A FPP-Oriented Tone Mapping Technique for High Dynamic Range Imagers using Temporal and Final Exposure Measurements

S. Vargas-Sierra, G. Liñán-Cembrano, E. Roca, A. Rodríguez-Vázquez
Instituto de Microelectrónica de Sevilla (IMSE-CNM), CSIC and Universidad de Sevilla
41092 Sevilla, Spain
Email: sonia@imse-cnm.csic.es

I. INTRODUCTION

High Dynamic Range (HDR) [1] vision is required in several applications like automotive –both for indoor and outdoor monitoring–, surveillance, scientific experiments, etc. CMOS technologies allow for including processing circuitry very close to the sensors, in the well-known focal-plane approach, giving us the possibility to process the raw information provided by photosensors in fancy dynamic range expansion algorithms [1][2], or even, to dynamically adapt the response of the sensors –i.e. the sensor's transduction function– according to the existing lighting conditions [3].

Almost all imagers reported –and commercialized– codify absorbed photons in terms of a voltage –or a voltage difference to be more precise– instead of directly using the photogenerated current –or carriers. Typically, photogenerated current is integrated for a given time –exposure– in a previously precharged capacitor, producing a quasi-linear relationship[1] between incremental voltage and photogenerated carriers, and consequently, incident photons. The most common alternative to this linear approach consists of forcing the photogenerated current to flow through a compressive-type current-to-voltage device (by definition: a non-linear resistor) to produce a voltage which is a compressed version of the photogenerated current. Logarithmic sensors [4], where the non-linear resistor's role is played by a MOS transistor in weak inversion, are the most remarkable example of this sensing mechanism.

However, working with HDR images requires employing long bit-words per pixel, which are more difficult to handle by either processors or visualization devices than the typical 8-bit coding per color channel. Tone Mapping (TM) techniques [5] can be applied to transform the colors (or intensities) of HDR images into a lower bit count representation in order to make the HDR images directly usable by conventional processors or displays. Obviously, here the goal is to minimize the loss of visual information –or to maximize image quality, which, as in our work, does not necessarily mean the same thing– after word-length reduction.

The tone mapping technique reported in this work is specially designed for a full implementation within a Focal Plane Processor (FPP) [6], thus it is both computationally simple (not intensive at least!) and requires neither intensive memory accesses nor memorization of many images for long time. The algorithm produces 7-bit images –stored at the pixel level in SRAM units– through a mechanism which dynamically adapts to the contents on the scene. Shortly, if we only have 2^7 codes available and the DR to cover is much wider, we need to assign output codes non-uniformly, more codes to some ranges of illuminations and less –or none– to other ranges. In our work, this decision is made upon the supposition that a down-scaled[2] (×1/4) version of the previous image is a good indicator of the probability of a range of illuminations to be significant in the current image. Besides, since the algorithm is to be fully integrated in a FPP, only required calculations are accumulations, comparisons, and divisions by integer constants.

II. INTEGRATION-MODE PIXELS

In Integration-Mode pixels, the photocurrent, I_{ph}, discharges a capacitor, C_{ph}, which has been previously initialized to V_{rst}. Voltage drop across this capacitor, V_{pixel}, evolves as shown in (1). Conversely, one could also measure the time it takes for V_{pixel} to reach some reference voltage V_{ref}, obtaining the expression in (2). Easily, one observes that with the same operation principle, we obtain a voltage that is directly proportional to the photogenerated current in the first case, and a time which is inversely proportional to it in the second case.

$$V_{pixel} = V_{rst} \quad \frac{I_{ph}}{C_{ph}} \; \Delta t \tag{1}$$

---

[1] Due to capacitor non-linearities.

[2] In order to reduce computational cost.

Fig. 1. Uniformly distributed I_{ph} in Integration Pixels.

