Camera Technology at the Dawn of Digital Renascence Era

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***Abstract*— Camera Technology has evolved tremendously in the last 10 years, the proliferation of camera-phones fueling unprecedented advancements on CMOS image sensors. As an emerging field, some of the problems are justified while others are bi-products of the chosen silicon technology and are not fundamental to advancement of image technology. This paper will review block by block some image processing components found in a cell-phone camera today, discussing for each its justification from technology choice vs image processing function, with emphasis on the signal degradation potential. Further, we present computational photography challenges that amplify the requirements for data with high SNR.**

***Index Terms*—camera-phones, edof, dpcm, demosaic**

I. Introduction

In today's technology, image processing and imaging related tasks are still very demanding both in computational power as well as in image quality. Oversampling current pixel rates is still a luxury that requires a good justification. In current consume imager CMOS sensor design, the trend is to shrink the pixel size, in order to increase 'resolution'. This tendency is especially visible in cellphone cameras, where pixels of 1.4u and less are becoming common. One of the drawbacks of this tendency is a reduced fill-factor and as a consequence an increased optical stack, as the metallization layers required for the interconnect of a CMOS pixel are taking more than the pixel itself – not to mention the associated increase of electrical crosstalk. The increased optical stack requires carefully designed microlenses to minimize optical crosstalk across the array. Overall, the end result is that pixel crosstalk is significant requiring spectral calibration and the resulting camera module exhibits vignetting of 40% and higher center to edge which in turn makes the processed image having a non-uniform noise response and a very complicated color behavior.

Error propagation is one of the basic tools that should be used in analysis of a new proposed computational method that is applied to images – this is often disregard and instead, visual image quality or PSNR are used to justify some gain. This presentation discusses some of the challenges in today CMOS image sensor technology, their implications then presents some case studies that require special consideration.

Often the question of image quality in cameraphones is blamed on sensor quality, but this seems to be more of an effect than a cause, as suggested in Fig.1.

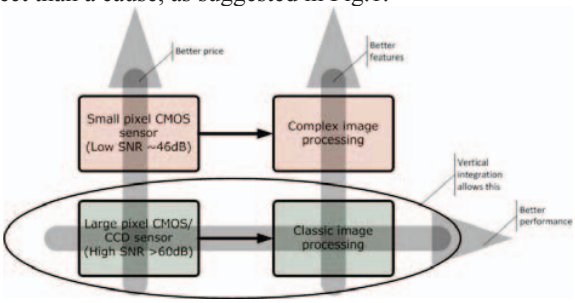


Fig. 1 – Industry partitioning is favorable developing small image sensors that require complex image processing

Current industry partitioning in sensor manufacturers and image processing companies is favorable to a development of small pixel sensors, as from business perspective it makes a lot of sense to sell more pixels/silicon area, whereas from marketing perspective it makes a lot of sense on image processing companies to develop complex features and complex processing that tries to counteract the implications of using small pixels.

CMOS pixels require several metal layers to interconnect, which creates an optical stack requiring microlens to improve the angle response [1], introducing undesired optical effects: vignetting and various types of cross-talk (see Fig.2), light scattering and diffraction. As several solutions are already in place to alleviate some of those issues, each has its own problems.

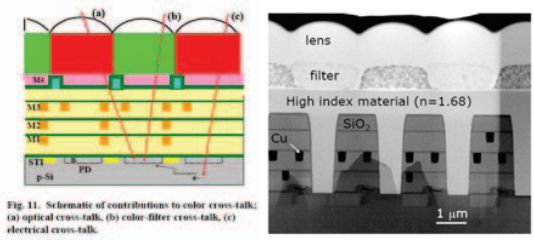


Fig. 11. Schematic of contributions to color cross-talk; (a) optical cross-talk, (b) color-filter cross-talk, (c) electrical cross-talk.

Fig. 2 – CMOS sensor pixels have various forms of cross-talk some due to the height of the optical stack

II. Image Processing Blocks

One of the consequences is that small pixels CMOS sensors present complex lens shading characteristics that are not

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uniform and are not radial. Also, the shading is different on each color channel and varies with the spectrum of the captured light, as can be seen in Fig. 3 (a). Another interesting effect is the fringes in the QE curve, due to numerous metallization layers – Fig. 3 (b).

