High Dynamic Range CMOS Image Sensors Featuring Multiple Integration and Auto-Calibration

M. Schwarz, A. Bußmann, T. Heimann, B.J. Hosticka, J.Huppertz, and O. Schrey

Abstract - **Industrial and automotive image acquisition systems require dedicated CMOS image sensors with increased optical dynamic range, high image quality, and a high local contrast. Whereas image sensors with high dynamic range can be realized using logarithmic pixel characteristic their image quality and contrast are rather poor. In this contribution we present image sensors that exhibit high local contrast, high optical dynamic range, and high image quality using linear integrating pixels featuring fast multiple integration. The resulting image is composed of multiple images typically captured at frame rates between 100 and 200 fps. To perform this task in real-time and especially to make it suitable for on-chip implementation dedicated algorithms for image composition from several frames and auto-calibration have been developed and will be presented in this contribution.**

1 Introduction

CMOS image sensors with linear integrating pixels allow capture of high dynamic images with up to 120dB [1,2]. In contrast to logarithmic sensors capturing high optical dynamic images here is based on acquisition of several consecutive images frames (typically 2 – 4 frames) with different integration time and forming a composite image. On this basis images with high dynamic range, high contrast, and high image quality can be computed with a minimum of algorithmic effort. Such method is well applicable for real-time implementation and on-chip integration. This paper describes a method that enables acquisition of images exhibiting high dynamic range. These images are computed from a set of successive images acquired at a higher rate of typically more than 100 fps. The paper also describes a real-time calibration procedure which not only allows the correct combination of the original images but also compensates for temperature and other drift effects during operation. Thus image sensors implementing these methods will be well applicable for applications requiring high quality images like inspection and placement systems as well as automotive applications, namely occupancy sensors, vehicle guidance systems, pre-crash-detection, and anti-theft systems.

Fraunhofer Institute of Microelectronic Circuits and Systems, Finkenstr. 61, Duisburg, Germany. E-mail: schwarz@ims.fhg.de, Tel. +49 203 3783 217, Fax: +49 203 3783 278.

2 Sensors Featuring Multiple Integration

In general all types of CMOS image sensors with integrating pixels can be used for building high dynamic range sensor systems featuring either a rolling or a synchronous electronic shutter. Variation of the integration time for each image yields a set of several consecutive images. Each of these images covers a different part of the optical dynamic range of the scene while a single image, of course, can only cover an optical range corresponding to the optical dynamic range (DNR) of the CMOS image sensor. In contrast to CCDs changing the integration time for each image does not affect the quality of the output signal at all. Two pixel principles for sensors with either rolling or synchronous shutter which can both be used here are shown in Figures 1 and 2, respectively [3,4]. Note that the figures indicate only the principle: both realizations are much more complex as they contain SC-amplifiers with correlated double sampling (CDS) circuits.

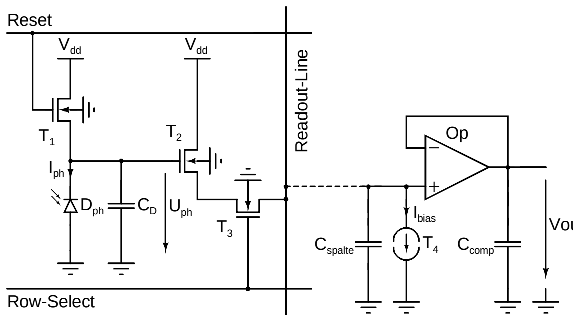

Figure 1: Pixel schematic of a linear integration CMOS image sensor with voltage readout and rolling shutter used for capturing scenes with high dynamic range.

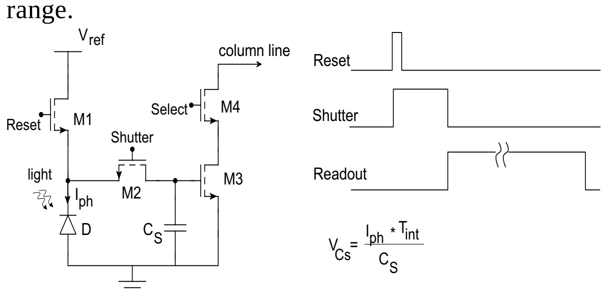

Figure 2: Pixel schematic of a linear integration CMOS imager synchronous shutter also suitable for capturing high dynamic range scenes.