TABLE I

TIME CONFIGURATION IN BINS

Bin	Subdivision Bin Time(μs)	Total Bin Time(μs)	Bin	Subdivision Bin Time(μs)	Total Bin Time(μs)
1	1	128	9	15	1920
2	1.5	192	10	20	2560
3	2	256	11	25	3200
4	2.5	320	12	30	3840
5	3	384	13	35	4480
6	5	640	14	40	5120
7	7	896	15	45	5760
8	10	1280	16	1	128

$$T_{ref} = \frac{C_{ph}}{I_{ph}}(V_{rst} - V_{ref}) \qquad (2)$$

Let us use Fig. 1 as an example. There, we are plotting the pixel voltage over time for a set of uniformly distributed photocurrents with a reset voltage of 3.3V and a maximum exposure of 40ms. If we measure voltage values at the end of the exposure, we see that uniformly distributed currents produce uniformly distributed pixel voltages –if not saturated. However, if we check the times required to saturate the sensor for increasing photocurrents (to reach 0V in this example), we see that times are gradually closer to each other despite the photocurrent difference is the same. These opposite behaviors are the basis of our algorithm for DR expansion.

III. TIME-VOLTAGE HISTOGRAM IMAGE

Our HDR algorithm combines these two kind of measurements, voltage measurements at the end of the exposure and crossing-time measurements during exposition. Our aim is to create an artificial image whose histogram can be used to determine the distribution of light intensities in the real scene. We call this artificial image the Histogram Image (HI). For FPP implementation purposes, we will restrict the final image (denoted as Tone-Mapped Image –TMI) to 7-bit and the HI to just 4 bits –meaning that only 16 bins are considered–, besides this HI is not full-resolution but a 1/4 down-scaled version of TMI (which will be QCIF[3] in the silicon implementation of this technique). Fig. 2 shows an example of the generation of HI for two different illuminations. As we see, we compare the pixel voltage with a fixed reference (1V in this case) and we store in a local SRAM the digital value of the 4-bit histogram curve (from 1 to 15) when the pixel voltage crosses the reference value. At the end of the 15th period, we ramp-up the reference signal V_{ref} very fast (from 1V to 3.3V in 128μs) to ensure those pixels not crossing previously will be assigned the value 16. Obviously, the key of this part of the algorithm is the duration of each code in the histogram curve. These are non-linearly distributed, as they are the crossing times for uniformly distributed illuminations, as shown in the Total Bin-Time column in Table I. The histogram of HI will be employed to determine how the 128 available codes (7-bit image) will be distributed during the application of the tone-mapping that creates the TMI.

IV. TONE-MAPPED IMAGE

In order to generate the TMI we proceed as follows (see Fig. 3). First of all, we have to say that we can either repeat the exposure, for still scenes, or use the previous HI result as an indicator of probability rather than an exact evaluation of the distribution of light intensities within the current scene. Again, we compare pixel voltage with the 1V reference and store the value of a 7-bit word at the crossing time. This 7-bit word signal, which is indeed the tone-mapping curve, is created from the histogram of HI. Once we know how many pixels do we have within each time bin (i.e. how many pixels crossed the 1V reference within the different time windows),

---

[3] 144x176 pixels.

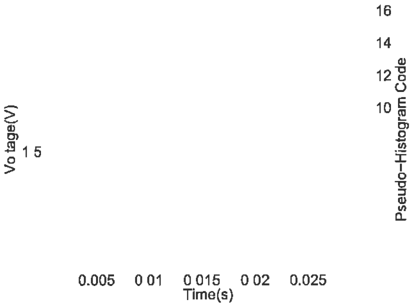

Fig. 2. Acquisition of Histogram Image.

