Compact CMOS Multispectral/Polarimetric Camera

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ABSTRACT

A novel, compact visible multispectral, polarimetric camera is under development. The prototype is capable of megapixel imaging with sixteen wavebands and three polarimetric images. The entire system encompasses a volume less than 125 mm x 100 mm x 75 mm. The system is based on commercial megapixel class CMOS sensors and incorporates real time processing of hyperspectral cube data using a proprietary processor system based on state of the art FPGA technology.

Keywords: Multispectral, Polarimeter, Lens Array, Camera Array

1. SYSTEM GOAL

The goal for the system was to leverage commercial off the shelf (COTS) technology to build a multispectral platform for real-time visible imaging. The system was to be scalable in the number of wavelengths and reconfigurable in filter response. An essential goal of the design was to leverage low cost sensor, filter, and optical components.

A critical element in the system was evaluating sensor technology for low cost COTS alternatives. Table 1 summarizes a few characteristics for comparing CCD and CMOS technology.

Table 1: Comparison of CCD and CMOS Technology

	CCD	CMOS
Noise	+ + +	+
No. Pixels	+	+ +
Cost	+	+ + +
Product Choices	+	+ +
Circuit Design	+	+ + +
Integration	+	+ + +
Instrument App.	+ + +	+
Product Lifetime	+ + +	+

The subjective comparison was meant to assist in the design of this system, not to suggest that one technology is superior to another. In fact, a quick comparison of the number of advantages of each sensor technology reveals that they are nearly equal in their total strength of advantages. However, the areas in which they excel are different. The comparison is detailed as:

- CCD technology is recognized as a low noise solution. Low cost CMOS sensors found in cellular phone applications typically have lower signal to noise ratio as well as sensitivity.

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- Pixel count in CMOS sensors has exceeded that of most commercial CCD sensors. There are notable exceptions in the field of instrumentation CCD's. However, the digital camera and cell phone markets have driven CMOS sensors to very high (> 5 Mp) pixel counts.

- The cost of CCD sensors is typically > $500/chip for pixel counts > 1 Mp. CMOS sensors are now distributed through large electronics distributors for less than $15/chip.

- The number of CMOS sensor product choices has exploded in recent years. In reviewing the offerings from Micron Semiconductor, OmniVision, and Cypress Semiconductor the total number of products (measured in part numbers) far exceeds that available for CCD sensors.

- The support circuitry for controlling the sensor and reading the image data for CMOS sensors has been made much easier than CCD sensors given the inherently digital interface.

- CMOS sensors are being developed with a system-on-chip approach. This level of integration offers functionality on board the image sensor including: ROI isolation, undersampling, white balance correction, electronic shutter, image uniformity correction, and computations to drive autofocus mechanisms.

- CCD sensor technology remains the leader in scientific and industrial applications. Product support and availability of technical data for color and monochrome system development is far superior with this technology and these products. This is due in part to the difference in target markets for the technologies. Most CMOS sensors have been targeting for mass market (e.g. cellular phone cameras, toys, digital still camera) applications. In this arena, specifications do not have a direct impact on sales as they do in instrument or scientific applications.

- Product lifetime of CCD sensor products is much longer than CMOS sensors. The rate at which CMOS sensors are consumed depletes inventory rapidly. The CMOS sensor market is driven by consumers that expect rapidly evolving products. It is not unusual to see end of life (EOL) notices in the CMOS sensor industry indicating that designers should choose more modern components. With these factors in consideration, the CCD sensor products have a much longer lifetime than the CMOS sensor products.

2. DESIGN CONCEPT

The design concept for the multispectral sensor is an array of single band cameras arranged in a single mechanical housing. Each camera has an individual CMOS sensor chip, objective, lens, and spectral (polarimetric) filter. This type of system may not have been economical with an array of CMOS sensors. However, the cost per pixel of an array of CMOS sensors is orders of magnitude lower than CCD sensors. The market for the CMOS sensors has also driven a standardization of a series of lenses. The costs for theses lenses has also been driven to be much lower than a typical C-mount lens without sacrificing performance. The system will be controlled by a single CPU. Data will be collected and pre-processed using a parallel, pipelined architecture.

The opto-mechanical design (see Figure 1) consists of a single PCB where all the sensors are mounted and a housing that holds the objective lenses and filters. Each lens is individually focused on the sensor found in its back focal plane. The focus of the entire array can be adjusted. Two PCB's are mounted to the back of the housing. The first contains the image sensors. The second PCB contains the processing elements.

