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Development of a Multi-spectral Camera for Computer vision applications

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ABSTRACT

The need to multispectral cameras is growing in different fields. The goal is to provide inexpensive, flexible, or high resolution acquisition set-ups for different applications. Production of cheap and easy-to-use multispectral cameras requires the design and development of specific multispectral camera sensors equipped with multispectral filter arrays. Filter arrays, band width, and spectral response of filters should be analyzed and determined before mounting the filters on the image sensor. In this study, a multispectral camera sensor was designed to be used for computer vision applications (e.g. crop/weed detection, fruit ripeness estimation etc.) covering visible range. The developed camera sensor is consisted of the image sensor, spectral filter array, a sensor board, and a driving board. A hybrid system is proposed that works using eight bands in visible range (i.e. 400-700 nm). A program was developed based on Genetic Algorithm to find the best combination of filters. The program selects the Gaussian filters using a genetic algorithm powered by wiener filter estimation method. For the selection of bands, minimum RMS of 0.0016 was obtained for the selected bands in visible. The developed camera provides eight high resolution spectral images.

Keywords

Multispectral camera; Spectral filter array; Image sensor; Hybrid sensor design; Genetic algorithm.

1. INTRODUCTION

The use of Multispectral (MS) cameras for various applications in different fields is growing as these cameras provide efficient information in a single-shot image [Shi17]. Also, MS imaging reduces the cost of hyperspectral imaging and analysis. Spectral bands in MS cameras are chosen based on the application and the cameras are designed specifically for special applications [Fre15]. Hence, the specific filter array would be mounted on the image sensor for the desired application. Design and fabrication of MS cameras is of high importance as reduction of cost and increasing the quality and resolution play significant roles. The cost of fabrication is quite high which limits the development of this technology [Lap17]. The most popular technologies currently used in some MS imaging systems are Dichroic filter, Fabry-Perot, Multi-Aperture Filtered Camera, and PixelTEQ Camera.

In previous research, several Multi-Spectral Filter Arrays (MSFA) and MS cameras have been designed and developed [Sun18, Bol18, Cao19, Gut19, Gen20].

[Fre15] proposed a design of a multispectral filter array with an extended spectral range spanning the visible and near-infrared range, using a single set of materials and realizable on a single substrate. They experimentally illustrated also the ability of multispectral nanostructured Fabry−Perot (FP) filters to provide precisely constant peak wavelength across the whole surface of an image sensor in the focal plane of an optical system. [Par17] designed a multispectral imaging system with an onboard flight controller for acquiring multispectral aerial images of crops. The MS system consisted of 6 bands and was used for several crops. [Shi18] proposed an MSFA for snapshot multispectral polarization imaging. The MSFA was a photonic crystal which was used as thin-film wavy multilayer structure. [Wil19] reported a manufacturing process that enables cost-effective wafer-level fabrication of custom MSFAs in a single lithographic step, maintaining high efficiencies (~75%) and narrow line widths (~25 nm) across the visible to near-infrared. In a recent report, [Yu20] designed a new multispectral imaging system, named multispectral curved compound eye camera (MCCEC). The proposed MS system consisted of three subsystems including a curved micro-lens array, an optical transformation subsystem, and the data processing unit.

In this work, the development of a fast and cheap MS camera for usage in a wide of computer vision applications is presented. The goal was to provide a sensor based on the MSFA (Multi-spectral filter array) technology that allows to cover from 380 nm to 780 nm in eight different spectral bands.

2. MATERIALS AND METHOD

2.1 Image sensor

2.1.1 Sensor selection

The Hybrid sensor was based on E2V Sapphire (Teledyne E2V, Model: EV76C570, UK) which is a 2k black and white sensor. The EV76C570 is a 2k CMOS image sensor designed with E2V's proprietary Eye-On-Si CMOS imaging technology (Table 1). It is ideal for many different types of applications where superior performance is required. The innovative pixel design offers excellent performance in low-light conditions with an electronic global (true snapshot) shutter, and offers a high-readout speed at 50 fps in full resolution.

2.1.2 Measurement of the spectral response

To estimate the spectral response of the filter, a global estimation of the MS imaging sensor was performed. To perform this calibration, four steps were defined:

- The energy generated by the monochromator from 350 to 1000 nm was measured
- The system generates a monochromatic light each 5 nm from 350 to 1000 nm. So the original CMOS sensor (without a filter mounted) was illuminated. The integrated time of the camera was set as constant.
- The second measure was done with the MS imaging sensor. An algorithm was built to extract from each moxel the pixel related to a specific filter.
- The filter spectral response was obtained from the CMOS sensor response measured in step 2.

