A GRADUATE LEVEL COURSE ON IMAGE SENSORS AND DIGITAL CAMERAS

Abbas El Gamal and Ting Chen

Information Systems Laboratory
Department of Electrical Engineering
Stanford University
Stanford, CA 94305
{abbas, tingchen}@stanford.edu

ABSTRACT

A graduate level course on the design and analysis of image sensors and digital cameras is described. The course uses a MATLAB based camera simulator. Information on the course and brief descriptions of several class projects are presented.

1. INTRODUCTION

Digital cameras are rapidly replacing film cameras as the preferred image capture devices. As a result major efforts are being spent on improving digital camera design. In particular CMOS image sensors are emerging as an alternative to CCDs. Using CMOS technology, image capture and processing can be integrated on a single chip, enabling many new imaging applications that require low cost, low power, and small size. The use of CMOS technology has also been attracting many new engineers and researchers to the field of image sensor and digital camera design. This field, however, has traditionally been highly specialized and proprietary with very few textbooks and research publications available and almost no courses developed. Another aspect of digital camera design that makes it difficult to research and teach is the breadth of the background needed. The study of digital camera system design requires some working knowledge of optics, photometry, device physics, circuits, noise analysis, color science, and image processing algorithms and architectures.

To satisfy the needs of interested Stanford graduate students we developed a one-quarter course on the design and analysis of image sensors and digital cameras. This paper will summarize the objectives, prerequisites, and syllabus of the course. We will describe a camera system simulation tool (vCam) that we developed as part of our research and used in the course. We will also provide several example course projects that used vCam. More information on the course can be found on the class webpage [1].

2. COURSE OBJECTIVES

The course objectives are
(i) to provide an introduction to the design and analysis of image sensors especially CMOS imagers,
(ii) to develop basic understanding of the signal path through digital camera,
(iii) to develop understanding of the performance measures and tradeoffs involved in the design of sensors and digital camera systems, and
(iv) to have fun using many basic EE knowledge to understand a "cool" system.

3. COURSE CONTENT

The course is intended for graduate students with interest in image sensors and image system engineering, *e.g.*, image processing, digital photography, computer vision, and graphics. Undergraduate level device, circuit, signal and system background is required for successful completion of the course. Due to the diverse and up-to-date nature of the topics covered, the course has no required textbook. Instead, a complete set of lecture notes has been developed. Course requirements include: weekly homework assignments, a take home midterm, and a class project. The homework and midterm exam problems require a mixture of hand analysis and simulation using MATLAB and vCam. The project involves either pre-assigned or self-pursued topics and usually requires three to four weeks to complete for students grouped in pairs.

Lecture topics include:
1. Photodetectors: photodiode and photogate; photocurrent, dark current, quantum efficiency, and spectral response.
2. Introduction to CCDs and CMOS passive and active pixel sensors
3. Noise analysis, sensor signal-to-noise ratio (SNR), and dynamic range.
4. Fixed pattern noise.
5. Spatial resolution and modulation transfer function.
6. Introduction to imaging optics.

7. Color Processing: color demosaicing, color correction and white balance.
8. Analysis of digital camera signal path, from the scene through the imaging optics, the sensor, the A/D converter, to the different color processing steps using vCam, a MATLAB based digital camera simulator.
9. Recent research topics, *e.g.*, digital pixel sensor and high dynamic range schemes.

4. DIGITAL CAMERA SIMULATOR

A digital camera, as depicted in Figure 1, is a complex system comprising components that use different technologies. Given the complexity of the system, simulation tools are needed to study any design tradeoffs and their ultimate effects on image quality. To the best of our knowledge no such simulation tools are commercially available. To adress this need, we developed our own camera simulator (vCam). Figure 2 shows vCam's imaging pipeline. The simulator provides models for the scene, the imaging optics, and the sensor. The simulator is written in MATLAB and is modular to facilitate future modifications and extensions.

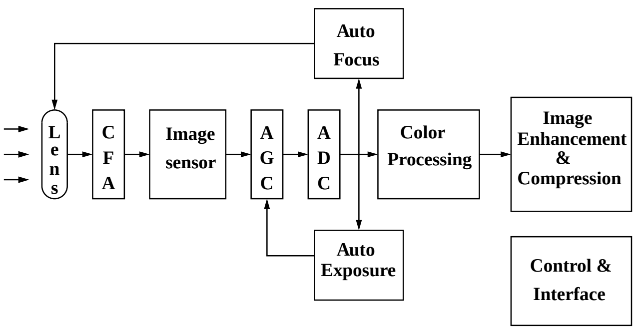

Fig. 1. Block diagram for a typical digital camera system

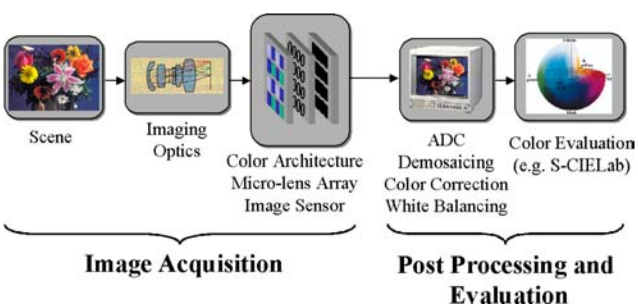

Fig. 2. vCam imaging pipeline

5. SAMPLE COURSE PROJECTS

An important requirement for the course is the final class project. Each year we proposed one or two projects that the students did in pairs. Most projects required the students to use vCam as a tool for optimizing or comparing design options. Several projects have been pursued further by the students resulting in a number of research publications. The following are brief descriptions of the most recent projects.

5.1. Pixel size study

An important parameter in the design of an image sensor is the choice of pixel size. A small pixel size is desirable because it results in a smaller die size and/or higher spatial resolution, while a large pixel size is desirable because it results in higher dynamic range and signal-to-noise ratio. We asked the students to investigate this tradeoff analytically and using vCam. This project was pursued further resulting in a conference paper [2].

5.2. High dynamic range schemes

An important figure of merit for image sensors is dynamic range, *i.e.*, the range of illumination that can be captured in a single image. Several schemes have been proposed to enhance CMOS image sensor dynamic range. The purpose of this project was to compare the performance of these schemes based on SNR and image quality using vCam. The projects confirmed the results of the hand analysis in [3].

5.3. "Honey Comb" pixel array

Fuji Film recently introduced a new CCD image sensor [4], which they called "Honey Comb" CCD. The main motivation for this structure is to enhance spatial resolution without increasing the number of pixels or die size (cost). The goal of this project was to use vCam to validate (or dispute) the claimed advantage of the "Honey Comb" array structure over the conventional rectangular pixel array. The projects have shown that for scenes with mainly vertical and horizontal spatial structures, the "Honey Comb" pattern is indeed better. No advantage was observed for other types of scenes.

6. REFERENCES

[1] "Introduction to Image Sensors and Digital Cameras," in *http://www.stanford.edu/class/ee392b*.

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