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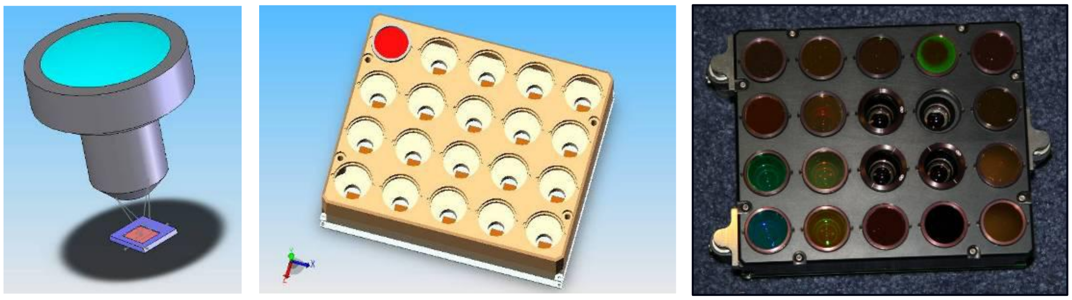

Figure 1: Opto-Mechanical Concept (Single Camera – Left; CAD Model – Middle; Photograph of Housing – Right)

3. ELECTRONIC ARCHITECTURE

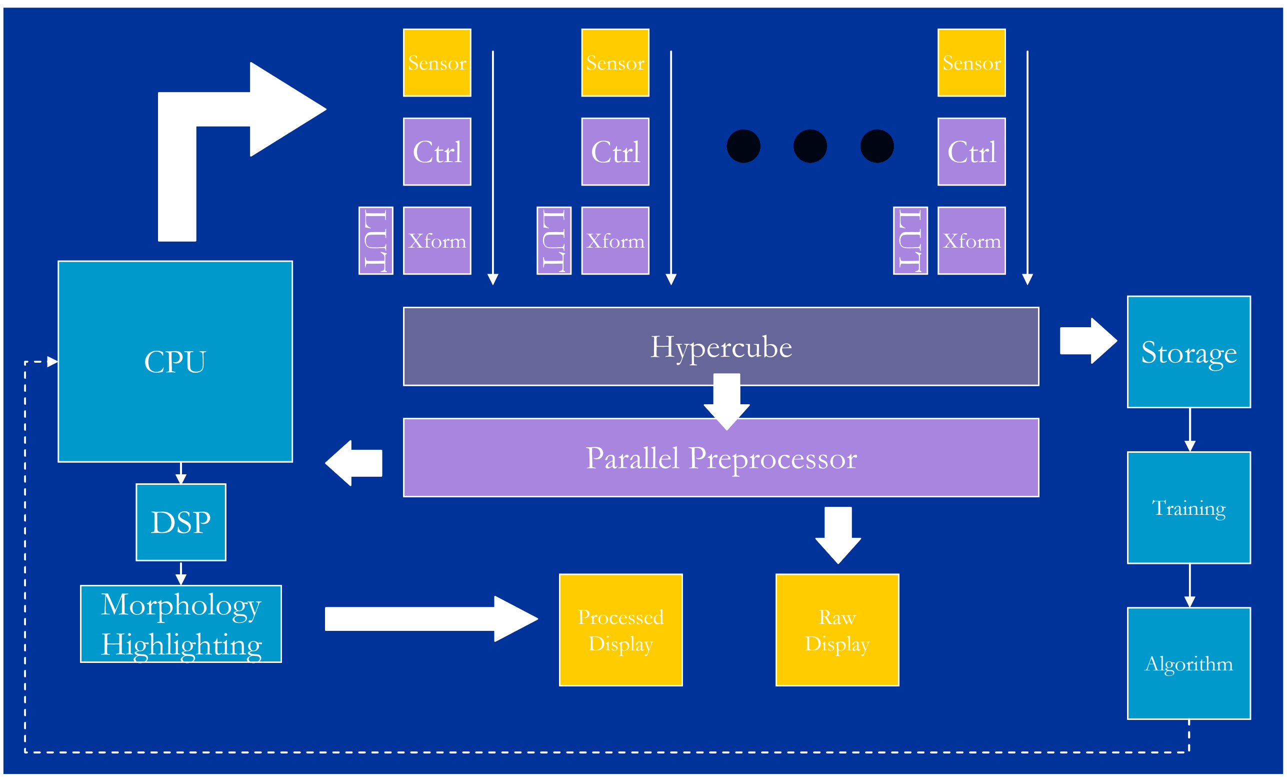

Figure 2: Electronic System Architecture

The system architecture is shown in Figure 2. Image sensors are arrayed with control logic and calibration logic. The control logic sets exposure duration and regions of interest (ROI). The calibration logic includes white balance, pixel selection, and affine transformation capability for registering the images. The sensor array is controlled by a CPU/DSP. Data travels from the image sensor array to a hypercube memory section where it can either be sent to storage or pre-processed. Storage can be used to analyze hypercubes offline. For example, the analysis may be used for algorithm development. After training the algorithm can be deployed on the CPU/DSP or the pre-processor. The pre-processor is implemented in an FPGA. The pre-processor is capable of parallel, pipelined linear algebraic operations combined with simple p-norm and threshold based classifiers. The output of the pre-processor is then sent back to the CPU/DSP. At this point, the pre-processed data can be morphologically processed (e.g. image segmentation, shape processing,

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edge/line location) and a video image can be created using the appropriate combination of image data and highlighting. Either this image data or the raw pre-processed image data can be displayed.

