Shutter Operations for CCD and CMOS Image Sensors

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Introduction:

In digital cameras, an image is captured by converting the light from an object into an electronic signal at the photosensitive area (photodiode) of a solid-state CCD or CMOS image sensor. The amount of the signal generated by the image sensor depends on the amount of the light that falls on the imager, both in terms of intensity and duration. Therefore, like conventional film cameras, digital cameras require a shutter to control exposure for image quality. This is generally done either by incorporating an external mechanical shutter in front of the image sensor or by incorporating an on-chip electronic shutter.

For digital cameras equipped with a mechanical shutter, the photodiode integration time depends on the duration of the opening of the mechanical shutter. Some image sensors provide electronic means for controlling integration time. These types of image sensors may allow the elimination of the mechanical shutter.

In this application note three electronic shutter mechanisms are described:

- CCD image sensor with electronic shutter;
- CMOS image sensor with a conventional rolling shutter;
- CMOS image sensor with a Kodak patented global shutter.

CCD Imager with Electronic Shutter:

Some types of CCD image sensors provide an electronic shutter mechanism. In a CCD imager with a built in electronic shutter, the entire imager is reset before integration to remove any residual signal in the photodiodes. The photodiodes then accumulate charge for some period of time. At the end of the integration period, all charges are simultaneously transferred to light shielded areas of the sensor. The charges are then shifted out of the light shielded areas of the sensor and read out.

An example of a CCD image sensor with this capability is the so-called interline CCD image sensor in which columns of photodiodes are interleaved with light shielded columns - vertical CCDs. The vertical CCDs are used to shift the charge vertically out of the imaging area. The light shield prevents further accumulation of charge during the readout process. The exposure time is the time between the reset of the imager and the transfer of charge from the photodiodes to the vertical CCDs.

Depending upon the design and the pixel size, even an interline CCD may require a shutter; this is the case with many contemporary consumer digital cameras.

CMOS Imager with Rolling Shutter:

The rolling shutter in a CMOS image sensor works analogously to a focal plane shutter in a film camera (indeed, the rolling shutter is sometimes referred to as an electronic focal plane shutter). Typically, the rows of pixels in the image sensor are reset in sequence, starting at the top of the image and proceeding row by row to the bottom. When this reset process has moved some distance down the image, the readout process begins: rows of pixels are read out in sequence, starting at the top of the image and proceeding row by row to the bottom in exactly the same fashion and at the same speed as the reset process.

The time delay between a row being reset and a row being read is the integration time. By varying the amount of time between when the reset sweeps past a row and when the readout of the row takes place, the integration time (hence, the exposure) can be controlled. In the rolling shutter, the integration time can be varied from a single line (reset followed by read in the next line) up to a full frame time (reset reaches the bottom of the image before reading starts at the top) or more. The Kodak KAC1310 1.3Mpixel image sensor provides a rolling shutter mode of operation.

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Since the integration process moves through the image over some length of time, some motion artifacts may become apparent. For example, if a vehicle is moving through the image during capture, then light from the top of vehicle will be integrated at some earlier time than light from the bottom of the vehicle, causing the bottom of the vehicle to appear slanted forward in the direction of motion. While this may cause the vehicle to look somewhat sporty, it is not a fully accurate representation of the vehicle. Depending on the relationship between moving objects in the image and the rolling shutter, various distortions may occur.

Note:
A similar effect may be noted in conventional film cameras that employ a focal plane shutter.

CMOS Imager with Global Shutter:

A CMOS image sensor employing the Kodak patented global shutter controls exposure in a similar fashion to an interline CCD described above. In the global shutter operation, the entire imager is reset before integration. The pixels are allowed to accumulate charge during the integration time. At the end of the integration time, the accumulated charge in each pixel is transferred to a light shielded storage area. Then the signals are read out from the light shielded area. Since all the pixels are reset at the same time, integrate over the same interval, and are transferred to a light shielded storage area at the same time, there is no potential for motion artifacts. The Kodak KAC0311 VGA CMOS imager provides both rolling shutter and global shutter modes of operation.

Application of Photoflash in CMOS Sensors:

Similarly to film cameras, photoflash is commonly used in digital cameras to provide sufficient light to expose the image properly in a low light environment. The duration of an electronic flash is generally very short (on the order of hundreds of microseconds to a millisecond or two), but the readout time for a CMOS image sensor may be much longer. Using a photoflash with a CMOS image sensor therefore requires special consideration.