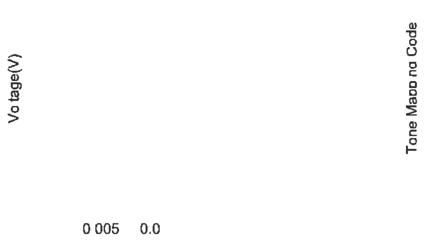

Fig. 3. Acquisition of Tone Mapped Image.

we can calculate the relative contribution of this bin to the final image –number of pixels in this bin over total number of pixels –, and assign output codes within a bin accordingly to the weight of this bin in HI. This operation enhances (by assigning more output codes) the most important light intensity bands in the image at the expense of the not so relevant ones. Also, for the last bin, that represents pixels which did not cross the 1 V reference, we do the same as for HI, we ramp-up the reference curve from 1V to 3.3V in 128μs and store the value of the tone mapping curve at the crossing time. It is worth to mention that within a bin, codes are uniformly distributed in time –according to the duration of that bin.

V. ALGORITHM

In order to execute this HDR technique one must go through these steps:

1) Define the duration of the Histogram bins.
2) Set default image levels per bin for the first image – a priori all bins could have the same number of codes, indeed this first image can be discarded as the important thing in the first frame is the creation of HI.
3) Capture Histogram Image.
4) Compute the Histogram.
5) Calculate how many levels per bin need to be assigned.
6) Compute the tone mapping curve –evaluate, according to the codes per bin and duration of each bin, when to increase the tone-mapping curve.
7) Capture the TMI.

As it has been already mentioned, we take the previous image as an indicator of probabilities of light intensity distribution within the current scene, besides, the generation of HI and TMI requires the same waveform for V_{ref}, thus, we can simultaneously create TMI for this frame and HI for the next one. At the end of a frame time (40ms by default), the data contained in the pixels are erased and the integration capacitors reset.

VI. SIMULATION RESULTS

In order to show the performance of this technique over a HDR image, we present here simulations results over a highly bimodal image. The starting point is a QCIF image which has been captured in multiple exposures and combined in a 24-bit HDR representation using Adobe Photoshop. The simulated photocurrent has been extrapolated from 1nA to 1fA, which implies a 120dB DR. The normalized original image is shown in Fig. 4. There, we can appreciate the high differences between the compact fluorescent lamp pixels, in red, and the poorly illuminated background, in blue, where almost nothing can be distinguished[4]. As already mentioned, the first step is the configuration in time of the bins, in this example the configuration is shown in Table I. Since bins follow each other in time, the maximum exposure for this configuration is 31.1ms. Now we simulate the evolution

TABLE II

LEVELS PER BIN CALCULATION

Bin	Pseudo Histogram(PH)	$\frac{PH}{49.5}$		Levels per Bin
1	205	4		4
2	86	1		2
3	197	3		4
4	309	6		6
5	369	7		7
6	675	1		14
7	1224	2		25
8	1150	2		23
9	660	1		13
10	438	8		9
11	234	4		5
12	167	3		3
13	181	3		4
14	141	2		3
15	55	1		1
16	245	4		5

of the different pixels ibution of
pixels among bins. The ig. 5 and
its histogram is display in the HI
image is 6336 (72·88), the QCIF
resolution. The levels p arding the
relevance of each bin i are using
7-bit coding for the TN er bin are
simply calculated by di in the bin
by $\frac{6336}{128}$ = 49.5. Obviou r-rounded
in order to have an inte in, on the
one hand, and to avoi 128 codes
on the other hand. In t leads to
the distribution of 119 bins. The
unassigned levels are c according
to the higher remainde lculations
are shown in Table II. created by
distributing these levels each bin.
Therefore, the tone-ma within the
bins so its slope will c ed to the
bin and the duration o resulting
tone-mapping curve, w es are the
limits between bins. Si et the 128
available codes, we divi s of equal
duration, amounting to intervals

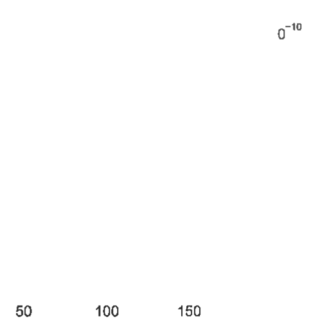

Fig. 4. Original HDR image.