Main features of the sensor	▪ 2 million (1600 x 1200) pixels, ▪ 4.5 µm^2 pixel size with micro-lens ▪ Optical format 1/1.8” ▪ 50 fps at full resolution
Performance characteristics	▪ Low power consumption (200mW) ▪ High sensitivity at low light level ▪ Operating temperature [-30° to +65°C] ▪ Peak QE > 48% ▪ B&W
Timing modes	▪ Global shutter in serial and overlap modes ▪ Rolling shutter and Global Reset modes ▪ Output format 8 or 10 bits parallel plus synchronization

Table 1. Technical properties of the image sensor.

2.2 Sensor development

2.2.1 Sensor structure

The global system has 3 blocks that work together for receiving correct images:

- The sensor block was designed to provide the control of the E2V CMOS sensor.
- The FPGA block which was designed via Xilinx's VIVADO platform, whose role was to enable the synchronization of data exchanges from the sensor board, viewing directly on a screen and data acquisition to the computer.
- The Computer block, which contained the software allowed the acquisition, processing and exploitation.

2.2.2 Sensor Board Design

The E2V's EV76C570 sensor offers a dynamic 10-bit output range in digital playback. It includes features such as the ability to have the output image histogram, the multiple ROIs (Region of Interest), the faulty pixel correction, the global shutter, etc. There is also the possibility of setting up a sequence to acquire successive images with different exposure times (up to four times). Because of this feature, then the reconfiguration of the sensor registers between each image is removed. It also has the distinction of having a good sensitivity to low light levels and low consumption (200mW). This low consumption makes it suitable and usable for on-board systems such as smart cameras, and battery-powered applications. The proposed architecture was designed to be able to adapt to a large number of affordable sensors on the market and then the choice of this type of conventional sensors is quite wise.

2.2.3 Hardware description and Specification

For the hardware, FPGA Zboard / Zybo development kit was used having main characteristics as follows:

- The ZYBO (ZYnq Board) is a feature-rich, ready-to-use, entry-level embedded software and digital circuit development platform built around the smallest member of the Xilinx Zynq-7000 family (i.e. Z-7010).
- The Z-7010 is based on the Xilinx all-programmable System-on-Chip (AP SoC) architecture, which tightly integrates a dual-core ARM Cortex-A9 processor with Xilinx 7-series Field Programmable Gate Array (FPGA) logic.
- When coupled with the rich set of multimedia and connectivity peripherals available on the ZYBO, the Zynq Z-7010 can host the whole system design.
- The on-board memories, video and audio I/O, dual-role USB, Ethernet, and SD slot will have your design up-and-ready with no additional hardware needed.

2.2.4 Hardware Block Design and Description

To carry out the Hardware design, the VIVADO/ Xilinx (version 2019.2) development platform was utilized which is a graphical programming environment. Of the benefits of using Vivado is that it allows to quickly detect programming code errors. The design block was performed to control the coming signals from the sensor, so a link between the processor part and the PL part was necessary. To create the design block of the project under Vivado, the IP (Intellectual Property) blocks were made available for this purpose. IPs are available coded modules that can be added to a design. All IPs are binary codded (protected). The block diagram below (Fig 1) gives the most important blocks used in the FPGA for data exchange with the sensor board and computer pour displaying the video.

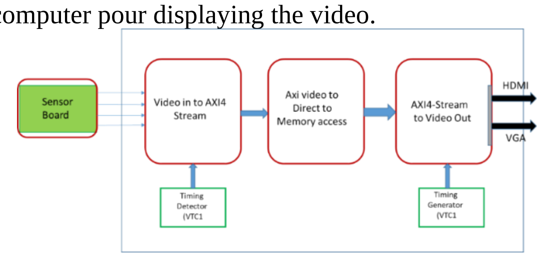

Figure 1. Block Diagram of the FPGA.

The sensor generates the 10 bits of data, in parallel. To be able to process the data, all IP blocks used in the design were as follows:

- *VDMA (Video Direct Memory Access):* To make the link between the microprocessor and memory and then between the Video In and Video Out blocks.
- *Video in to axi4-stream:* Entrance block, receiving sensor data.
- *Axi4-stream to video out*: Exit block that transfers data to HDMI/VGA outputs for visualization.
- *VTC:* Block that detects and generates pixel flows.
- *AXI Interconnect:* It is a block that connects one or more master devices mapped in memory to one or more slave devices mapped in memory.
- *AXI Quad SPI:* Connects the AXI4 interface with the slave SPI blocks that supports the Dual or Quad SPI protocol.