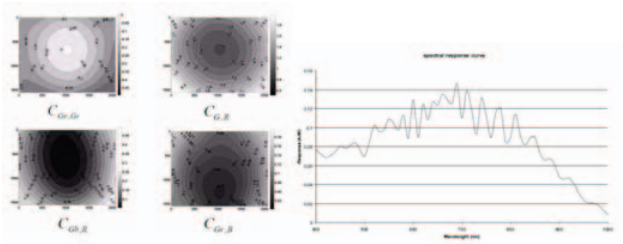


Fig. 3 – Left (a) lens shading on each channel [2]; Right (b) QE fringes in sensor response [3]

A. Lens Shading Correction

For this block the following assumptions are not true:
- It is radial – it's not
- It is only on luminance (ie. affects all colors the same) – it's not
- It is not illuminant dependant – it is
- It can be ignored because it is low (<5%) – it is >30%, sometimes 70%
- Both greens have the same roll-off – not true

In addition the following issues are making the problem even more complex:
- As the correction is anisotropic, per channel and per module, the error propagation implications are degrading accordingly any pixel based noise model.
- To be efficient, it is done in RAW domain, usually before most processing, therefore, all processing is influenced by this.

B. Bad Pixel Correction

Another challenging block is the bad pixel correction stage. One of the big challenges here is the fine line between noise reduction and bad pixel correction, due to the high pixel response nonuniformity (PRNU) that CMOS pixels have. Similarities between the two:
- detection: pixels that have values deemed 'unnatural'
- correction: detected pixels are replaced with an estimated value based on neighboring pixels

The problem: for low SNR sensors, PRNU can look both as noise as 'bad pixels'. In Fig. 4 the grey area would represent normal pixel response [4], but as exposure/gain increases, the grey area widens thus making the PRNU distribution to span closer to the bad pixel area.

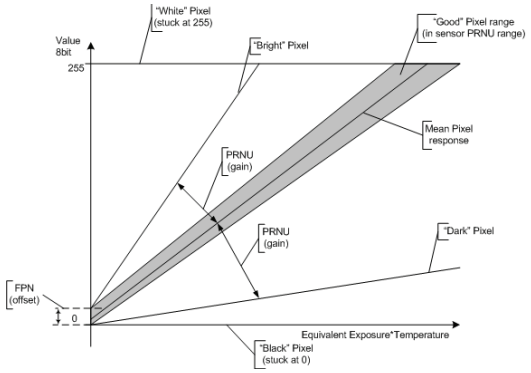


Fig. 4 – Bad Pixel and PRNU

Therefore for camera-phones, PRNU:
- has two components:
  - Offset part: driven by dark current generation (temperature and exposure)
  - Gain part: driven by small pixel response differences to light
- requires full frame processing to correct
- requires per sensor calibration
- usually corrected as random noise

Additional pixel defects: Pixel nonlinearities (both low-end and high-end) .

C. RAW data DPCM compression

Another complexity added is due to the DPCM compression used in most of the camera-phone sensors today [5]. DPCM compression is very simple compression, visually lossless, and is used for interface bandwidth reduction (ie. 10bit->8bit->10bit). In effect, the MTF of the resultant image is degraded, up to a point where it is loosing its integrity ([6] introduces MTF integrity diagram – depicted in Fig. 5 to present the effect of DPCM on measured MTF on different light levels)

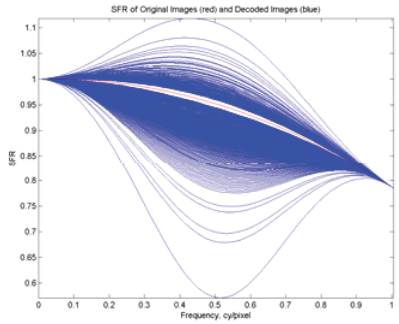


Fig. 5 – MTF Integrity plot shows DPCM compression effects on edges.