The number of required images for capturing a single high dynamic image frame not only depends on the desired total optical dynamic range but also on the desired Signal to Noise Ratio (SNR) where $SNR_{\min}$ is the minimal required SNR for a given application. To ensure this minimum SNR an overlap in the imager characteristic within the optical dynamic range is required. The overlap guarantees that an irradiance causing saturation in one images exceeds a minimal signal level in one of the other images. This minimal level is defined by $SNR_{\min}$. Thus a higher $SNR_{\min}$ requires more overlap and more overlap results either in a decreased total dynamic range or requires an increased number of images with different integration times for the frame computation. Fig. 3 illustrates this principle of overlapping linear segments. It can be easily seen, that $V_{\max} / V_{\min} = V_{\max} / (SNR_{\min} V_{noise})$. Typically, $SNR_{\min}$ should be at least 30dB to allow r = 5 bit quantization in the critical overlapping region. If it is known that a sensor system including analog to digital conversion features m=10 usable bits, the total optic dynamic range can be easily expressed by $DNR = n\, 20dB \log 2^m / 2^r$ with n the number of images with different integration times. Thus for n = 4, m = 10 and r = 5, a dynamic range of 120 dB can be covered while in this case the sensor dynamic range for a single integration time is only $E_{\max} / NEP = 20dB \log 2^{10} = 60dB$, where NEP is the noise equivalent optical power [W/m²] and $E_{\max}$ is the maximum irradiance causing imager saturation [W/m²]. As long as there is no change in amplification, optical and electrical dynamic range are the same.

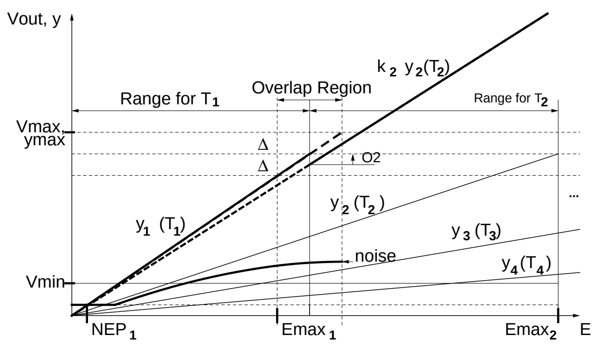

Figure 3: Overlapping of linear regions required for forming a single continuous linear characteristic for a minimum required SNR expressed here by $V_{\min}$.

For the experiment a CIF format (360 x 288 pixel) CMOS image sensor with rolling shutter according to Fig. 1 was used. This sensor has been fabricated at our institute [3] and allows readout of up to 140 fps in full frame readout mode. Figure 4 shows images of a high dynamic scene representing the longest (left) and the shortest (right) integration time. Since these images were taken with the CIF format CMOS sensor, more than 35 fps with high dynamic range are feasible even when 4 images are required for computation of one high dynamic range frame. But, of course, there remains a problem of reduced integration time for individual images. The remaining maximum integration time will be only one quarter of the time required for capturing all four images. However, not only the optical dynamic range is important but also the sensor system sensitivity. Although the input referred noise of the imager (except for the photon noise) is not affected by the integration time, the noise equivalent power NEP increases by the same factor the integration time is reduced.