The developed sensor card was connected to the Zedboard (DPGA from Digilent) via a deported and very flexible connection.

2.3 MSFA design

2.3.1 Architecture of the filter

The Fabry-Perot theory was used to create the filter array. The approach is called Color Shade. Due to several constraints, the MSFA was designed in the to solve the problem of energy balancing which is generally the weakness of MS imaging systems [Tho17]. In several Multispectral Systems the problem of energy balancing can be solved by acting on either the bandwidth of the amplitude of each filter element. So to overcome to this weakness, a complex distribution of the MSFA distribution was proposed. Fig. 2 presents a basic MFSA used in this project.

P1	P5	P2	P6
P7	P3	P8	P4
P2	P6	P1	P5
P8	P4	P7	P3

Figure 2. Spatial Distribution for MSFA moxel.

2.3.2 Band selection

The test was carried out using 1269 matt Munsell spectral reflectance data. A white noise of SNR=100 has also been added to the data. The bandwidth is constant and equal to 30 nm which is a good compromise of an overlap filter and a narrow one. All data rearranged between 380-780 nm with 5 nm intervals. Fitness function was ΔE2000 between Wiener filter estimation the actual Munsell spectral data.

3. RESULTS AND DISCUSSION

3.1 Image sensor

Figure 3 shows the spectral response of the E2V sensor. The spectral response was done by projecting light to the sensor by wavelength steps of 5 nm. This figure shows the sensitivity of the sensor for different wavelengths. This spectral response of the sensor should be taken into account for assembly of the MFA and image reconstruction.

The performance of the whole camera and sensor board is observed in Fig. 4. This figure represents the gray-scale images taken by the image sensor which means that the data has been collected well, converted and constructed the image correctly.

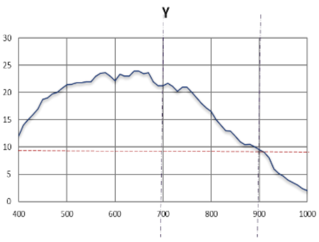

Figure 3. Spectral response of EV76C570 sensor and its impact on the MSI camera.

3.2 MSFA

The statistical results of RMS and goodness of fitness coefficient (GFC) error metrics of the spectral data were calculated. Mean of RMS error for 7 and 8 selected filters exhibit 56 percent improvement in comparison with the 3 selected filters. Moreover, 99% of the reconstructed data using 7 or 8 selected filters have been able to provide a GFC ≥ 0.95.

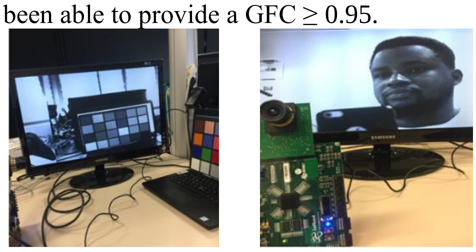

Figure 4. Online imaging using the camera.

When applying the filter on the CMOS, the global response is obtained by spectral response of each filter. We observe that the impact of the sensor leads to amplify the difference between different filters. The central filters are less impacted, while the extreme filters are mitigated (Fig. 5).

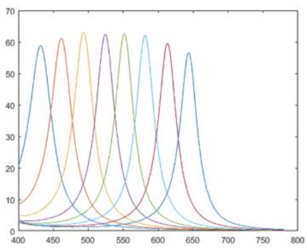

Figure 5. Set of 8 filters without the sensor

4. Conclusions

In this work, a MS camera was developed to be used for different computer vision applications including agricultural systems for weed detection or fruit ripeness estimation. The aim of the study was to prepare the image sensor, the firmware and software and the MSFA for the development of cheaper and faster MS cameras. A monochrome CMOS sensor was used as the camera sensor and its spectral response was evaluated. For the creation of the MSFA, the Fabry-Perot theory was utilized. A distribution of the MSFA was proposed including of 4x4 pixels, with a total of 16 pixels. The best combination of wavelengths was carried of using genetic algorithm. Mean of RMS error for 7 and 8 selected filters exhibit 56 percent improvement in comparison with the 3 selected filters. The camera works properly and an amount of 99% of the reconstructed data using 7 or 8 selected filters have been able to provide a GFC of more than 0.95.

5. ACKNOWLEDGMENTS

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