A Study of CMOS Cameras

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ABSTRACT
Recent advances in CMOS imaging technology, enable the creation of single chip digital cameras. This paper will discuss the basic operation of a CMOS Camera, its key features, and take a brief look at . the rival CCD technology and compare the operational features of the cameras, developed through the use of these technologies.

I. INTRODUCTION

Until recently, CCDs were the only image sensors, used in digital cameras. They have been well developed through their use in astronomical cameras, video camcorders and scanners. However there is an exciting new technology, CMOS Imaging, which offers better features .

CMOS stands for complementary metal-oxide semiconductor, the architecture of most computer CPUs and memory modules. High performance CMOS image sensors use active pixel architectures, invented at NASA's Jet Propulsion Laboratory in Pasadena, CA.

CMOS cameras, draw much less power than CCD s. CMOS sensors, use the same manufacturing technologies as microprocessors and memory modules, and thus they are easier to produce and less expensive. CMOS technology helps to combine many camera functions on-chip, in a cost effective manner.

II. OPERATION OF A CMOS CAMERA

A. A Broad Look at Operational Components

A camera has the following components (Figure 1).
1. Optics.
2. Image Sensing.
3. Digital Signal Processing.
4. Interfacing.

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B. Optics

The purpose of a lens is to collect and focus photons of light. Lenses are classified by format, mounting, focal length and f-number.

1. A len's format is a specification of the size of the image, the lens can produce. The measurement of a len's format is related to the diagonal size of the image sensor[23].
2. The lens is designed to mount into a standard fixture, that surrounds the image sensor and there are several standards in CMOS camera systems, like C-mount, CS-mount and S-mount[23].
3. Focal length indicates the magnification obtained from a lens for a given imaging condition[23].
4. f-number is the focal ratio, the ratio of the len's focal length to its aperture. It ranges from f/1.4 to f/8. Smaller f-numbers let in more light, while larger f-numbers allow more latitude for focus[23].

An imaging lens is needed to provide an accurate representation of the image to be captured. Light from the object passes through the lens and form an image where the sensor is located. Two parameters, resolution and format, are considered to match the size, number and distribution of the sensor's pixels to similar quantities in the lens' image. The lens should be able to resolve the image features to the sensor pixel size[23].

C. Light Collection and Color Filtering

Micro-lenses funnel light to the photo-sensitive part of each pixel (Figure 2). On their way, the photons pass through a color filter array (CFA), where the process begins of obtaining color from the monochrome chip. Getting color out of a sensor means being able to separately measure the red (R), green (G) and blue (B) photons. To do this, each pixel is covered with either a red, a green or a blue filter according to a specific pattern, like the Bayer CFA pattern (Figure 3). Since each pixel has been made sensitive only to one color, the overall sensitivity is lower than a monochrome sensor.

