Wide Dynamic Range Imaging Techniques

A high-resolution image sensor is only the start of the story. How you process its output will ultimately determine image quality.

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Executive Summary

Images captured in real life have varying illumination levels in a scene. The ability of the image sensor to capture all the illumination levels (contrast) with fidelity will result in a wide dynamic range (WDR) image. The key factor for achieving WDR is to identify the dark and bright portions of the image and control the integration of the pixels, avoiding saturation. Pixels getting impinged with high illumination needs saturation control and the pixels impinged with the dark portion of the image need more integration time. Hence the contrast of the scene is restored by the imager. This article describes wide dynamic range imaging techniques for CMOS image sensors.

Introduction

Digital imaging technology has progressed from digital still cameras into an array of portable applications such as cellular handsets, where it serves as a differentiating feature. In applications such as automotive sensors and medical equipment, digital imaging serves as the foundation of higher-order functionality such as machine vision, instrumentation, document scanning, motion analysis and scientific high-speed image analysis.

Image resolution is often seen as the most important factor determining the quality of an image. However, in all of these applications, from those that produce images for viewing or perform complex analysis of images, dynamic range plays a key role in determining how efficient and effective later imaging processing will be. Dynamic range directly affects final image quality as well as the effectiveness of any compression or analytics technologies.

The dynamic range of CMOS image sensors is defined by their ability to capture dark as well as bright sections within an image while maintaining the highest fidelity. Real-life images have varying illumination levels throughout a scene. An image sensor must have wide dynamic range (WDR) in order to capture all the illumination levels (contrast) of an image. The wider the dynamic range of the sensor, the more illumination levels that can be captured.

The key to achieving sufficient WDR is identifying the dark and bright portions of the image and controlling the integration of the pixels to avoid saturation. Pixels impinged with high illumination need saturation control, while pixels impinged within the dark portion of the image need longer integration times. In this way, the contrast of the scene can be restored by the imager. This article describes the definition of wide dynamic range and appropriate imaging techniques to use with CMOS image sensors.

Dynamic Range

Dynamic range is the ratio of the maximum signal output of the sensor to the smallest signal output of the sensor. The higher the dynamic range of the sensor, the greater the fidelity of the optical image transformation from the object scanned. The sensor generates its maximum output for brighter portions of the image and its minimum output for darker portions. The maximum output of the sensor without saturation is limited by the well capacity of the photo diode, while the minimum detectable output is limited by the noise floor of the sensor. Figure 1 illustrates the noise floor in detail, where dynamic range (db) = 20 log (sensor’s maximum output / sensor’s minimum output).

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A higher dynamic range results in a better transformation of the object to an image, accurately capturing the varying light intensities of a scene from the brightest to the darkest parts, including shadows. Factors that affect dynamic range include:

- Dark current of the sensor
- Saturation of the pixels
- Quantum efficiency/well capacity of the photo diode

**Signal-to-Noise Ratio**

The signal-to-noise ratio (SNR) is a measure of a captured image’s immunity to noise. SNR is the ratio of the peak light intensity without saturation to the scene background noise. A camera with a higher SNR typically produces low noise video in darker scenes. Photodiodes generally have better SNR when they are charged to more than half of their total capacity. However, they cannot be charged beyond saturation.

There are two basic noise sources in a CMOS image sensor:

1. Temporal noise caused by the photo diode and MOSFET, shot noise, thermal noise and 1/f noise as envisaged in electronic circuits.

2. Fixed pattern noise caused because of the pixel output variation for the same illumination. The sources of fixed pattern noise are device and interconnect mismatches.

