Expanding the Dynamic Range of Focal Plane Arrays using an Orthogonal Code Readout (OCR)

Abstract

An Orthogonal Code Readout (OCR) implements digital electron wells in the focal plane array readout with minimal impact on pixel architecture. OCR electronically expands the dynamic range of CMOS machine vision image arrays. When employed as a thermal array readout, OCR simplifies thermal detector array fabrication by eliminating the need for large electron well capacitors.

Orthogonal Code Readout

- OCR-enabled cameras image through glare and capture the details of both bright and dark areas in a partially-shaded, sunlit scene.
- OCR uses orthogonal codes to sample the intensities of all of the pixels in a focal plane array (FPA).
  - Many pixels are sampled simultaneously by basing the sums on orthogonal codes.
  - An image is formed in the digital processor by retrieving the orthogonal time sequences representing individual pixel current
- When OCR is implemented, the dynamic range of a pixel is not limited by per-pixel capacitance for electron storage.

Orthogonal Code Readout

- An Orthogonal Code Readout expands the dynamic range of CMOS machine-vision image arrays that have limited electron storage capacity.
- Some versions of CMOS with OCR combine large detector fill-factor with wide dynamic range.
- Using OCR as a thermal array readout integrated circuit (ROIC) simplifies FPA fabrication by eliminating the need for large electron well capacitors.
- A further advantage of OCR is that it improves image quantization.
  - Each pixel intensity is sampled multiple times, each time in combination with different signals.
  - If the same analog to digital converter (ADC) is used to digitize image data and OCR data, the OCR image will be better quantized

Benefits of Implementing OCR

- OCR widens the dynamic range of any CMOS pixel architecture.
- OCR simplifies the fabrication of infrared focal planes
- OCR implements a global shutter.
- Exposure time is not limited by scene illumination.
- OCR processing decreases quantization error.
- OCR shares the same motion-blur characteristics as non-OCR imagers.

Briefing Outline

- OCR implementation and operation
- The effect of OCR on digital quantization error.
- OCR implementation problems and solutions
- Examples to illustrate that, with proper choice of orthogonal code set, motion has the same effect on OCR imaging as on traditional imaging.
- Conclusions

OCR Implementation and Operation

- The photo charge generated by the photo detector in the figure at right is stored on the detector capacitance.
- The photo electrons are discharged at some regular interval by selecting either the Add or Subtract FET in each pixel.
- The bottom figure shows twelve pixels arranged in a four by three image array.
- The two FET in each pixel connect the photo diode signal to either the plus or minus input of a differential sample and hold.
- In this example, all three pixels in each of the four columns are treated alike, so only the processing for a single row of four pixels is described in detail.