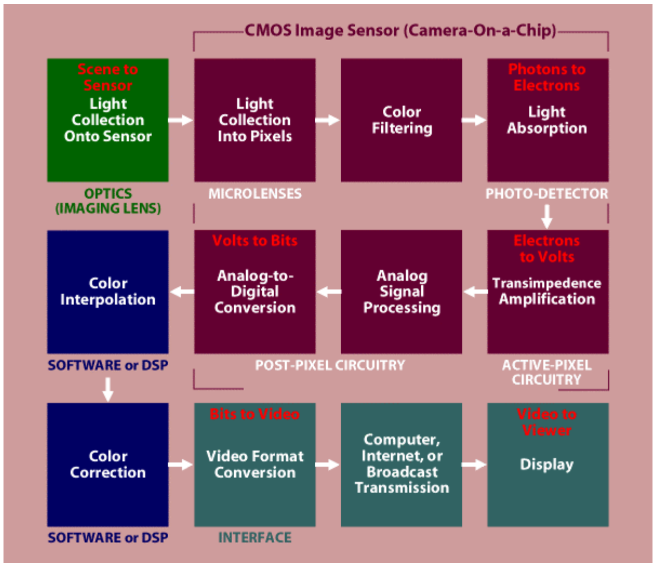

Figure 1: Block Diagram of a CMOS Camera

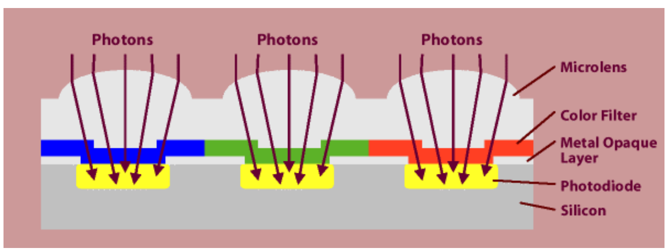

Figure 2: Light Collection into pixels

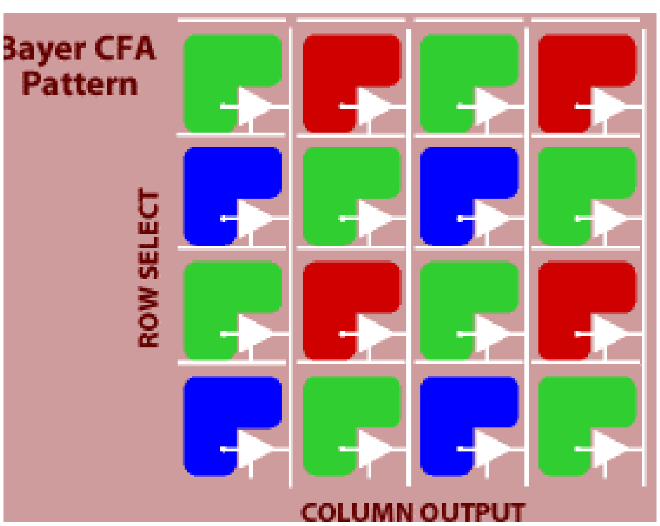

Figure 3: Bayer Color Filter Array

D. Photons to Electrons

Illumination is measured in terms of unit of lux. If a candle of light is one foot away from an object, it gives one foot-candle of illuminance onto the object. This is about 10 lux.

A critical parameter in an imaging system is the number of photons that reach a pixel during a given exposure interval. To determine this number, the illuminance onto the image plane is calculated from the illuminance onto the object and the object's and lens' various optical parameters.

The illuminance onto the image plane, is given as

$$Ii = Io\left(\frac{R}{\beta}\right)\left(\frac{\Pi}{4}\right)\left(\frac{T}{\left[f/\#\right]^2}\right) \qquad [1]$$

where Io is the illuminance onto the object, R is the reflectance of the object (0-1), b is the solid angle that the bulk of the light incident onto the object scatters into (0-4), T is transmittance of the lens, and [f/#]2 is the square of the lens number. The number of photons per pixel per exposure

$$p \approx \left(10000 \times z^2\right)\left(Ii\ \tau\right) \qquad [2]$$

where z is the sensor's pixel pitch in microns and t is the exposure time in seconds. Generally, 5,000<p<500,000.

Each pixel contains the photo-detector element (photo-diode) and the amplifier element (active transistor circuitry) (Figure 4). When a photon is absorbed in the photo-sensitive part of a pixel (the photo-detector), an electron is generated in the pixel (Figure 5). In the active pixel architecture, the source follower transistor buffers the charge onto the bus, and provides current to charge and discharge the bus capacitance quickly. The reset transistor controls integration time and provides for electronic shutter control[11]. The row select transistor gives half the coordinate readout capability to the pixel array. After photocharge integration, the charge transfers to the capacitance of the column bus, where the charge-integrating amplifier at the end of the bus senses the resulting voltage. The column bus voltage resets the photodiode and the pixel is ready for another integration period.

