Reducing Motion Blur by Adjusting Integration Time for Scanning Camera with TDI CMOS

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***Abstract*—CMOS image sensors are being used for more and more remote sensing camera systems because the system with CMOS can be compact and requires less power. Drawbacks of the CMOS from the point of performance are being improved nowadays. TDI CMOS image sensors are being utilized for high resolution earth observation camera systems. Intrinsic weak point of the TDI CMOS, compared to the TDI CCD, is the motion blur but lots of ways are being introduced to overcome it. As the motion blur is not critical in the TDI CCD camera thanks to the multi-phased clocking scheme, some TDI CMOS samples the signal more than once to mimic TDI CCD. One active area (photo diode) can be divided into two or more sections for better synchronization. Physical gap of the mask can be placed between pixels to mitigate the blur in the scanning direction. In this case, the motion blur can be minimized effectively, but the amount of the signal that can be collected will be reduced. Motion blur compensation is being achieved with the sacrifice of another design parameters. In this paper, alternative way of utilizing TDI CMOS camera system is introduced. Thanks to the TDI function, SNR performance is less challenging compared to the MTF that is degraded by the motion blur. Therefore, the capability of the proximity electronics adjusting the integration time make it possible to reduce the motion blur with the expense of abundant signal. Instead of physical masking between pixels, if the integration time is reduced from the line time, the resultant effects are the same but, the system can also be operated with full integration time. That means it can be selectable. Depending on the characteristics of the target, SNR prioritized image or MTF prioritized image can be selectively obtained.**

***Index Terms*—CMOS, TDI, CCD, multi-phased clocking, motion blur, synchronization, integration time, signal to noise ratio, MTF**

I. Introduction

The image sensor is the crucial component in the earth observation electro-optical camera system. Architecture and performance of the image sensor greatly affect the configuration of the camera system and eventually the quality of the image data from the system.

The CCDs (Charge Coupled Device) have been used for such remote sensing instruments for many decades. Its performances are good enough to satisfy most of the needs from the users. Nevertheless, the CCD has a few drawbacks. The CCD needs to be supported by the relatively heavy proximity electronics because many kinds of voltages and clocks should be provided. High power consumption is also another burden to be handled properly. The CMOS (Complementary Metal Oxide Semiconductor) is another widely used sensor in many applications. Much of the functions that are supported by the proximity electronics for the CCD are being implemented inside the CMOS. The system with CMOS can be compact and consumes less power. Even though the CMOS has many advantages over the CCD from the point of implementation, its performances are being considered not to be comparable to the CCD. But, CMOS is being improved nowadays to make it comparable to the CCD maintaining its original advantages.

TABLE I. Comparison of CCD and CMOS

	CCD	CMOS
Power consumption	High	Low
Required voltages (supporting electronics)	Heavy	Light
Required control clocks	Many	A few
On-chip ADC	No	Possible
Pattern noise	Relatively better	Relatively worse
Fill factor	High	Low
Random access	Impossible	Possible
Charge domain operation (On-chip accumulation)	Possible	Impossible
Multi-phase clocking (synchronized sampling)	Possible	Impossible
Dynamic range (Full well capacity)	Relatively better	Relatively worse
Electronic shutter	Limited	Better
Radiation immunity	Relatively better	Relatively worse

General comparison of the CCD and the CMOS is summarized in the Table I. Even though some of special sensors may not fit to this comparison, typical CCD and CMOS sensors will not be deviated from this comparison.

Many of the low earth orbit satellites observe ground targets with the camera system that are equipped with linear CCD. Each pixel in the CCD samples the scene as the rectangular sampler with discrete time interval. The irradiance coming into the rectangular CCD pixels are not usually enough to achieve high signal to noise ratio (SNR) because the integration time is not long enough. Time delayed integration (TDI) CCD is being used to achieve required SNR. It is well known that the SNR of the CCD with n TDI stages will be increased proportional to the square root of n. In this case, the charge transfer in the

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sensor should be synchronized with the scanning speed in order to achieve good MTF.

However, when the rectangular CCD pixels are scanning the scene, even though they are sampled in an exact time for the synchronization, if they are retrieved once per each line time, the blurring of the image in the along-track direction cannot be avoided because the rectangular sampler is scanning two physical pixels during each line time. Therefore, along track MTF cannot be better than cross-track MTF. This is caused by the discrete sampling with continuous scanning and it can be mitigated by adopting multi-phased CCD where the charge moves more continuously, a few times in one line time, in the direction of scanning [1]. This kind of multi-phasing is possible only in the CCD, not in the CMOS. In some application, physical masking on the edges of the rectangular pixels is also being adopted in order to prevent some portion of the motion blur.