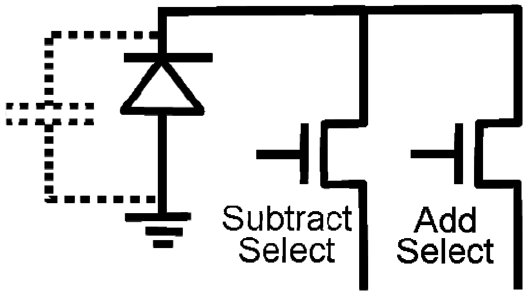


Fig. 1

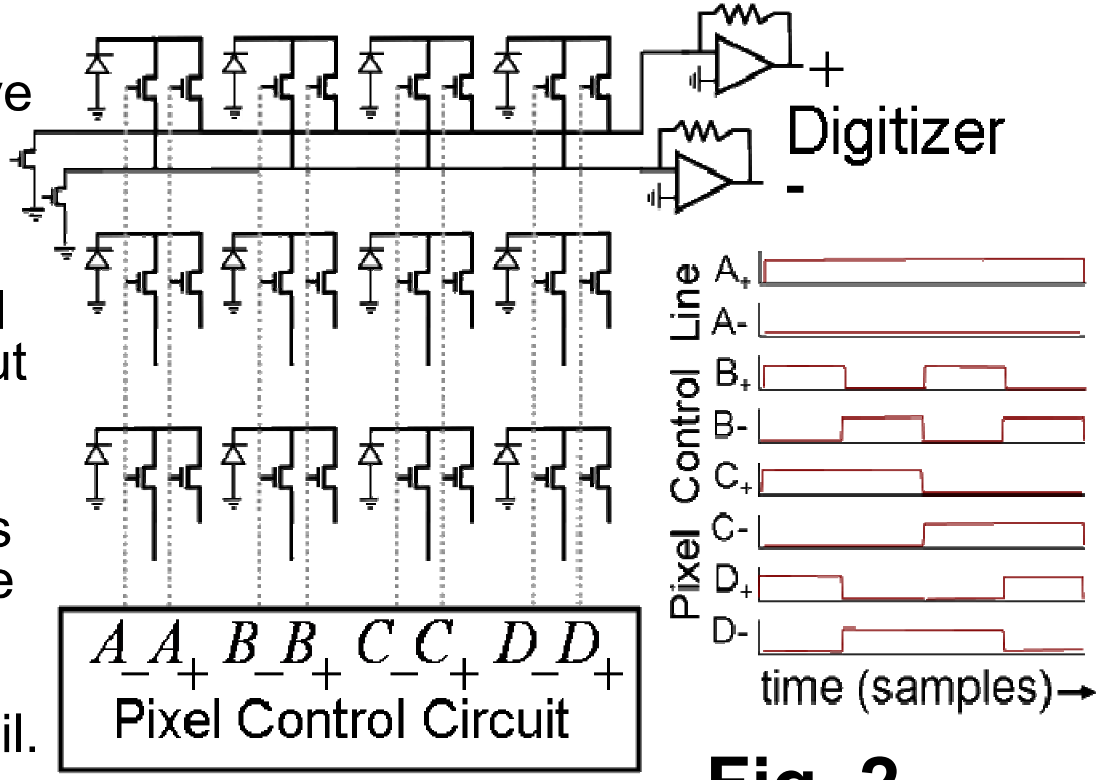


Fig. 2

OCR Implementation and Operation

- Four signals PA, PB, PC, and PD from pixels A, B, C, and D are encoded using a four element Hadamard matrix to yield four sample values SA, SB, SC, and SD.

$$[S_A\ S_B\ S_C\ S_D] = \left[\mathrm{P_A\ P_B\ P_C\ P_D}\ \right] * \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \tag{1}$$

$$[S_A\ S_B\ S_C\ S_D] = \left[(\mathrm{P_A + P_B + P_C + P_D})\ (\mathrm{P_A - P_B + P_C - P_D})\ (\mathrm{P_A + P_B - P_C - P_D})\ (\mathrm{P_A - P_B - P_C + P_D})\right]$$

where (*) indicates matrix multiply. To retrieve pixel intensity values PA, PB, PC, and PD

$$\left[P_A\ P_B\ P_C\ P_D\right] = \left[S_A\ S_B\ S_C\ S_D\right] * \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}. \tag{2}$$

- If the number of pixels in a row is NN, then NN pixels are summed for each sample and NN samples are taken over the exposure period. Pixel values Pixel(1:NN) are retrieved by the summation shown in Eq. 3.