D. Bayer Pattern Demosaic

Bayer pattern demosaic is a well known block in today's camera-phones, and one of the most successful algorithms is AHD [7], which performs excellent when the stock photo "Lighthouse of Maine" picture is used. However, [8] shows

that this is not enough: in presence of noise or an image that is not white balanced, the algorithm can degrade. Therefore, for this block, the assumptions usually not valid for a real camera are:

- Input image is white balanced – it is not
- Input image has low color crosstalk – it doesn't
- Input image has no noise – it has

For this block, the algorithm checkmarks should be:

- High Frequency restoration
- Artifacts
- Noise robustness
- White balance robustness

E. Color Processing

Usually at this point, color processing follows, as depicted in Fig. 6 – the luminance used as input to the auto-exposure algorithm is a result of color processing, which is usually a multiplication with gains >1.

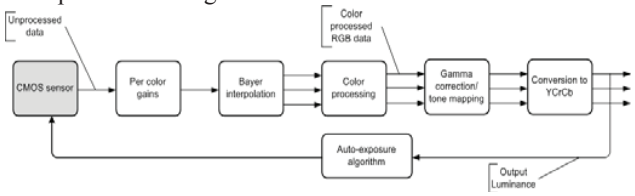


Fig.6 – Color processing and auto-exposure system level implications

Form system level perspective:

- color correction is applied before luminance is calculated
- exposure adjustment is done based on resultant luminance

Following simple error propagation, the implication is: linear color processing with above unity gains degrades sensor signal – situation depicted in Fig.7 [9]

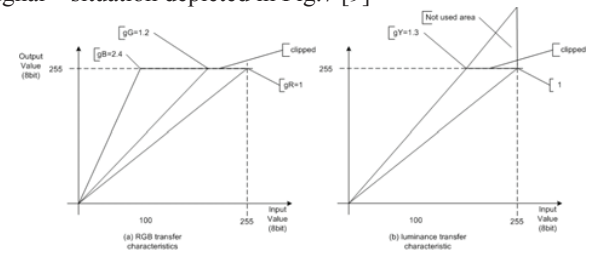


Fig. 7 – color transfer characteristics with above unity gains

F. EDOF (Extended Depth of Field)

Going in computational photography domain, one of the new techniques used for camera-phones is EDOF (Extended Depth of Field). One of the many web quotes is [10] "…allows further miniaturization of camera-phones by embedding functions such as the EDoF processor used to maximize the camera's depth of field. This saves designers implementing auto-focusing capability and also keeps the cost and mechanical size in line with standard Fixed-Focus modules."
In [11] a method proposes an evaluation methodology for EDOF and a commercial camera-phone with EDOF is compared with one without – the results are reproduced from [11] in Fig. 8.

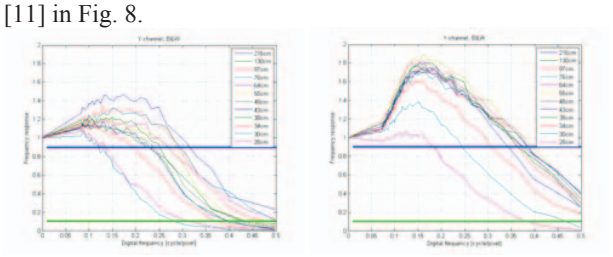


Fig. 8 – Left – EDOF camera-phone; Right AF camera-phone

This shows that the sensor used, has to have very good SNR to begin with, to be able to apply complex processing. Also, it is needed to consider the artifacts introduced by a novel method along with its associated SNR degradation.

G. HDR (High Dynamic Range)

Another favorite technique is HDR (High Dynamic Range) . What is claimed: through multiple exposures (or equivalent – Fig.9) the dynamic range of a captured image is increased. Some of the techniques used are:

- multiple reset levels of the pixel resulting in a close to logarithmic transfer characteristic [3]
- logarithmic pixel response
- multiple exposures
- pixels with different sizes on the same array

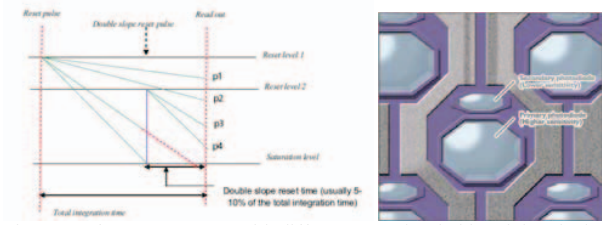


Fig. 9 – Left: CMOS sensor with different reset thresholds; Right: pixels with different sizes

Essentially, all those approaches are trying to accomplish the same: counteract a small pixel size through a non-linear transfer characteristic.