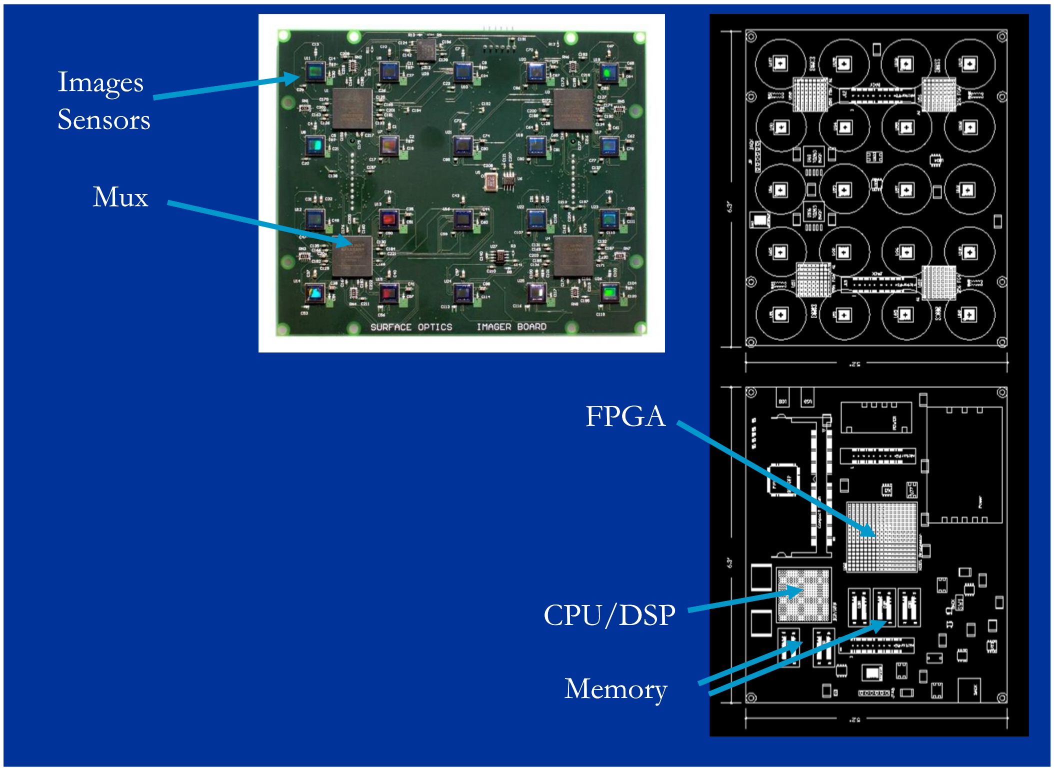

Figure 3: PCB Layout

The implementation of this architecture is shown in Figure 3. The layout was optimized based on the lens aperture size and total number of sensors selected for this design. Xilinx FPGA was chosen to implement the pre-processor. The TI DaVinci chipset was chosen to implement the CPU/DSP.

4. FILTERS/SPECTRAL RESPONSE

In keeping with the low cost COTS design goal, COTS filters were selected to cover the visible spectrum. The initial choice for the sensor was a monochrome sensor. However, the CMOS monochrome sensors are in low demand. One development cycle that was encountered for CMOS sensors targeting the cellular phone industry was to introduce a monochrome version of the sensor in limited quantities to prove out the design. The monochrome sensor was then followed by a color version of the same sensor. An EOL notice for the monochrome sensor was issued some time later. The consequence of this strategy is a very limited supply of monochrome sensors with a short life cycle. For this reason, an RGB sensor with an integrated Bayer filter was considered.