However, not a little methods have been introduced to overcome that kind of motion blur in the system with TDI CMOS [2]-[5]. Collected charges are sampled more than once for one line time or the photo diode is divided into four sections to simulate multi-phasing. But, most of them are to be implemented with the expense of increased design complexity.

In this paper, a simple way of reducing the motion blur in the TDI CMOS by reducing the integration time, is introduced and it is based on the fact that the SNR is big enough thanks to the TDI functions. Depending on the radiance from the target, selective acquisition of MTF prioritized image or SNR prioritized image is possible without increasing design complexity of the TDI CMOS sensor. Optimal synchronized exposure control can be applied because it is achieved by adjusting the timing of the clock which can be handled as one of many imaging parameters.

II. Motion Blur in the Scanning Pixel

Due to the fact that the detector pixels are rectangular shaped samplers and each line is read after scanning one line, the energy collected in one pixel (or one line) of the push broom camera includes the information from two pixels. Intensity of the energy from those two pixels are distributed as a form of the triangular as shown in following Fig. 1. It is well known as the motion blur observed in the scanning camera system.

In case of the CCD camera where the charge is moved in the detector at the same speed of scanning the scene, charge transfer in the active area is accomplished with three or four phase shifting. With the increased number of clocking phase for the charge transfer, the movement of the charge and movement of the scene by the scanning, can be synchronized well and it will reduce the motion blur dramatically. Therefore, the motion blur in the camera using the TDI CCD is not any more issue because the amount of the motion blur is negligible.

Detector MTF of the staring camera system can be up to 63.7% at the Nyquist frequency. However, in case of scanning system as shown in Fig. 1, un-wanted information from adjacent pixels can be 25% of the collected signal in a pixel and it results in dramatic MTF degradation.

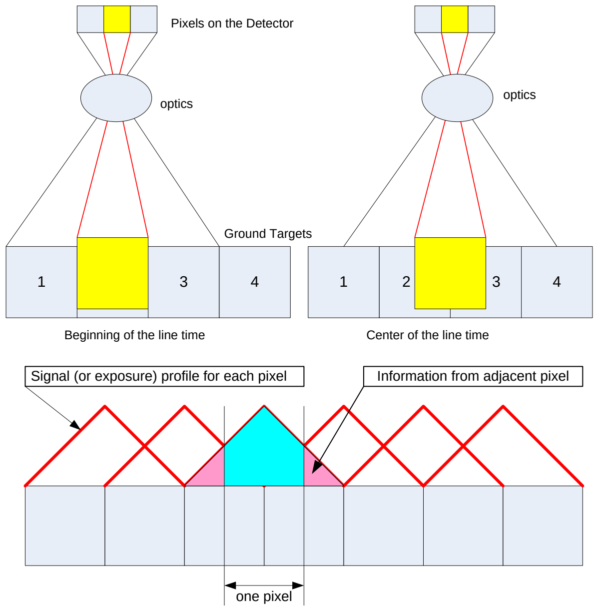

Figure 1. Amount of motion blur (one sample per line time)

III. Improved CMOS Image Sensor

The CMOS image sensors are being used for more and more camera systems because of its various advantages mentioned in the previous section. In addition to that, the performance of the CMOS image sensors are being improved and becoming to be comparable to the CCD. Back-side illumination [6], [7] is also being adopted to improve the quantum efficiency, especially in the short wave length spectral range.

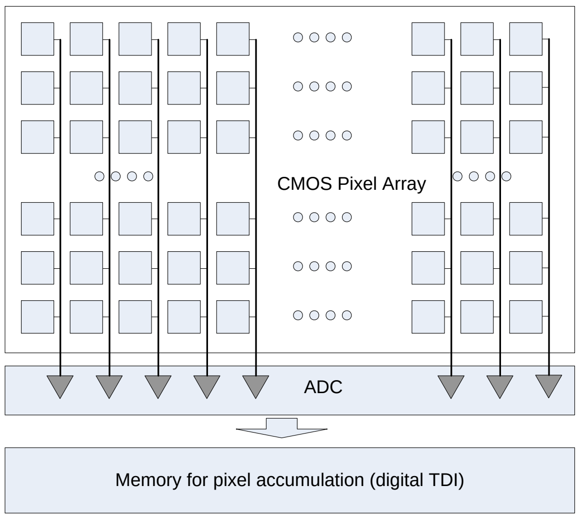

Figure 2. Accumulation of the signal in digital domain

One of the typical drawbacks of the CMOS sensor was relatively poor fill factor but it is also being improved by adopting micro-lens or three dimensional pixel design. One of the most important advantages that the CCD has, is that the CCD can accumulate the charges in the active pixel area, which is called time delayed integration (TDI). Many of the high resolution earth observation camera system is utilizing the TDI CCDs. Intrinsically, this kind of on-chip accumulation of TDI is not possible in the CMOS sensors because each pixel is to be sampled individually. However, not a little CMOS image sensors with the TDI function is being introduced [2]-[5] to provide high sensitivity and signal to noise ratio. The TDI CMOS is configured as two dimensional array that is the same case as TDI CCD, but accumulation of the signals are mostly handled outside of the chip, in the digital domain of the proximity electronics [8]. As shown in the Fig. 2, each pixel line is read and converted to the digital data and accumulated in the image memory to increase the signal to noise ratio.