---

[4] The images are represented in matlab's colorjet colormap instead of gray for the sake of an improved visual perception of the details.

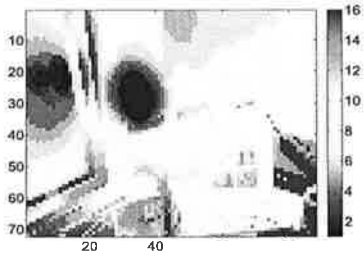

Fig. 5. Histogram Image.

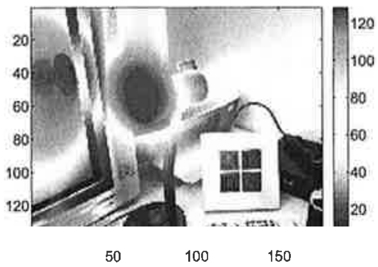

Fig. 8. Tone Mapped Image.

in the whole image. Thus, the x-axis in Fig. 7 represents the code values in these evaluation times. The shape of the tone-mapping curve when the x-axis is the time has been already shown in Fig. 3.

The final step is to simulate the capture of the TMI using this tone mapping curve. The resulting TMI is shown in Fig. 8. Here the action of the algorithm is clearly noticeable. Despite the photocurrents spread over several orders of magnitude, the image shows the details for both the poorly illuminated objects of the background, the spiral of the compact fluorescent lamp, and even the numbers in the LCD clock.

VII. CONCLUSION

We have designed a Dynamic Range improving algorithm for Vision Systems on a Chip based on a tone mapping technique. The algorithm employs conventional integration pixels, comparators, and reduced local memory, thus being very suitable for Focal Plane Processor implementation. This technique reduces the amount of data of the HDR image to just 7-bit per pixels while preserving the relevant information in the visual scene. A Vision Chip is being developed with the reported tone mapping system using Austrian Microsystems 0.35 microns OPTO technology.

10

Fig. 6. HI Histogram.

1500 2000

Fig. 7. Tone Mapping Curve.

ACKNOWLEDGMENT

This work is partially funded by TEC2009-11812 (WiVis-Net), CENIT ADAPTA, V-MOTE 2006-TIC-2352, PIMA and FEDER 2007-2013.

Ms. Sonia Vargas-Sierra would like to thank Universidad de Sevilla for supporting her via FIUS.

REFERENCES

[1] A. Spivak, A. Belenky, A. Fish, and O. Yadid-Pecht, "Wide-dynamic-range cmos image sensors - comparative performance analysis," *Electron Devices, IEEE Transactions on*, vol. 56, no. 11, pp. 2446 –2461, nov. 2009.

[2] M. Sasaki, M. Mase, S. Kawahito, and Y. Tadokoro, "A wide-dynamic-range cmos image sensor based on multiple short exposure-time readout with multiple-resolution column-parallel adc," *Sensors Journal, IEEE*, vol. 7, no. 1, pp. 151–158, 2007.

[3] S. Decker, R. McGrath, K Brehmer, and C. Sodini, "A 256x256 cmos imaging array with wide dynamic range pixels and column-parallel digital output," in *Solid-State Circuits Conference, 1998. Digest of Technical Papers. 45th ISSCC 1998 IEEE International*, 1998, pp. 176–177, 433.

[4] H.-Y. Cheng, B. Choubey, and S. Collins, "An integrating wide dynamic-range image sensor with a logarithmic response," *Electron Devices, IEEE Transactions on*, vol. 56, no. 11, pp. 2423 –2428, nov. 2009.

[5] E. Reinhard, M. Stark, P. Shirley, and J. Ferwerda, "Photographic tone reproduction for digital images," *ACM Trans. Graph.*, vol. 21, no. 3, pp. 267–276, 2002.

[6] A. Moini, *Vision Chips*. Norwell, MA, USA: Kluwer Academic Publishers, 1999.