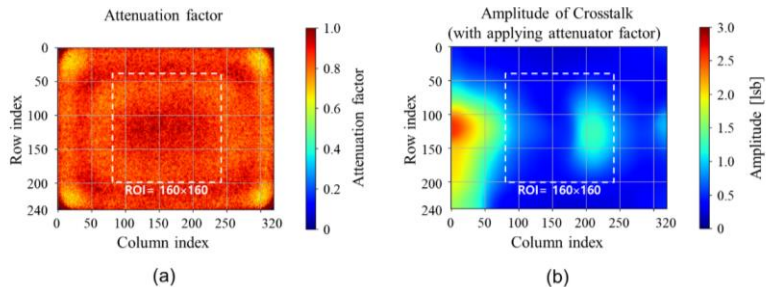


Figure 6. (a) Attenuation factor. (b) Amplitude image of acquired crosstalk pattern in consideration of the attenuator factor.

device cover glass is stored into the near distance taps A_0, A_1, and A_2. Therefore, the crosstalk signal does not affect the A_3. Figure 4 illustrate the crosstalk pattern captured in the wide empty space. It shows the impacts of the crosstalk across each tap. The crosstalk signal presents in A_0, A_1, and A_2, but the A_3 is crosstalk free. It means that we can achieve the attenuation factor, α, by the $A_{3,\text{cover glass}}$ divided by A_3.

Finally, the proposed method outputs the crosstalk pattern I_{XT} and Q_{XT} to reduce the handing data in size.

IV. Hardware Implementation And Measurement Results

The proposed method is implemented with the QVGA depth-output iToF module (QVGA depth output after 2 × 2 analog binning) in [3]. Figure 5 shows implementation setup for the crosstalk acquisition and verification, respectively. The modulation and demodulation are implemented by 100-MHz-period rectangular pulses having the duty ratio of 50 and 25 %, respectively. The maximum EIT of the iToF sensor is 0.4 ms with the auto exposure function. The depth frame rate is 30 fps.

Figure 6 shows the crosstalk-acquisition result by using our proposed method. Figure 6(a) shows the obtained attenuation factor, α. Here, since this factor represents the attenuation value of the device cover glass, the value is less than 1. Figure 6(b) shows an amplitude $\left(=\sqrt{I_{XT}^2+Q_{XT}^2}/2\right)$ image of the obtained crosstalk. The crosstalk pattern spreads from left to right. This is because the emitter is on the left side of the sensor. The average of the attenuation factor at the marked ROI (= 160×160 at the center) region is measured to be 0.86, which means the transmittance of the device cover glass is 0.93 (because the emitted light passes through the cover glass twice).

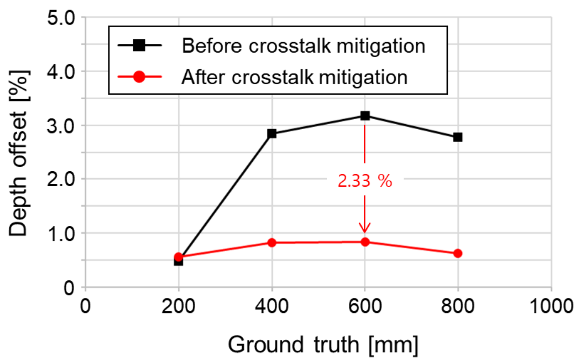


Figure 7. Depth offset of ROI region as a function of ground truth. The size of the ROI is 160 × 160 pixel and located at the center.

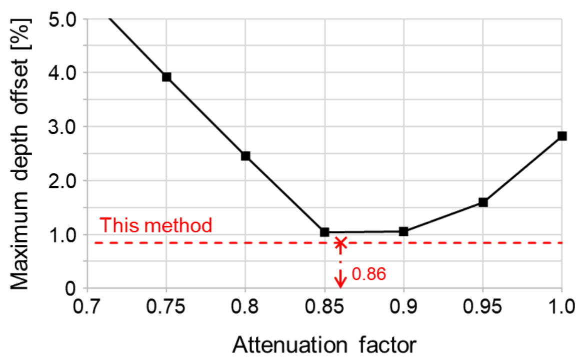
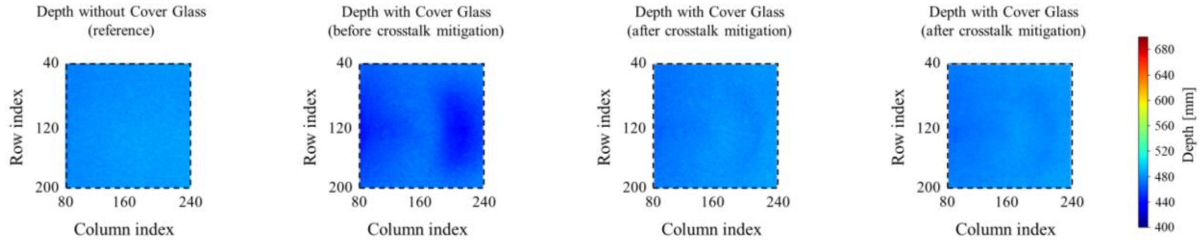


Figure 8. Maximum depth offset of ROI region as a function of attenuation factor after crosstalk mitigation method. The attenuation factor is intentionally changed from 0.7 to 1. The size of the ROI is 160 × 160 pixel and located at the center.