Due to the fact that the accumulation of the signal needs to be handled in the digital domain and each pixel should be read one by one, the speed of the pixel clock should be increased. Nevertheless, digital domain accumulation is considered as a good way of increasing signal to noise ratio.

IV. CMOS Clocking and Shuttering

Traditionally, the CMOS image sensor has been controlled with rolling shutter scheme because it is simple and easy to be implemented. Because resetting, integration, and sampling in the rolling shutter scheme are handled individually for each line, the image frame can include a distortion, especially for the fast moving objects. In case of global shuttering, pixels in the full frame start and stop the integration at the same time and each pixel needs to have a separate storage, so called pixel level memory to support high frame rate. These pixel level storage enables simultaneous read-out and eventually avoidance of the distortion.

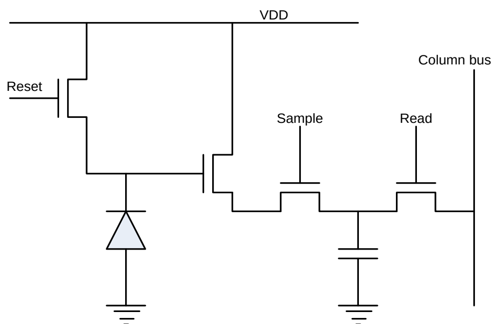

Figure 3. CMOS Pixel with snapshot storage

Due to the fact that the time delayed integration works effectively when the acquisition of the individual images to be accumulated are synchronized precisely, the TDI CMOS is being implemented with the extension of the global shuttering. Snapshot of the full frame is supported by the pixel memory and subsequent integration can be initiated while the pixel memories are being read-out. Typical structure of the pixels which have pixel memory is shown in the Fig. 3.

All the pixels in a frame start to be exposed to the scene at the same time and sampled at the same time after integration. These sampling period and scanning of the scene need to be exactly synchronized. At the end of each integration time, the collected charge need to be saved to the pixel memory and read out while the photo-diode is integrating the next scene [9].

V. Reducing Motion Blur

As mentioned before, synchronized sampling of the signal is essential to the implementation of the time delayed integration. However, the scene is passing by in a continuous manner while the acquisition of the signal is performed in a discrete manner even though the sampling and transferring to the adjacent pixel is performed at the same speed with the scanning. This is a fundamental issue of the motion blur and this is mitigated in the CCD by implementing multi-phased charge transfer [1]. As the number of the phase increases, the discrepancy between the movement of the scene and that of the charge on the active area reduces. As shown in the Fig. 1, if the charge is sampled once per line time, 25% of the collected signal belong to the adjacent pixel. On the other hand, when the charge is controlled to be moved four times per line time (4 phase clocking) as shown in the Fig. 4, the amount of the signal which is collected in the current pixel but belong to the adjacent pixels is reduced down to about 6.25% as depicted in the Fig. 5.

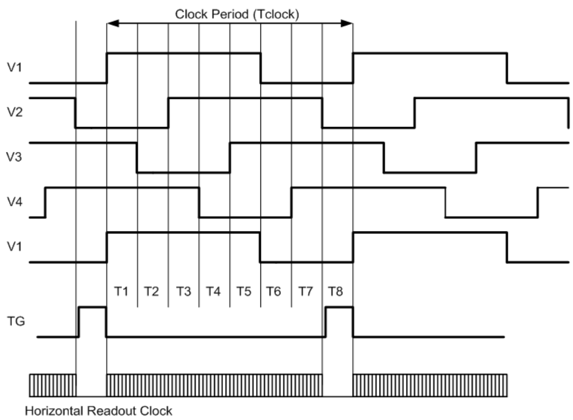

Figure 4. Four phase clocking for charge transfer

As mentioned earlier, four phase clocking, can be applied only to the CCD where the charge can be moved in the active area before sampling. It cannot be implemented in the CMOS where each pixel is sampled line by line, eventually pixel by pixel. This is the critical drawback of the previous design of TDI CMOS.