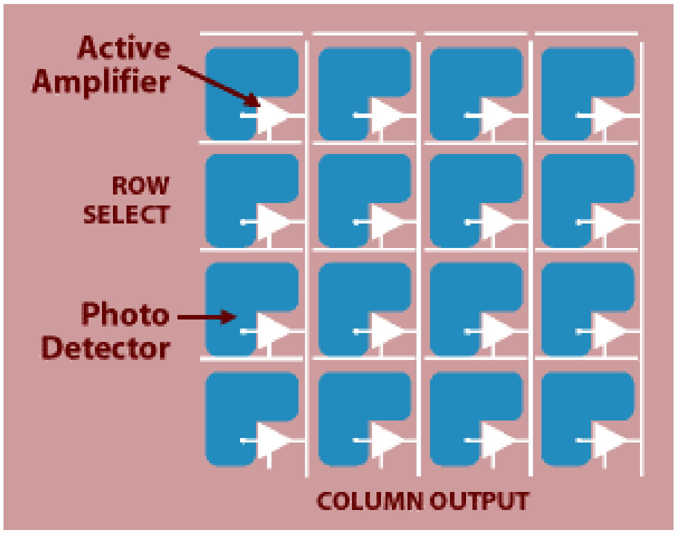

Figure 4: Image Sensor Pixel Array

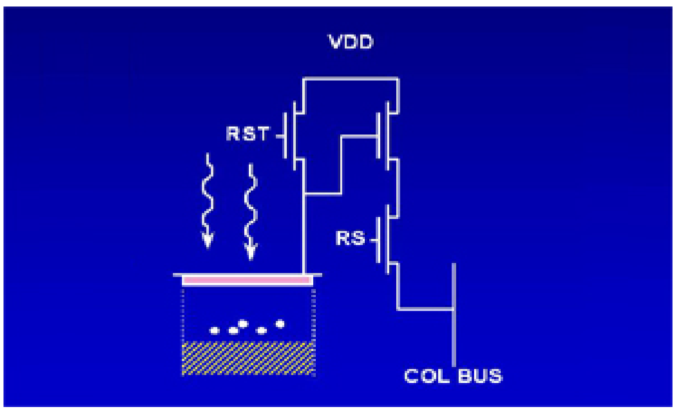

Figure 5: Active Pixel Architecture

The bigger the pixel, the more light it can collect. Thus, big pixel sensors work best under low-light conditions. For the same number of pixels, bigger pixels results in bigger chip, which means higher cost. Conversely, smaller pixels enable smaller chip sizes and lower chip prices, as well as lower lens costs. But there are limitations on pixel size reduction. Smaller pixels are less sensitive to light, the optics required to resolve the pixels becomes expensive and requires expensive fabrication possesses.

E. *Analog signal Processing and Digital Conversion*

At the stage of analog signal processing, fixed-pattern noise (FPN) is cancelled[18]. Corellated double sampling is performed and then a gain step is performed[10].

Analog-to-digital conversion is performed either in a column-parallel fashion or serially (Figure 6). The column-parallel approach has the advantage of using slow converters to achieve a high conversion rate, while serial ADCs enable a smaller chip size[2,3,4, 14].

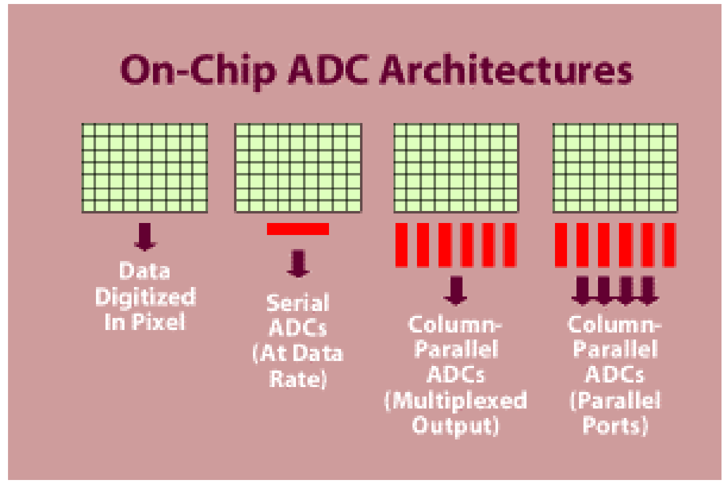

Figure 6: Analog-to-Digital Converter Architectures

F. *Digital Signal Processing*

Digital signal processing consists of two stages.
1. Color Interpolation
2. Color Correction

Color image sensors typically put out sequential RGB color, since each pixel is covered by either a red, a green, or a blue filter. To obtain red, green, and blue information form each pixel and 8 bits for each color, a 24-bit RGB signal per pixel, color interpolation is needed. This process averages out the color values of appropriate neighboring pixels, to guess each pixel's unknown color data.

Color interpolation works well, as long as the color in the image changes slowly in the spatial dimension relative to the CFA pattern. But for edges and other fine details, color may be interpolated incorrectly and artifacts may occur. This is called aliasing[20]. Using a blurring filter, to discard fine details, reduces aliasing[20].