We measure the depth offset to verify our proposed crosstalk mitigation method by using the obtained crosstalk pattern. Figure 7 shows the depth offset as a function of ground truth from 200 to 800 mm. The depth offset is calculated as,



	(a)	(b)	(c)	(d)
Depth in ROI [mm]	500.00	481.10	496.40	496.66
Depth offset [%]	0	3.78	0.72	0.67
EIT [ms]	0.4	0.4	0.4	1.2
Frame rate [fps]	30	30	30	30
Sensor Temp. [°C]	28.50	31.00	30.50	34.00
Emitter Temp. [°C]	30.18	32.96	32.41	40.37

Figure 9. Captured depth images at ground truth = 500 mm. (a) without device cover glass as reference, (b) with device cover glass before crosstalk mitigation and (c)-(d) with device cover glass after crosstalk mitigation.

$$\text{Depth offset} = \frac{|\varphi_{\text{with glass}} - \varphi_{\text{without glass}}|}{\text{Ground truth}} \times 100 \quad (2).$$

When the mitigation method is not applied, the depth offset is measured to be 3.17 % at the distance of 600 mm. However, when the proposed crosstalk mitigation method is applied, the depth offset is improved to less than 1 % in range of ground truth.

We also verify the attenuation factor which help to find the crosstalk pattern. In this verification, we use the maximum depth offset which is defined as the worst depth offset measured within the ground truth range. Figure 8 shows the maximum depth offset as a function of the attenuation factor after the crosstalk mitigation. We intentionally change the attenuation factor from 0.7 to 1.0. The minimum value of the maximum depth offset is obtained to be 1.04 % at the intentionally searched attenuation factor of 0.85. The attenuation factor (0.86) calculated by using the crosstalk-free tap is similar to the intentionally searched value of 0.85. Therefore, our calculation method with the crosstalk-free tap is an efficient way to find the attenuation factor.

Figure 9 shows the captured depth images at ground truth of 500 mm within the 160×160 ROI region. Figure 9(a) is the depth image without the device cover glass. Figure 9(b)-(d) are the depth images with the device cover glass. As shown in Figure 9(b), without using the crosstalk mitigation, the depth offset (expressed in dark blue) is observed in the same shape as the crosstalk pattern of Figure 6(b). However, as shown in Figure 9(c) and (d), after using the crosstalk mitigation, the depth offset and crosstalk pattern are suppressed.

Figure 9(c) and (d) show the depth images having different EIT. The change of the EIT varies the crosstalk amount and the temperature of the sensor and emitter. The EITs of Figure 9(c) and (d) are 0.4 and 1.2 ms. Therefore, the temperature conditions of Figure 9(c) are lower than those of Figure 9(d). Although they have different operating conditions, the depths of Figure 9(c) and (d) are measured to be 496.4 and 496.7 mm, which is only 0.3-mm difference. It shows that our mitigation method is tolerable to the sensor's real-time driving environments because it is designed in consideration of temperature change and EIT change.

V. Conclusion

We proposed a real-time crosstalk mitigation method and applied it to the on-chip ISP of the 4-tap iToF sensor. First, we acquired the crosstalk pattern by using the attenuation of the device cover glass measured by an crosstalk-free tap. The results showed that our proposed method can achieve the depth offset to less than 1 % which is 2.33-% point lower than the system without the crosstalk mitigation method. We also measured the maximum depth offset as a function of the intentionally searched attenuation factor and compare it with the attenuation factor obtained at the crosstalk acquisition process. It showed that the obtained factor from the acquisition process has the minimum value of the maximum depth offset among the other intentionally searched values. Finally, we showed that our real-time crosstalk mitigation method is tolerable to the sensor's driving environment such as EIT and temperature.

References

[1] C. Bamji et al., "A review of indirect time-of-flight technologies," *IEEE Trans. Electron Devices*, vol. 69, no. 6, pp. 2779-2793, Feb. 2022.

[2] STMicroelectronics, VL53L0X ranging module cover window guidelines, AN4907 application note, 2020.

[3] J. Park et al., "An indirect time-of-flight CMOS image sensor achieving sub-ms motion lagging and 60fps depth image from on-chip ISP," in *Proc. IEEE Symp. VLSI Technol. Circuits*, pp. 1-2, 2023.

[4] M. S. Keel, et al., "Wiggling error self-calibration for indirect ToF image sensors," in *Proc. IISW*, 1-4, 2021.