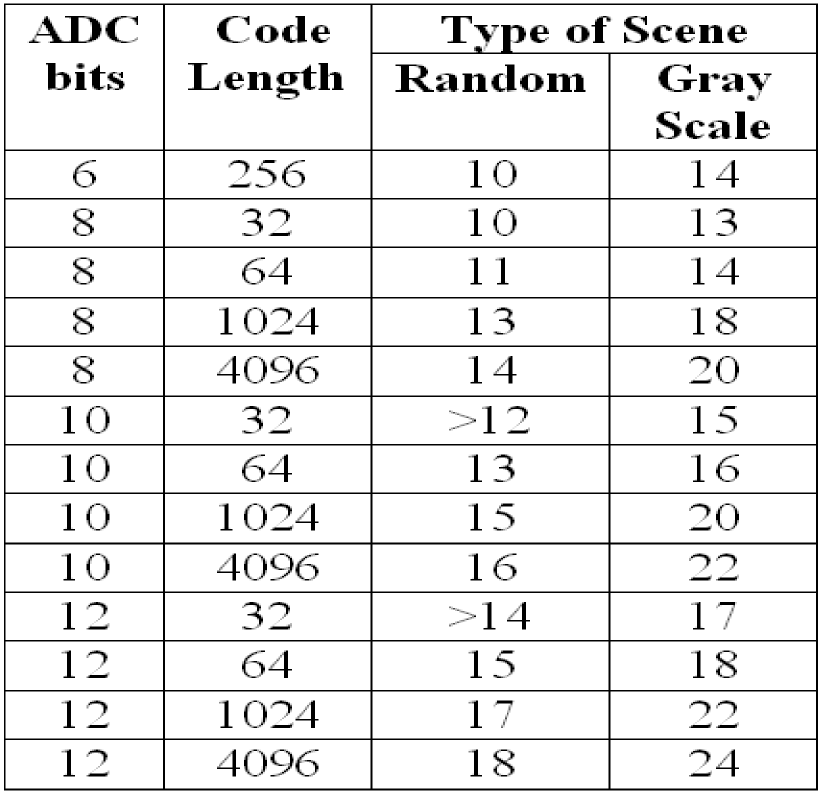
$$Pixel(1:NN) = \sum_m Sample(m)\, H(m, 1:NN) \tag{3}$$

The effect of OCR on digital quantization error

- When using OCR, each pixel intensity is sampled multiple times, each time in combination with different signals.
- If the same ADC is used to digitize image data and OCR data, the OCR data will be better quantized.
- Quantization improvement depends upon the characteristics of the data being digitized; quantization error depends upon the scene.
- At left in the figure below, the 256 by 256 pixel cameraman picture is degraded to six bits (64 gray levels).
- The major quantization problems are visible in the sky and buildings in the background of the left-hand picture.
- At right, the Hadamard OCR samples are digitized with six bit quantization, and the whole picture is well-quantized.

The effect of OCR on digital quantization error

- If the OCR code length is N, then quantization improves by N for uniform areas like gray scales or the sky in the cameraman picture.
- If the picture consists of uniformly distributed random values, then quantization is improved by the √N.
- The table provides image quantization for various combinations of hardware ADC, OCR code length, and image types.



ADC bits	Code Length	Type of Scene	
		Random	Gray Scale
6	256	10	14
8	32	10	13
8	64	11	14
8	1024	13	18
8	4096	14	20
10	32	>12	15
10	64	13	16
10	1024	15	20
10	4096	16	22
12	32	>14	17
12	64	15	18
12	1024	17	22
12	4096	18	24

OCR implementation problems and solutions

- With low scene illumination, a many-pixel version of the implementation illustrated in Figures 1 and 2 is not shot noise limited
  - The rapid OCR samples limit the photo charge collected for each sample
  - Given few electrons per sample, the pixel amplitude varies excessively between samples.
  - The orthogonal code is not decoded correctly, and a degraded image is the result.
    - The problem does not cause spatial displacement of image detail.
    - Rather, the problem results in excess noise.
- That noise problem can be solved by incorporating a temporal filter in each pixel.

Solving the low light level noise problem

- Some form of temporal filtering is required in order to keep pixel amplitude reasonably constant.
- Two examples are presented, both capable in theory of providing shot noise limited performance at low light levels.
  - First solution: In Fig. 1, use the photo detector capacitance and the FET source-to-drain resistance to form a low pass filter.
  - Second solution: Use an active CMOS pixel to integrate signal prior to sampling.