Figure 2 shows a three-transistor APD pixel circuit widely used in CMOS image sensors. The first MOSFET is used to reset the photo diode to a known voltage by pulsing the gate (reset) signal. The photo diode’s stray capacitance is charged to a known voltage (reset voltage) and the photo diode is allowed to integrate the charge. Due to electron hole re-combination, the reset voltage is pulled down, depending upon the light intensity impinging on the photo diode. If the pixel is saturated, the whole charge across the photodiode will be depleted completely. The second MOSFET is a source follower, while the third MOSFET switches the selected row/pixel to the bit line, which in turn is connected to the column amplifier. The actual voltage integrated by the photo diode is the reset voltage minus the voltage across the diode after integration.
Hence the photo diode is operated with one reset for one integration cycle. This method is called linear integration (open loop with no control of saturation of the pixel). If the photo diode needs saturation, control multiple resets are applied with varying integration times optimally chosen for the end application to achieve a wide dynamic range. The first reset voltage would be the largest voltage level as per the design, and second, third and so on will be smaller voltage levels.

The steps involved in the multi-reset system are:

1. Reset the photo diode with the maximum reset voltage $V_{R1}$ allowed and allow integration time $T_1$.

2. Reset the photo diode with smaller voltage $V_{R2}$ (voltage less than $V_{R1}$). With this reset voltage, the pixels saturated will have a source of the MOSFET less than the drain, and the MOSFET will conduct a voltage across the photo diode equal to the new reset voltage. If the pixel is not saturated, the source voltage will be less than $V_{R2}$ and the MOSFET will not charge the photo diode to the new reset voltage. The photo diode will continue integration with time $T_2$. This pixel corresponds to the dark portion of the image and receives more integration time, which is desirable.

3. The resets are repeated until the last barrier (reset) voltage completes the integration.
Pixel Response with Multi-Barrier Operation

Pixels impinging with the brighter portion of the image are reset and pixels impinging with the darker portion receive more integration time to develop the charge. In this way, the saturation is controlled.

Parameters of control to achieve dynamic range:

- Integration time
- Barrier voltage (reset voltage is also called barrier voltage)

By choosing a suitable combination of barrier voltage and integration time, the desired wide dynamic range can be achieved.

The three-transistor pixel (Figure 2) allows multiple resets and integration time control. External circuits are required to detect the saturation and reset the pixel. Also required is a compression/transfer function table to decide the barrier voltage and integration times. In this way, the required dynamic range can be controlled and achieved based on the end application.

Achieving Wider Dynamic Range

Techniques to achieve wide dynamic range include:

- Double shot exposure. To increase the dynamic range of an image, pixels are integrated two times, once with a shorter integration time to capture the brighter portion of the object scanned, and again with a longer integration time to capture the darkest portion of the object scanned. The final image is comprised of the two frames of data through signal processing.

- Multiple image detectors. Using this approach, multiple detectors capture the same scene at the same time using beam splitters to project multiple copies of the same image onto each detector at the same time. Each detector is preset for a predetermined exposure time (electronic control) or optical attenuators (optical control). This method is suitable for generating high dynamic range images in real time. Additionally, the camera or the scene can be moving during scanning.
• Saturation detection per pixel. Each pixel of the CMOS array has a saturation detection circuit, such as a comparator, to compare for a known voltage across the diode to detect and reset in case of saturation. This approach imposes the overhead of a saturation detection circuit per pixel, which is too expensive for large pixel arrays.

• Multi-reset with different integration times. Pixels based on an APD as described in Figure 2 can be reset several times during the integration period. The minimum requirement is to have two barriers (reset voltages) with different integration times. Again, the first barrier would be larger than the following barrier. The second barrier voltage can be selected based on the well capacity and the previous integration output (Figure 3).

Figure 4: Images illustrating (left) linear integration and (right) the improvement with multi-slope integration as captured by an IBIS-5 image sensor from Cypress

Dynamic range is one of the important factors affecting the image quality of CMOS sensors. The wider the dynamic range, the better a digital imaging system will be able to accurately capture the varying light intensities of a scene. By varying the combination of barrier voltage and integration time, as well as applying different techniques to widen the dynamic range, developers can exercise more accurate control of image quality across a broad range of imaging applications.
References