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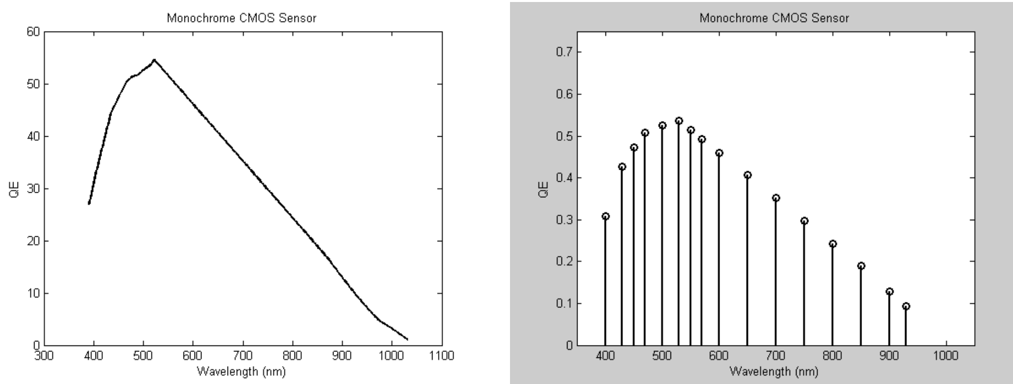

Figure 4: Monochrome Sensor (QE – Left; Response for Filter Center Wavelengths – Right)

Typical quantum efficiency (QE) for a CMOS monochrome sensor is shown in Figure 4. The filters in this example had 10 nm and 40 nm bandwidths. As can be seen, there is significant response beyond the visible spectrum.

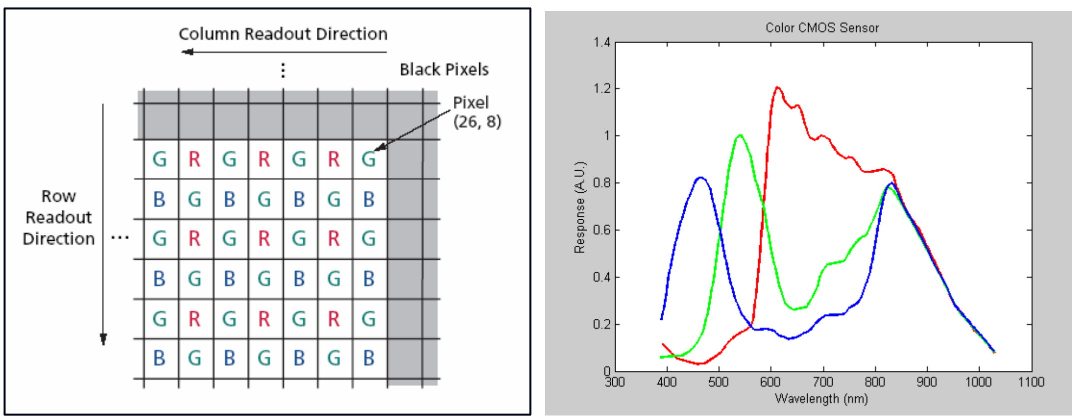

Figure 5: Bayer Filter for CMOS Sensor and Color Filter Response

Commercial CMOS RGB sensors have integrated Bayer filters (see Figure 5). The color filter response (see Figure 5) indicates that the various color filters do not have equal total transmission for white spectrum. The filter center wavelengths were overlaid upon the color filter response (see Figure 6). As can be seen from the graph, there is significant response for at least one of the three color filters at each of the center wavelengths. In some portions of the spectrum (blue) only one pixel in the Bayer array will be used. Towards the infrared portion of the spectrum, data from all three (RGB) filters can be used.

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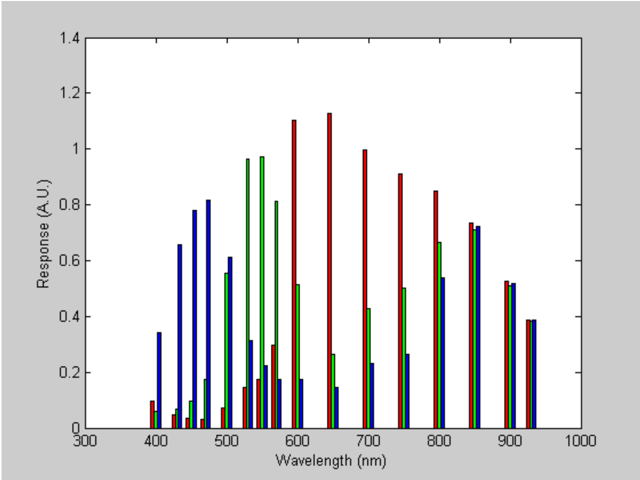

Figure 6: Filter Center Wavelengths Combined with Color Filter Response

Using the COTS filters, images were captured with a commercial, high resolution CMOS RGB SLR camera (see Figure 7). Each of the images represents 1000 x 1000 pixels. For completeness a panchromatic and three polarimetric images were included.

Figure 7: Images with COTS Filters and Commercial CMOS RGB SLR

5. SUMMARY

The design of a unique array style multispectral/polarimetric camera has been described. CMOS and CCD image sensors were compared for this application. CMOS sensors were selected. The optical, mechanical, and electrical designs were described. An electronic architecture was diagrammed that leveraged modern FPGA and video processing chipsets. Finally, the spectral response of the array camera was described.

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