Shot noise limited imaging using a passive pixel

- The FET in Fig. 1 can be treated as switched variable resistors.
  - Source to drain resistance is controlled by gate voltage.
  - Gate switching (toggling) can also be used to implement a high effective resistance.
  - The FET grounds are virtual and sense current flow.
- After low pass implementation, pixel current is proportional to photo flux.
- Saturation is avoided by setting FET resistance correctly.
- Creating a low pass filter in each pixel does not increase signal current but does reduce sample-to-sample variations to the point that shot-noise-limited performance is re-established.

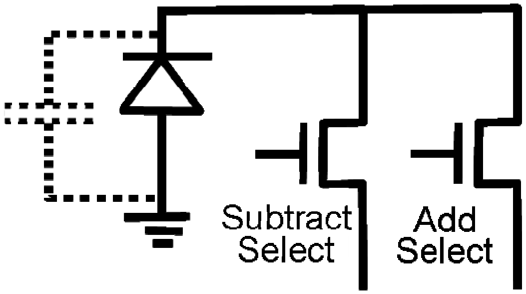


Fig. 1

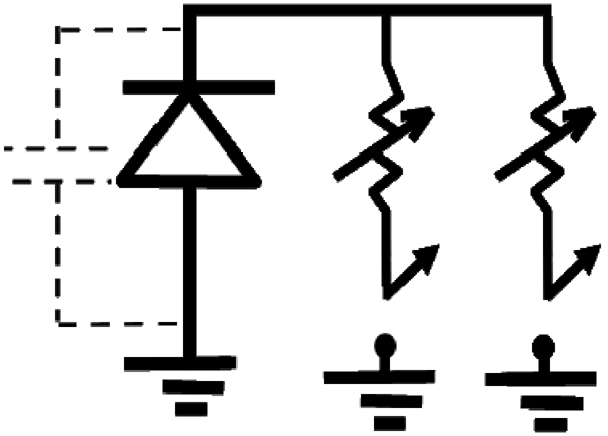


Fig. 3

Shot noise limited imaging using an active pixel

- An active pixel can be read without dumping the photo charge.
- Substituting the active pixel in Fig. 4 for the passive pixel in Fig. 1 improves noise behavior markedly, and the large dynamic range benefit of OCR is enabled.

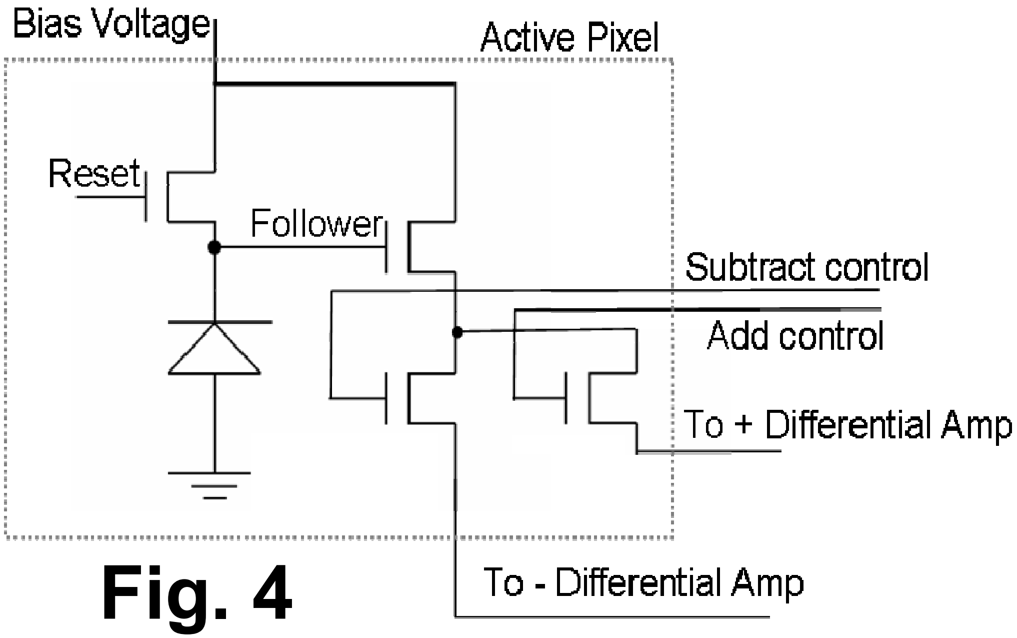


Fig. 4

- Any active pixel architecture can be used with OCR.