The initial 24-bit RGB triplet of data is raw color and must be balanced. The blue signal, for example is a combination of the blue photons, multiplied by the relative response of the blue filter, multiplied by the relative response of the silicon to blue photons. The filter and silicon responses are quite different from a person's eye response, so the blue to the sensor is different from the blue to the person. To make a blue, more acceptable to human vision, the sensor blue is processed further. Gain is changed, and some green or red is added to make it truer.

$$\overline{B} = b1 \times R + b2 \times G + b3 \times B \qquad [3]$$

where b1, b2, and b3 are the weights for each of the mix of red, green and blue to the new blue. Corresponding equations can be written for red and green. This is basically a matrix operation, where the weights define a color-correction matrix. Though this procedure is less than perfect, the weights can still be determined with accuracy.

G. *Interfacing*

Digital RGB output from the sensor, can be converted to any of the several video formats.

1. Digital USB, for computer use.
2. Analog NTSC, for TV in North America and Japan.
3. Analog PAL, for TV in Europe and India.
4. Analog RGB.

III. BRIEF ON CCD TECHNOLOGY

Charge-coupled devices were first developed in 1969 as a way to store data using bubble memory. In 1974, the first imaging CCD was produced by Fairchild Electronics with a format of 100x100 pixels[1,16,17, 22].

CCDs capture light on the small photosites on their surface. These photosites, are photodiodes or photogates. The charges on the first row of pixels, are transferred to a read-out register. From the register, the signals are then amplified and converted into digital. Once the row has been read, its charges on the read-out register are deleted, and the next row enters the read-out register. The charges on each row, are thus coupled on the row above and thus the name charge coupled devices (Figure 7). In this way, each row can be read, one row at a time[16, 22].

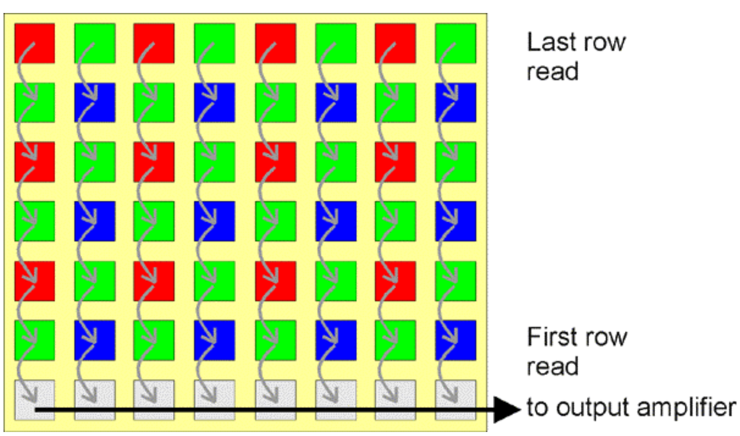

Figure 7: Charge Read-out in CCD Technology

It is technically feasible to use CCD technology to integrate other camera functions, like clock drivers, timing logic and digital signal processing on the same chip as the photosites, but its is not economical (Figure 8)[17, 22].

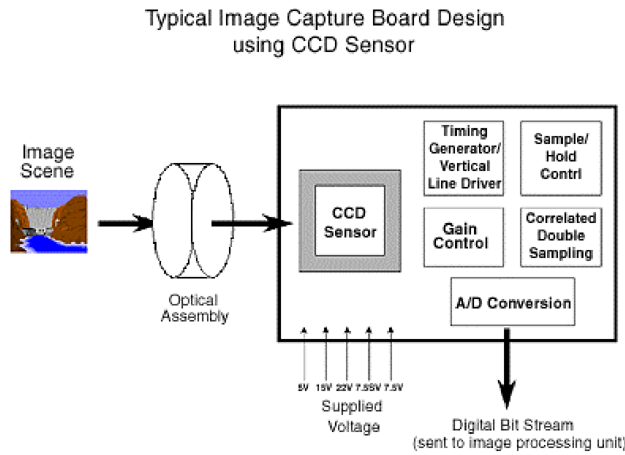

Figure 8: A CCD Camera

IV. FEATURE COMPARISON

We will compare and discuss the features of these two camera technologies.

A. *Lower Cost and On-chip integration in CMOS Cameras*

CCD sensors use specialized fabrication that use dedicated and costly manufacturing processes[5,6,17, 22]. In contrast, CMOS image sensors relies on standard manufacturing technology which produces microprocessors and memory modules[15]. This standardization results in vast economies of scale. CMOS processes enable VLSI designs, and this is used by active pixel architectures to incorporate all necessary camera functions like noise cancellation, A-to-D conversion, correlated double sampling, timing control, gain control, electronic shutter control, digital signal processing onto one chip[10, 11,12, 13]. Such integration creates a compact, reliable and cost effective camera system.