However, a few alternative ways to mitigate such a motion blur happening in the TDI CMOS have been introduced [2]-[5]. In order to reduce the effect of the motion blur on the TDI CMOS, a design to read the same pixel four times per each line time was introduced in “Ref. [2]”. Active area of the photo diode can be divided into four sections in the scanning direction and they are sharing the read-out circuit in another design [5]. Placing physical gap can be inserted between pixels in the scan direction [4]. This gap between pixels can reduce the motion blur and can also be used to secure read-out time of the frame. These designs which were proposed to reduce the motion blur can be achieved with careful consideration and significant modification of complicated pixel design. They are increasing complexity of pixel structure or require the sacrifice of another performance parameters. Some of them also have side effects such as diminished fill factor.

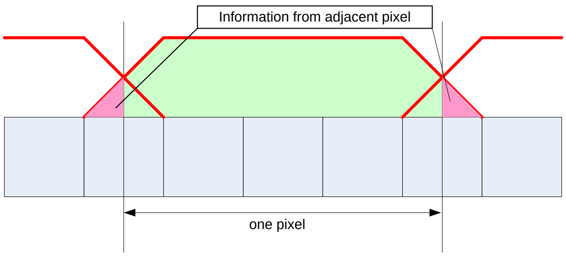

Figure 5. Amount of motion blur (4 phase clocking)

Another approach to reduce the motion blur can be considered without increasing the complexity of the TDI CMOS design. The effect of the motion blur can be reduced with the expense of abundant signal to noise ratio. In the camera system with TDI image sensor, the synchronization between scanning and sampling of the signal is very important to fulfill MTF requirements. It should be synchronized in the geometric domain and also in the time domain. The requirement of the signal to noise ratio is to be increased by the increased TDI stages. It is proportional to the square root of the number of TDI stages.

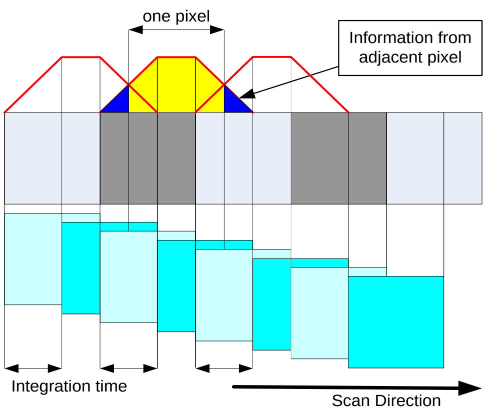

Figure 6. Reducing motion blur by under sampling

Integration time of the image sensor is controlled by the proximity electronics and it is usually one of many imaging parameters. In the push broom camera system, the frame time (or line time) should be synchronized with the target scanning speed but the integration time is adjustable together with the TDI stages depending on the radiance of the individual scene. By decreasing the integration time and increasing the number of TDI stages, the amount of the motion blur can be decreased as shown in Fig. 6. It is a kind of sub-sampling and only part of the line time is used for collecting signals. In the example in Fig. 6, 60% of the line time is used to integrate incoming signal. As mentioned earlier, the motion blur will be about 25% when the integration time is the same as the line time. However, the motion blur can be reduced down to 15% with the expense of the integration time. Reduced integration time can be compensated with increasing the number of TDI stages.

TABLE II. RELATIVE ESTIMATION OF MOTION BLUR

Clocking & Integration Time	Relative amount of motion blur
TDI CCD (4phase clocking)	6.25%
TDI CMOS (100% line time)	25%
TDI CMOS (60% line time)	15%

It will be effective because the synchronization accuracy can usually be achievable. By controlling the integration time for reducing motion blur without changing the structure of the CMOS pixel, the camera system can provide both of the images; one is relatively dark and clear image and another is bright and relatively blurred image. Table II shows the summary of the relative motion blur depending on the image sensor and control method.

VI. CONCLUSION

Motion blur of the TDI CCD camera in the scan direction is considered as negligible thanks to the multi-phased charge transfer scheme which results in better synchronization of the scene velocity and the charge transfer speed. The proportion of the signal which is belong to the adjacent pixels can be minimized.

Time delayed integration concept is being adopted in the system with the CMOS sensor to improve SNR performance. In that case, signal accumulation is being done in the digital domain. Due to the fact that the charge in the active region cannot be moved in the CMOS sensor to synchronize with moving target, the ways to reduce the effect of the motion blur are being introduced [2]-[5].

The motion blur in the TDI CMOS image sensor can be mitigated with the expense of other performance parameters. Reducing the motion blur can be achieved by reducing the integration time and diminished integration time can be compensated by increasing the number of TDI stages. Reduced integration time maintaining the same line time in the scanning camera system shows the same effects as the smaller pixel size with bigger pitch size. Therefore, the MTF can be increased while the SNR is decreased.

By implementing the integration time as a controllable imaging parameter, the target with big radiance can be captured with reduced motion blur with the expense of abundant signal. When the target is dark, the integration time can be recovered to have bright images. Therefore, the motion blur can be reduced selectively. Depending on the characteristics of the target, SNR prioritized image or MTF prioritized image can be selectively obtained.

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