Shot noise limited imaging using an active pixel

- The OCR coding operation is the same as previously described except:
  - The active pixel is reset after some number (N) of OCR samples.
  - If (n) is the count from 1 to N, and if P sample trains are taken such that N multiplied by P equals the Hadamard Code length, then the sample amplitudes are normalized by dividing by the count from last reset (n).
  - The normalization by (n) can be applied in the digital processor rather than in hardware.
    - The pixels summed for each sample is governed by a row in the Hadamard matrix.
    - The image is formed by multiplying that Hadamard row by the that sample value.
    - The normalization factor can be applied when forming the image.

Shot noise limited imaging with low illumination

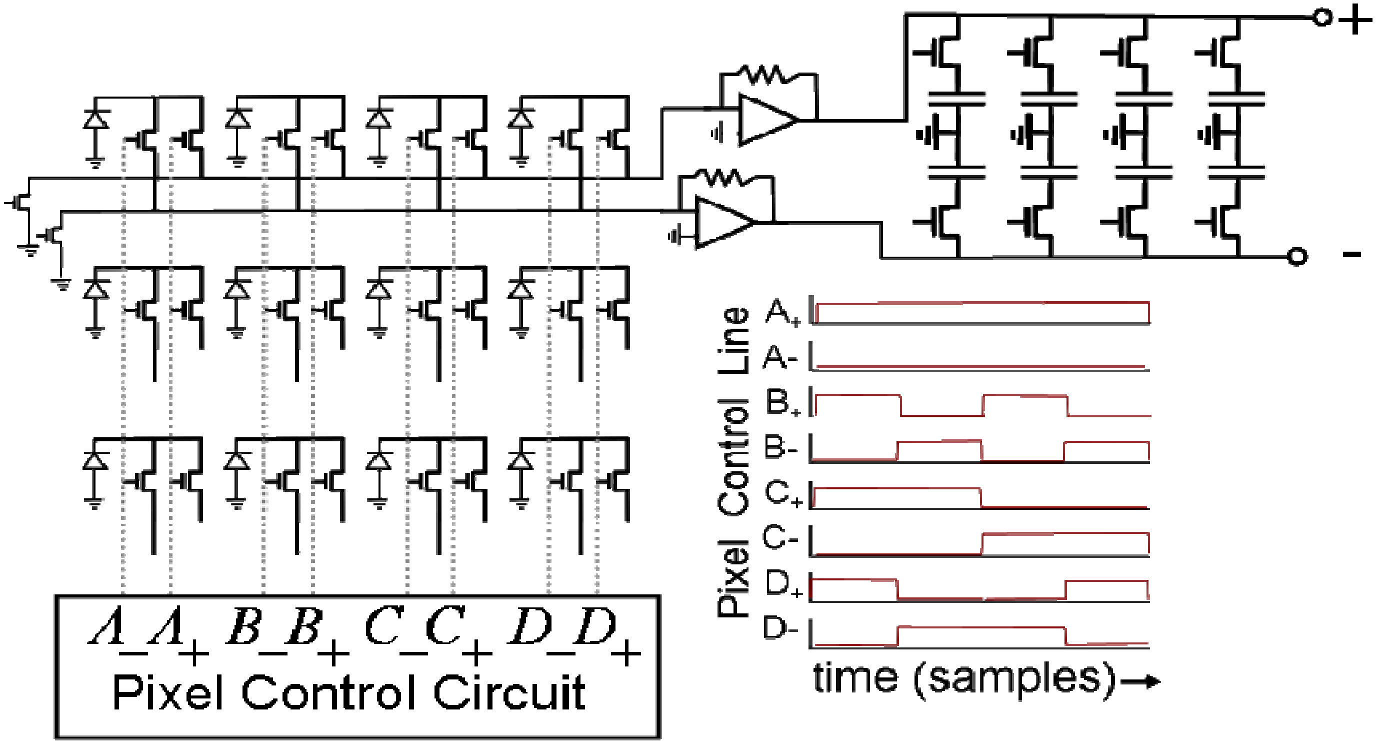
- Orthogonal Code Readout will not work well when the scene is poorly lit unless signal temporal filtering is provided in the pixel.
- However, there are many ways to provide temporal filtering.
  - A low pass filter can be implemented in a passive pixel.
  - Any active pixel architecture can be combined with orthogonal code readout to implement a low-noise and wide dynamic range image array.

