NON-LINEAR FILTERS FOR WHITESPOT COMPENSATION

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ABSTRACT

There is growing interest in CMOS imagers, imagers which can be fabricated in standard CMOS process instead of a CCD process. One problem with these imagers are the white spots resulting from high junction leakage due to point defects in the photodiode; these high leakage currents show up as spatially invariant “salt” noise.

We propose two new non-linear filtering algorithms to compensate for the white spots. Conditional replacement of a pixel (CRP) is an image enhancement technique superior to a median filter with less implementation complexity. The second algorithm is a dark current estimator (DCE), in which the dark current variations in the defective pixels are progressively estimated and compensated. Neither algorithm requires a mechanical shutter or a specific calibration image.

These algorithms are described in detail, and the results of simulations are presented.

1. INTRODUCTION

Most modern electronic imagers are fabricated using a charge coupled device (CCD) process. In this type of imager, a photodiode or photogate is used to convert the light into charge. This charge is then shifted out of the pixel array to an amplifier, which converts the charge to a voltage and drives the signal off-chip. This charge shifting relies on the ability to transfer charge between adjacent MOS capacitors in a CCD process with almost no loss. A solid state imager can also be fabricated using a CMOS process. In a CMOS imager, a photodiode or phototransistor has a leakage current which is proportional to the light. This current is then amplified and sent out of the imager; it is sometimes converted to a voltage along the way. One common method of amplification, described in [1], is shown in Figure 1. The signal from the photodiode, which is composed of both photon generated as well as leakage current, charges the gate capacitance of an MOS transistor M3. This transistor then acts as a current source when the pixel's row and column are selected.

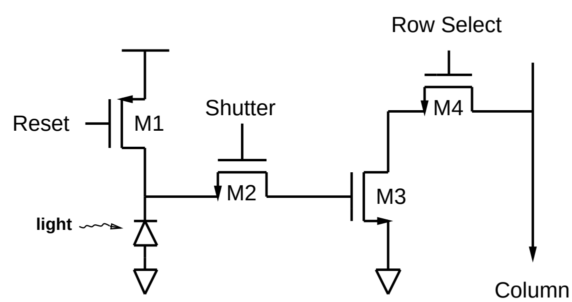

Figure 1: Sample CMOS imager pixel.

In the past, commercial imagers were not fabricated in CMOS processes because of fixed pattern noise problems and because the available device sizes and line widths resulted in a very large pixel size. However, with a modern CMOS process, it is possible to achieve a pixel size of 5.6μm x 5.6μm[2]. Also, techniques, such as correlated double sampling [3], have been developed to eliminate much of the noise. As a result, a number of experimental CMOS imagers have been developed [1, 2, 4], and a few products using CMOS imagers are now on the market [5].

CMOS imagers have three chief advantages over CCD imagers. First, CCD imagers are fabricated in a special purpose CCD process. This CCD process is optimized for imagers; thus, it is usually not cost effective to fabricate other chips in a CCD fab. A CMOS imager, on the other hand, can be fabricated in a conventional digital CMOS process. Second, a commercial CCD imager commonly consumes a lot of power and requires a 12V power supply [6] while a CMOS imager use less power and can operate at 5V (and 3.3V imagers are being developed). Thus, not only does the CCD imager use more power, but it also requires additional circuits to generate the 12V since most current system voltages are at 1.2V, 3.3V, or 5V. Also, not only is a high power imager a problem for mobile applications, such as a videocamera, but the higher power circuit usually requires a more expensive package. Finally, an imager fabricated in CMOS can incorporate additional image processing circuits, such as an ADC, on the imager itself. This can significantly lower the overall system cost and power. It is difficult to add such additional circuitry to a CCD imager at a reasonable cost.

One common problem with imagers is that point defects due to processing impurities create variations in the dark current, which is the leakage current of the photodiode in the absence of light. These dark current variations often appear as white spots and correspond to spatially invariant "salt" noise. This problem is often worse for an imager fabricated in a digital CMOS process than for CCD imagers since the CMOS process is generally not optimized for imagers.

There are four common ways to eliminate whitespot noise. The simplest method is to throw away any imagers which have too much whitespot noise. This lowers the effective yield of the process and thus increases the cost. The second method is to measure the noise when the imager is built, save the information in an EPROM, and subtract it from every image [7]. This solution adds cost and complexity; also, it usually does not take into account the variations in whitespot noise due to temperature. The third method is to first cover the imager with a mechanical shutter, store the resulting dark image, and then subtract this dark image from the regular image. This method can work well for a still photo camera but not for a PC camera, videocamera, or other applications where the imager is not frequently covered with a mechanical shutter. Also, like the EPROM solution, it requires extra hardware.