We have found a solution to this problem which benefits from the rolling shutter and the fast readout capability of our CMOS image sensor. As illustrated in Fig. 5 integration starts with the shortest integration time T_n (here T_4 at the bottom of Fig. 5) which is, of course, much shorter than the longest integration time T_1. While T_1 requires a full frame period for integration and readout, at least all of the short integration time slots T_2 to T_n will fit within one additional frame time (assuming that $T_{i+1} \le T_i / 2$). Using this optimized integration and readout scheme the time for capturing of all four images is $T_1 + T_2 + T_3 + T_4 + 4\, T_{readout}$ which is much shorter than $4\, T_1 + 4\, T_{readout}$ for sensors with fast readout capability. It is obvious, that this also minimizes the amount of memory for intermediate storage, since using this scheme only the image data within the sensor rows corresponding to the short integration regions for T_2, ..., T_n need to be stored until readout of the frame for T_1. So also the memory required for all four images will be smaller than one frame if $T_{i+1} = T_i / 2$ or ½ frame if $T_{i+1} = T_i / 4$ instead of 3 full frames when not using this optimized scheme. Since readout here is a continuous process with n readout address pointers which are wrapped every second frame, ring-buffers are used to hold the intermediate data of the short integration time slots T_2, ..., T_n.

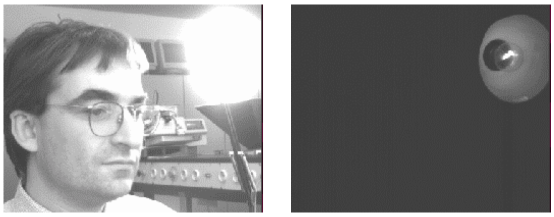

Figure 4: Two images captured from a high dynamic range lab scene with light bright bulb representing the longest (left) and shortest (right) integration time.

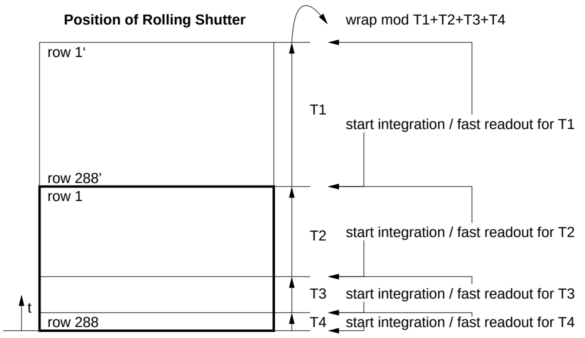

Figure 5: Improved readout scheme.

After capturing also the final image for T_1, the high dynamic range image is reconstructed pixel by pixel from the image data for integration T_1 by combining the gray value $y_1 = y(T_1)$ separately for each pixel-coordinate with the gray values $y_2 = y(T_2)$,..., $y_n = y(T_n)$ of the same pixel-coordinate according to

$$y_{HighDyn} = \sum_{i=1}^{n} \left[O_i + k_i \cdot y_i \right] \cdot R_i ,$$

with

$$k_i = \begin{cases} 1 & i = 1 \\ T_{i-1} / T_i = 2^s & else \end{cases}$$

and

$$R_i = \begin{cases} 0 & (y_i > y_{max} - \Delta) \vee (R_{i-1} = 1) \vee \ldots \vee (R_1 = 1) \\ 1 & 0 \leq y_i < y_{max} - \Delta \end{cases}$$

and O_i an offset value required for fitting the partially linear segments into a single linear characteristic for the whole dynamic range. Here O_i can be found by an adaptive process described in the following section, the gain factors k_i has been chosen in powers of 2 because scaling can be executed in hardware by a simple s bit shift.

3. Sensor Auto-Calibration Procedure

For automatic calibration of the offset values O_i which are required for generation of one continuous sensor characteristic according to Fig. 3, besides other possibilities, a gradient method is most practical for hardware implementation. Besides of fitting the curve segments in the overlap region (see Fig. 3) our automatic calibration procedure also compensates for drift effects like temperature and long-time drift. The offset values for each segment are calculated using the following rules, where for each frame all four offsets O_i are updated by an averaged delta value

$$\Delta \overline{O}_i = -\alpha \cdot \sum_{\forall Pixel} signo\left(\Delta O_i\right) U_i ,$$

$$signo(x) = \begin{cases} -1 & x < 0 \\ 0 & x = 0 \\ 1 & x > 0 \end{cases}$$

$$U_i = \begin{cases} 1 & y_{\max} > y_{i-1} > y_{max} - 2\Delta \\ 0 & otherwise \end{cases}$$

where α is an adaptation speed coefficient and ΔO_i is the difference of the pixel gray values of two segments in the overlapping region (see Fig. 4) defined by U_i. Thus adaptation is only carried out for pixels inside the overlapped region. The equation for calculation of ΔO_i is given by

$$\Delta O_i = (k_i y_i + O_i) - (k_{i-1} y_{i-1} + O_{i-1}),$$

with y_0 and O_0 both set to zero to allow zero adjustment.