B. *Low power usage in CMOS Cameras*

Active pixel architectures consume much less power, upto 100x less, than their CCD counterparts, which are inherently power hungry[12, 13, 16 22]. This is because CCDs are essentially capacitive devices, needing external control signals and large clock swings to achieve acceptable charge transfer efficiencies. A CCD system typically uses 2-5 watts, compared to 20-50 milliwatts for the same pixel throughput in CMOS cameras[16,17, 22]

C. Flexibility of Operation

In CMOS image sensors, both the photo-detector and the readout amplifier are part of each pixel. This allows the integrated charge to be converted into a voltage inside each pixel, which can be read out over X-Y wires, instead of using charge domain shift register, as in CCDs[16, 22]. This column and row addressability allows for windowing, which can be utilized for on-chip electronic pan, tilt and zoom, and provides much flexibility in applications that need image compression, motion detection and target tracking.

D. Higher Quality Images in CMOS Cameras

In CMOS image sensors, the RMS input-reffered noise, approximately –50dB and fixed pattern noise (FPN)(–40dB) is comparable to very high-end CCDs[10, 18, 19, 22]. Active pixel architectures use intra-pixel amplification in conjunction with temporal and FPN suppression circuitry, which produces exceptional imagery with high quantum efficiency and avoids column streaking due to blooming pixels, in CCDs[10,12, 13, 20, 21, 22, 24]. This is because CCDs use charge domain shift registers that can leak charge to adjacent pixels when the CCD register overflows.

E. Better Quality Low Light Images in CCD Cameras.

While CMOS image sensors excel in the capture of outdoor pictures, they suffer in low light conditions. Their sensitivity to light is decreased because part of each photosite is covered with noise-filters and color filters[9]. The percentage of a pixel devoted to collecting light is called the pixel's fill factor[7, 8, 21, 24]. It is close to 100% for CCDs, but much less for CMOS cameras.

F. Noise Level

There are two dimensions of noise: read (temporal) noise and fixed pattern noise (FPN)[10, 18]. In CCD-based cameras, FPN is often small because the charge packet associated with each pixel's signal is converted to a voltage at one common output node[10, 22]. The temporal noise in CCD is dominated by either reset and white noise of the output amplifier, or the excess noise of the camera interface. Reset noise is eliminated by sampling the reset and signal levels and subtracting one value from the other on a pixel by pixel basis, in a process known as correlated double sampling[10,18].

Conversely, CMOS imagers are fundamentally superior to CCDs with respect to temporal noise, because the amplifier at each pixel operates at much lower bandwidth than the output amplifier[18]. But the fact that each pixel's photo-charge is independently converted to a voltage is a drawback in CMOS imagers. The resulting FPN can limit imaging performance more than temporal noise. Hence more signal processing is required to limit FPN, which is achieved by the on-chip circuitry in CMOS sensors[10, 18].

G. Faster Frame Rates in CMOS Cameras

Active pixels in CMOS cameras can drive an image array's column buses at greater speed than is possible on CCDs and on-chip A-to-D conversion eases the driving of high-speed signals off-chip[12, 13]. This yields very high frame rates in the order of 500 frames per second at megapixel resolution. An added benefit is the output signal's low sensitivity to crosstalk.

H. Smart functions in CMOS Cameras

CMOS active pixel architectures allow signal processing to be integrated on-chip[12, 13]. In addition to standard camera functions, like auto gain control, auto exposure control etc., many higher level DSP functions like anti-jitter, image compression, color encoding, computer interface circuits, multi-resolution imaging, motion tracking, video conferencing and wireless control, can be realized. These features can be incorporated in CCD cameras off-chip only, because of economic constraints in on-chip CCD processes[16,17].

V. CONCLUSIONS

CMOS video imagers can be implemented in consumer products such as camcorders, digital cameras, toys, security cameras and digital cellular phone systems. Business and industrial applications include videoconfercning, machine vision, medical instrumentation, broadcasting etc.

The key to replacing CCDs is to integrate the necessary on-chip circuitry to eliminate FPN[10]. Since CMOS readily facilitates such integration, CMOS cameras are poised to replace the current CCD based ones.

Future generation of CMOS image sensors will be based on process geometries of 0.25mm and smaller. These devices will be able to provide resolution of 5 –25 million pixels at video frame rates, matching the resolution of photographic film.

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