OCR implementation problems and solutions

- The OCR implementation illustrated in Fig. 2 requires digitizing all OCR data within an exposure time.
- We would like to have a frame time to digitize all the image data.
- The following slides describe two approaches that provide more time to digitize data.
  - One approach incorporates an array of capacitors to temporally store the OCR data.
  - The second approach uses an active pixel with separate photo charge storage.

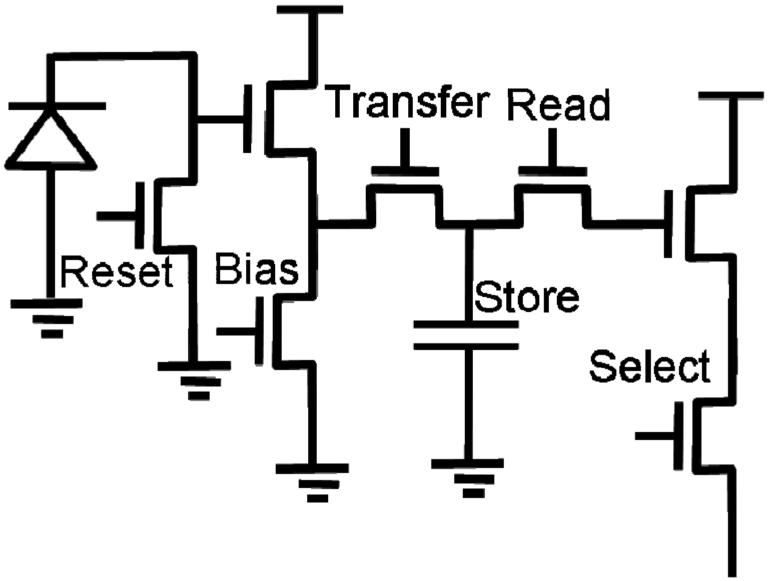
Providing more time to digitize data

- One approach to provide more time to digitize data is to add a sample and hold array as shown at upper right in the figure.
- Each OCR sample is held in a separate capacitor pair.



Providing more time to digitize data

- A second option is to add an in-pixel sample and hold as shown in the figure below.
- OCR samples are taken during exposure. Once exposure time has elapsed, the transfer gate is opened, but OCR sampling continues until code completion.
- Once the transfer gate is opened, the divide by (n) normalization stops, but the relative contribution of samples taken with the transfer gate in a different state must be assessed and the code correctly normalized.



Avoiding Hadamard Code Related Motion Artifacts

- The theory described earlier assumes a static scene, and that assumption is seldom completely valid.
- Like other cameras, a camera that implements OCR is subject to motion blur.
- It is important that implementing OCR not make the motion blur worse than occurs with existing camera technology.
- That standard can be achieved by proper selection of orthogonal codes.
- The figure below illustrates the type of motion simulated. The camera is panned diagonally up such that the scene moves down in the image.