The following cases are described below:
- CMOS image sensor (rolling or global electronic shutter) with a mechanical shutter;
- CMOS imager with a global shutter;
- CMOS imager with a rolling shutter.

Photoflash Used with CMOS Sensor and Mechanical Shutter:

If a mechanical shutter is used in conjunction with a CMOS image sensor, the photoflash operation is as follows:
1. The integration time of the CMOS imager's electronic shutter is adjusted so that all the pixels are integrating light at the same time;
2. The mechanical shutter is opened;
3. The photoflash is fired;
4. The mechanical shutter is closed;
5. The imager is read out.

The Kodak KAC1310 image sensor provides a signal, STROBE, which indicates, in some modes of operation, when the reset operation has reached the bottom of the image; the signal therefore provides an indication that all the pixels are integrating light. This convenient signal may be used to begin the sequence of operations starting with opening the mechanical shutter (Step 2 above).

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Photoflash Used with CMOS Sensor with Global Shutter:

A CMOS sensor with global shutter can accommodate the photoflash quite easily. In this case, the photoflash operation is as follows:

1. All the pixels of the imager are reset simultaneously;
2. The photoflash is fired;
3. The accumulated charges at each pixel are transferred simultaneously to light shielded storage areas;
4. The light shielded areas of the imager are read out.

The time between step 1 and step 3 needs to be only as long as the duration of the photoflash. As mentioned above, this can be a very short time. The resulting exposure will primarily due to the illumination provided by the photoflash, and will depend a little on the ambient light illumination.

Photoflash Used with CMOS Sensor with Rolling Shutter:

It is more challenging to operate a photoflash with a CMOS image sensor operating in a rolling shutter mode. Since the duration of the photoflash is very short compared to the overall readout time of the imager, the photoflash can only be used when all the pixels of the imager are integrating at the same time. To see why this is, consider the case when the time between reset and readout is less than a full frame time, say one-quarter the number of lines of the imager. In this case, as the integration process moves through the imager area, only those areas of the imager that are integrating during the photoflash will be affected by the photoflash. Depending on the timing of the photoflash, this will lead to a properly exposed band in the middle of the image (exposed by the photoflash) with underexposed areas above and below (integrating before and after the photoflash and hence integrating only available light).

Based on these considerations, the operation of a photoflash with a CMOS imager operating in rolling shutter mode is as follows:

1. The integration time of the imager is adjusted so that all the pixels are integrating simultaneously for the duration of the photoflash;
2. The reset process progresses through the image row by row until the entire imager is reset;
3. The photoflash is fired;
4. The imager is read out row by row until the entire imager is read out.

Note:
The Kodak KAC1310's STROBE signal (mentioned in the mechanical shutter discussion above) may be used here as well. In this case, it provides an indication of when to fire the photoflash (Step 3).

Since all the pixels of the image sensor must be integrating simultaneously, the amount of time for the reset process to sweep completely through the image plus some amount of time for the photoflash, sets the minimum exposure time to use for photoflash operation. For a KAC-1310 sensor operated at 10MHz, the minimum exposure time at this mode will be greater than 130ms. At this minimum exposure time, there is some ambient light level, I_{amb}, that will properly expose the image; no photoflash is required at this light level. Hence, the ambient light level should be less than this level (I_{amb})in order to use photoflash.

It is clear from this discussion that the net exposure in this mode will result from integrating both ambient light and the light from the photoflash. As previously mentioned, to obtain the best image quality, the ambient light level should probably be significantly below the minimum light level at which the photoflash can be used so that the photoflash contributes a significant portion of the exposure illumination. Depending on the speed at which the reset and readout processes can take place, the minimum exposure time to use with photoflash may be sufficiently long to open the possibility of image blur due to camera or subject motion during the exposure. To the extent that the exposure light is provided by the short duration photoflash, this blur may be minimized.

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For example, if the photoflash provides 75% of the exposure light, then only 25% of the light from ambient sources is integrated over the entire integration time; that 25% is the only light which can contribute to image blur. The ratio of the flash to ambient exposure light, is dependent upon the system configuration, including the sensor type, the sensor filter type (RGB or CYM for example), the IR cutoff filter, operating speed, and flash type. And, of course, the ambient light level.

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