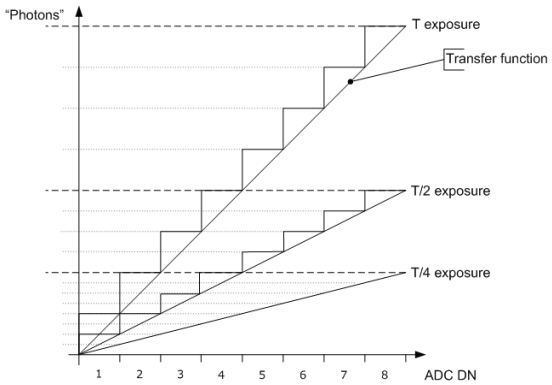


Fig.10 – Transfer characteristic quantization for different exposures and same pixel size

One of the problems with this is that the upper area of the transfer characteristic cannot be improved in the same way the lower area is. Fundamentally, this is due to the fact that the pixel is small, and cannot hold the charge required to sample the difference on the high end. To illustrate the difference, in Fig. 11, a CCD sensor is measured in normal mode with various exposures and in binned mode. The curve used, is plotting SNR vs luminance, as dynamic range expressed only as a ration is not enough to quantify this type of effect (HDR).

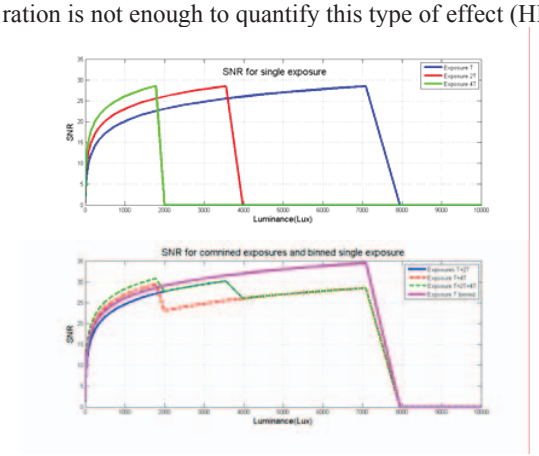


Fig.11 – Dynamic range curve (SNR vs luminance for 1x vs 4x size pixel and multiple exposures of a 1x pixel

As it can be seen, the equivalent curve of a combined image cannot be better than the envelope of each curve (plus some increase in the overlapping area due to noise reduction if average is performed).
In consequence:

- dynamic range is not expressed appropriately through a ratio – it needs a curve (ie. dynamic range vs signal).
- the standard HDR methods would really increase dynamic range if density of intensity sampling would be uniform.
- the incorrectly understood claim of HDR is an increased number of bits. The true achievement of the HDR methods is effectively a nonuniform sampling of the range.

III. Conclusions

A. Use Cases

As conclusions, we would like to list some of the 'traps' of image processing for camera-phones or other devices with CMOS image sensors with small pixels:

- Bad pixel beware: there's a thin line between bad pixel and noise reduction, but they are not interchangeable.
- Lens roll-off beware: after this block, noise is anisotropic.
- Demosaic beware: input data is not white-balanced, noisy and colors are correlated.
- Color correction/Gamma beware: low color saturation means high color crosstalk – the noise increase tradeoff might not justify it. White balance is not a replacement for illuminant correction
- Tone mapping beware: after this block, transfer characteristic is nonlinear and content dependant.

Auto Exposure bewares: backlight situations require 'HDR' treatment.

B. Camera System

Also, at camera system level, some of the 'traps' are:

- Beware of system level perspective and always consider error propagation.
- Beware of techniques that appear to increase the amount of information in the image or claim visually lossless interference:
    - check MTF integrity if edge processing is suspected (ie. DPCM compression).
    - check 3D MTF if EDOF is claimed.
    - check SNR over the whole output range if HDR is claimed.
- Beware of 'RAW' data! Unless you know what's happening in the camera, RAW is not RAW – this cuts off most commercial cameras.

Canon quote (***EOS-1D Mark III***):'Even when high-speed noise reduction is turned "off," varying amounts of noise reduction are still applied to all images, even RAW images.'[12]

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