The complete algorithm can been implemented using a comparator, up-down-counter, and shift element and thus is well suited for on-chip integration.
Figure 6 shows a high dynamic range image calculated using this principle. While all of the applications described above benefit from linear high dynamic range images and the high image quality, displaying and printing these images is a problem which has been solved here by simply reducing the global contrast while the local contrast remains unchanged.

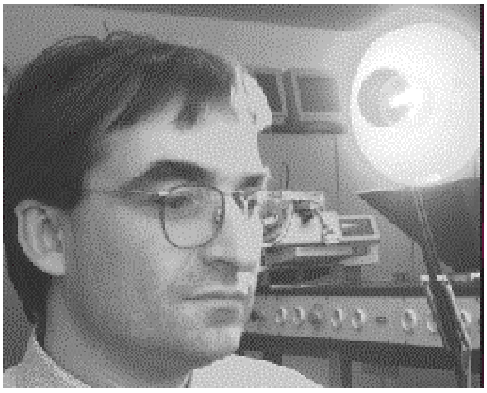

Figure 6: High dynamic range image captured with an improved readout scheme and composed using auto-adaptive curve fitting from raw images shown in Fig. 4.

4 Conclusions

A CMOS image sensor featuring high dynamic range by using multiple integration has been presented. Our approach benefits from an improved readout scheme and auto-calibration for merging several images into one high dynamic frame. Thus for a given high dynamic application the noise equivalent power can be reduced and the optical dynamic range can be increased when using this scheme. At the same time linearity in the overlapping regions and compensation for drift effects have been improved using the auto-calibration process. Since all steps of the multi-integration readout scheme and automatic calibration of the sensor characteristic can be easily implemented on-chip we have shown the feasibility of single chip high dynamic CMOS image sensors with linear sensor characteristic which can overcome some of the problems of other types of imagers.

Since also color in combination with high dynamic image range sensors is of great interest for many applications, e.g. street-sign recognition for driver assistance systems, color filters, and color processing have been added to the CIF sensor as described in [5].

References

[1] M. Schanz, C. Nitta, T. Eckart, B.J. Hosticka, and R. Wertheimer, 256x256 Pixel CMOS Imager with Linear Readout and 120dB Dynamic Range, In Proc. Workshop of Charge-Coupled Devices and Advanced Image Sensors, pp. 246-249, Karuziwa (Japan), 1999.

[2] O. Yadid-Pecht, B. Pain, C. Staller, C. Clark, and E. Fossum, CMOS Active Pixel Sensor Star Tracker with Regional Electronic Shutter, 1996.

[3] M. Schwarz, R. Hauschild, B.J. Hosticka, J. Huppertz, T. Kneip, S. Kolnsberg, L. Ewe, and K. Trieu, Single Chip CMOS Imagers and Flexible Microelectronic Stimulator for a Retina Implant System, Sensors and Actuators A, vol. A83 nos. 1-3, 22. May 2000, pp. 40-46, Sendai (Japan), 2000.

[4] N. Stevanovic, M. Hillebrand, B.J. Hosticka, and A. Teuner, A CMOS Image Sensor for High-Speed Imaging, In Digest of Techn. Papers IEEE Int. Solid-State Circ. Conf. 2000, pp. 104-105, San Francisco (USA), 2000.

[5] T. Heimann, M. Schwarz, B.J. Hosticka, Color Filter Array and Color Correction for High Dynamic Range CMOS Image Sensors, submitted for ECCTD 2001.