The fourth way to eliminate whitespot noise is to use a filter to eliminate the noise while preserving the image. We propose an efficient non-linear filtering algorithm, called "Conditional Replacement of a Pixel" (CRP), to compensate for whitespot noise which does not require any extra external memory and requires only a small amount of extra circuitry on the imager chip. The algorithm exploits the fact that image processing can be done on the imager itself when the imager is fabricated in a CMOS process.

2. ALGORITHM CONSTRAINTS

There are several strict requirements which must be met by the CRP algorithm. First, it should be implemented on the imager itself so that the customer does not need to supply extra circuits to implement the algorithm. Second, it must be able to run at full frame rate video speeds. Third, the cost added to the imager by the CRP circuit area must not exceed the cost of simply throwing away bad imagers. For example, if the yield is 90%, then the CRP circuit must not increase the chip area by more than 10%; otherwise, the solution is more expensive than the original problem.[1] Fourth, the output of the imager must be an analog signal since, at present time, most video systems are designed for an imager with an analog output. However, since most imagers will eventually have digital outputs, the algorithm must also be able to incorporate an ADC at a later date. Finally, the algorithm must be able to handle the variations in whitespot noise due to temperature variations.

The point defects which cause whitespot noise do not cause a corresponding blackspot noise. The reason for this is that the noise is the result of variations in the leakage current of a photodiode in the absence of light. A defect can cause this leakage to become arbitrarily large, but it can't become less than zero. Since it is very small already (on the order of 100pA), a defect which causes it to become zero will usually not be noticeable.

3. ALGORITHM AND IMPLEMENTATION

The CRP algorithm works as follows: For each pixel value P, the maximum M of the 8 surrounding pixels is found. If P is greater than M by more than a threshold D, then the pixel is assumed to be bad. Otherwise, it is assumed to be good. Good pixels are passed to the output without modification; bad pixels are replaced by M. The algorithm relies on the fact that, except for isolated whitespots, most pixels are next to at least one other pixel that is greater than or approximately equal to themselves.

The CRP circuit implementation is shown in Figure 2. The pixel buffer stores three rows of pixel values. Since these values are stored in an analog fashion (as the charge on the gate of an MOS transistor), they are not shifted from one storage circuit to another since the pixel value would quickly become corrupted. Instead, the switch fabric uses CMOS pass gates to route the appropriate pixel values to the MAX circuit. The MAX circuit calculates the maximum M of the 8 pixels around the center pixel, compares it to the center pixel,

[1] The yield depends on the yield of the specific fab used to produce the imager. These yields vary greatly and they depend on the circuit being fabricated. For example, a point defect which causes a large leakage current may be acceptable for a CMOS logic chip since it will only increase the DC power by a small amount, but it will not be acceptable for an imager if the variation is noticeable to the naked eye.

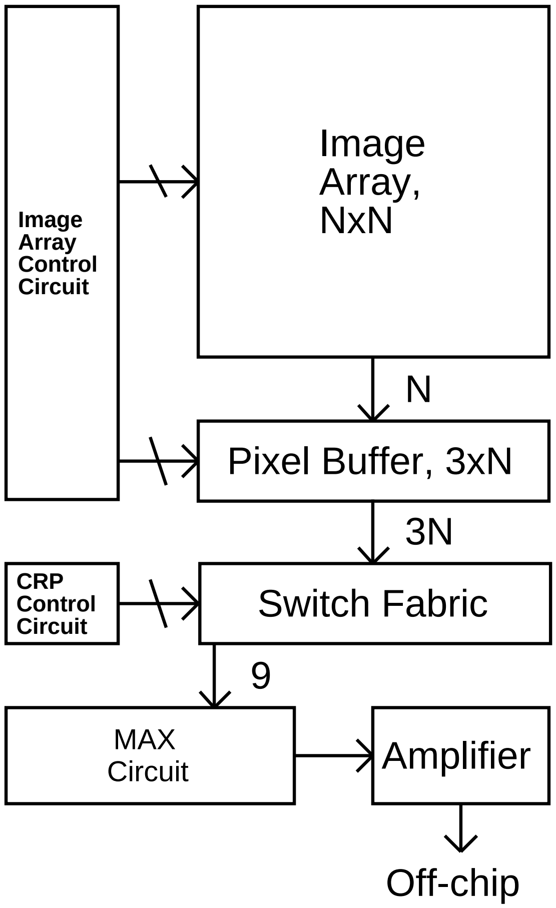

Figure 2: Block diagram of imager with CRP circuit.

and outputs either the center pixel or the maximum M to the amplifier which drives the signal off-chip.