Avoiding Hadamard Code Related Motion Artifacts

- If a typical Hadamard Matrix is used to control which pixels are combined for each OCR sample, then motion artifacts occur.
- The 512 by 385 pixel pictures below illustrate the artifact problem.
- The scene was moved relative to the camera by 16 pixels horizontally and 16 pixels vertically during the exposure time.
- Picture A is OCR and C is normal motion blur.
- For Picture B, the OCR samples were collected with the rows in the Hadamard Matrix re-ordered as shown on the next slide.
- As long as the re-ordered matrix is used to control sampling, motion artifacts are avoided.

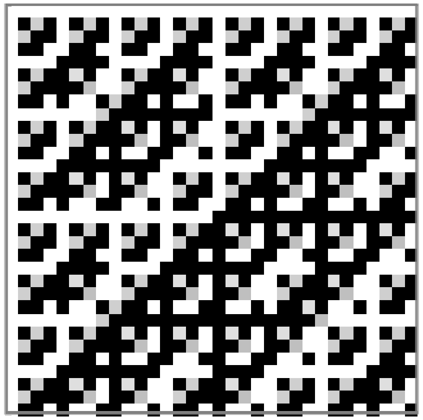
A

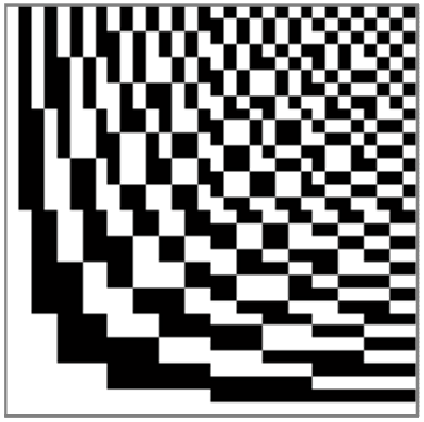
B

C

Avoiding Hadamard Code Related Motion Artifacts

- The matrices shown below are only 32 by 32 and not the 512 by 512 used to collect the images on the last slide.
- A smaller matrix is used here so that the individual elements are easily identified.
- The matrix illustrated at left is in normal order; that is, the left-hand picture is what is typically called a Hadamard matrix.
- The row arrangement shown at right is in descending sequency order. Sequency is the number of times the amplitude changes from minus one to one or from one to minus one in a row.
- The right-hand matrix is derived from the left-hand matrix by placing the rows in descending sequency order.





Summary and Conclusions

- The Orthogonal Code Readout (OCR) expands the dynamic range of CMOS pixels by electronically adding deep, digital electron wells.
- The exposure time is divided into short, contiguous intervals. During each interval, the CMOS pixel integrates photo electrons in the traditional fashion.
- Simultaneously, OCR samples and stores pixel intensities. The pixels are reset before saturation occurs, and the in-pixel signal integration is re-started.
- The OCR samples are digitally processed to recover pixel intensities integrated over the complete exposure time.
- OCR retains the sensitivity behavior of the active pixel while also enhancing dynamic range.
- The sensitivity of the active pixel is retained because photo electrons are integrated in-pixel, but the continual reads allow pixel reset before saturation occurs. The signal integration for each pixel occurs first in the pixel and then in the digital processor.

Summary and Conclusions

- OCR can also be used as a thermal FPA ROIC, but the advantage for thermal imagers is simplification of FPA fabrication.
- For example, since large electron storage capacitors are not needed, direct deposit of the infrared photo detectors onto the ROIC might be possible.
- If bump bonding or press-fitting the detector array and ROIC is necessary, OCR still provides an unlimited digital electron well while freeing ROIC space for new image processing circuitry.
- When implementing OCR, motion artifacts are avoided by using short Hadamard Codes or by using sequenced codes of any length.
- The primary engineering challenge when implementing OCR is that orthogonal coding requires code completion. That is, all of the sequences (the rows) in the Hadamard Matrix must be applied and the samples taken. OCR implementation requires either a capacitor array to store OCR samples or fast digitization.

Summary and Conclusions

- For further information about Orthogonal Code Readout or to discuss implementing OCR in your camera or focal plane array designs, please contact Richard Vollmerhausen at 407 807 9731 or email richard@RHVelectro-optics.com.