A simplified schematic of the circuit used to calculate the maximum of the 8 pixels surrounding a given pixel is shown in Figure 3. There are 8 transistors whose sources are connected to V_{max}; the pixel value for the center pixel is not an input to the circuit. The center pixel value does go through a similar source follower circuit so that it may be easily compared with V_{max}.

The CRP imager can easily be modified for digital outputs by replacing the amplifier with an ADC.

4. SIMULATION RESULTS AND COMPARISON TO OTHER ALGORITHMS

The CRP algorithm was simulated using a test image. Figure 4 is an image for an imager with no whitespot noise. Whitespot noise was then added, as shown in Figure 5, to simulate the effect of an imager with de-

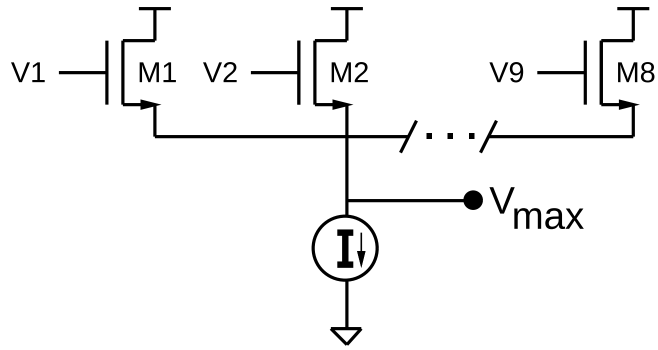

Figure 3: Schematic of analog maximum value circuit. The pixel under consideration, represented by V_5, is excluded from the circuit.

fects. Note that most imagers usually do not have this much whitespot noise, and are not as noticeable under normal amounts of gain. Figure 5 represents a worst case scenario. Figure 6 shows the output of the CRP algorithm applied to Figure 5 using a threshold value of $D = 1\%$. The whitespots are eliminated without any noticeable modification of the rest of the image.

Figure 4: Original image, no noise.

A common filter for eliminating whitespot-type noise is a median filter. An example of a simple median filter using a 3x3 window applied to the noisy image is shown in Figure 7. Although it also removes the whitespots, it blurs the parts of the image with fine detail.

A number of other algorithms have been proposed to overcome the problems associated with simple median filters [8, 9, 10]. However, these solutions are usually too complex to be implemented with a small circuit on an imager. They are adaptive in nature, requiring information from previous or future images, or they require variable weights, or they require data from other parts of the image. In [11], a multi-stage median algorithm similar to CRP is proposed. A fairly simple

Figure 5: Original image with noise.

Figure 6: Image corrected with the CRP algorithm, $D = 1\%$.

maximum/minimum circuit is used to determine if a pixel is bad or good, as in CRP. However, it uses a median value to replace a bad pixel rather than the maximum of the surrounding pixels. The problem with using the median value is that it is difficult to calculate the median of 8 numbers in a small digital or circuit. Most analog median circuits for 8 numbers are also large [12, 13]; the one area-efficient analog median circuit, presented in [14], would still double the area or cut the speed in half. Implementation of a median circuit on an imager would use much more area. The maximum value circuit, on the other hand, already exists on-chip, so no extra circuitry is needed.

5. IMPROVEMENTS

One problem with the CRP algorithm is that isolated bright points in the actual image will often be eliminated. This problem can be reduced by storing a small amount of information from image to image using a modified version of the CRP called the dark current estimator (DCE). The DCE algorithm calculates the

Figure 7: Image corrected with a median filter.

difference between the value of a pixel P and the maximum of the values of the surrounding pixels M. Those pixels that are higher than M by a threshold are considered bad, and the correction factor, equal to $P - M$, is stored. This stored difference is updated for every image with the new difference if the new difference is larger than the stored value. Only the pixels which repeatedly have the largest correction factors (above a certain threshold) would be kept.

The DCE algorithm relies on the fact that only a small number of pixels have noticeable whitespot noise, so the amount of memory needed will be small. The addressing of this memory would need to be digital, of course, but the storage mechanism for the memory would be analog so that small analog maximum, comparison, and output circuits could be used. An analog memory would have the additional benefit that, due to leakage currents, the stored value would decay to zero (or some other known value). Thus, erroneous noise corrections due to actual temporary whitespots in the image would not remain for very long.

6. CONCLUSION

We have presented an algorithm for whitespot removal, conditional replacement of a pixel, that eliminates whitespot noise resulting from dark current variations without the blurring effect of a median filter. Unlike many other noise suppression algorithms, CRP can be efficiently implemented in an analog circuit on a CMOS imager so that its operation is transparent to the user. The algorithm simulations have been presented, and the circuits for the imager are currently being designed. We have also proposed an improved version, the dark current estimator, which uses a small memory to improve its accuracy. This algorithm is currently being simulated, and the architecture of the memory is being designed.

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