

Physics 402 Laboratory

Experiment D-9

COMPUTER OPTICS WITH CCD CAMERA

References:

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3. F. A. Jenkins, H. E. White, *Fundamentals of Optics*, 4th ed., pp. 191-192, McGraw-Hill, New York (1976).
4. C. Harris, *Silicon Eye: A CCD Imaging System*, Sky and Telescope, April 1986, pp. 407.
5. P. Horowitz, W. Hill, *The Art of Electronics*, 2nd ed., pp. 998-1001, Cambridge University Press, Cambridge, Massachusetts (1989).
6. Manual for CCD Camera Controller, Photometric Ltd. (on file).
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Introduction

The purpose of this experiment is to study the focusing characteristics of a CCD camera, nature of its dark current, and the relationship between $f \#$ and the intensity.

A CCD (charge-coupled device) is an optoelectronic sensor that converts optical energy to electrical energy. During the exposure the incident photons are converted into electron-hole pairs in a semiconductor material (usually silicon). The electrons are accumulated in the depleted zone created by means of a photodiode or a MOS (Metal-Oxide-Semiconductor) structure, while the holes are recorded in the substrate. This photodiode or MOS structure represents one element of a one-dimensional or two-dimensional array of such elements. The

photoelectrons from each of the photoelements are stored in their respective MOS capacitors. After the exposure, the accumulated charge on each MOS capacitor is transferred sequentially to a readout stage where the amount of charge is converted to a proportional voltage signal. These analog voltage signals are converted to digital signals (binary numbers) by an analog-to-digital converter and stored in the computer memory. If an image is formed on the CCD by using a lens, then the image is stored in the computer memory and is reproducible by proper programming.

CCDs are more efficient than photographic film. Quantum efficiency is defined as a ratio (expressed in percent) of the number of collected photoelectrons to the incident photons on the photoelement area. In a film it is usually a few percent but in CCDs, as high as 80% is achieved. Also a CCD's response is directly proportional to the exposure time whereas a film's is nonlinear. Dynamic range is a measure of detector's response to the very low and very high light intensities. In a film it is only a factor of few hundred but a CCD may have a range over 5000.

When the temperature of a CCD rises about 32°C, the rate of thermal electrons is increased by a factor of 10 and it contributes to dark current or noise. In one part of this experiment, liquid nitrogen (temperature ~ -196°C) is used to reduce the temperature of the CCD, and in turn its dark current, to study the effect of dark current.

Experimental Apparatus

The apparatus includes of a PowerMac 7100/80AV computer with a CCD controller card, PS200 power supply for the camera control system and IP Lab commercial imaging software. Imaging software is user-friendly and a few tutorials come with it to familiarize the user to the software.

The CCD camera has a variable focal length (zoom) lens system with 3 ring-adjustments: one for aperture size ($f/\#$ ¹ from 4 to 22), one focusing ring to adjust the object distance (0.45 m to 2 m), and a "zoom" ring to adjust the focal length ($f = 35$ mm to 80 mm) of the system (without changing the location of the focal plane). The CCD array (an integrated circuit chip - Thompson's TH7882 - with array size of 384x576) itself is embedded on a heat sink inside a cryogenic dewar which has an opening on the top to fill with liquid nitrogen. The camera has an external heating element which is regulated by a thermoelectric cooler. The thermoelectric cooler has a digital readout to display the temperature of the CCD. The attainable final temperature is at least 150°C below the ambient temperature. The camera also has an electronic shutter whose speed is controllable from the computer.

¹ $f/\# = \text{focal length (f)} / \text{diameter of lens (D)}$.

Observe caution when using liquid nitrogen. Permanent eye damage may result if the eye contacts directly with liquid nitrogen. Wear protective goggles or glasses and gloves during filling. Exposure of liquid nitrogen to skin may cause painful frost-bite.

Part I. Getting started

The system is turned on by switching on the outlet strip at the rear of the rack. The PS200 power supply unit has a switch at the rear and turn it on if necessary. Press the 'on' key of the PowerMac, located at the top right corner of the keyboard to boot the computer. Double click with the mouse on the folder 'CCD EXPT' and then the 'IPLAB Spectrum H-SU2' folder. A new menu panel will appear. In the 'Control' menu select 'Acquire' to take a picture. A new panel will appear. Select 'Expose' function, and click on the readout function with 384x576 (wxh). Exposure time is adjustable; start out with 50 ms initially. There are 2 modes: full mode (384x576 pixels) and frame mode (384x288). Start out with the full mode.

To make a picture remove the lens cap and adjust the f-number and the focus to approximate positions. When you click the mouse you will hear the camera click, and shortly thereafter an image will appear on the monitor. You can then play with the focus and the f-stop to get a good image. You will notice that the image is brighter at the bottom. This is caused by dark current, which will be discussed later.

The image is made up of 221,184 pixels (384x576). The origin of the image is at far left top corner and its pixel is designated as (0 x 0). Each pixel has a value assigned to it representing intensity of light. The computer can display these pixels on the monitor as well as perform operations on the numerical data array.

Part II. Focusing the camera

Consider the operation of a camera lens. Its job is to produce an image at the film plane which remains fixed. This is done by moving a part of the compound lens, effectively moving the principle plane of the lens back and forth. In the thin lens model the entire lens moves.

When the focusing ring is set to 1 meter, it means that an object 1 meter away from the lens will be in focus AT THE FILM PLANE. As it turns out, the CCD array does not sit at the film plane. Consequently the reading on the focusing ring differs from the actual distance of an object in focus. From the following equations, derive an expression for S_{or} [or for $\frac{1}{(S_{or} - f)}$] as a function of S_{oc} , f , and x . S_{oc} is the object distance indicated on the focusing ring, and S_{or}

is the real object distance. S_i is the distance from the lens to the nominal film plane. f is the focal length of the lens, indicated on the zoom lens focussing ring (start out with a focal length of 50 mm). x is the distance from the film plane to the CCD array. x , as defined, is positive when the CCD array is further from the lens than the film plane. See Figure 1.

$$\frac{1}{S_{oc}} + \frac{1}{S_i} = \frac{1}{f} \qquad \frac{1}{S_{or}} + \frac{1}{S_i + x} = \frac{1}{f}$$

Or in Newtonian form:

$$(S_{oc} - f)(S_i - f) = f^2; \quad (S_{or} - f)(S_i + x - f) = f^2.$$

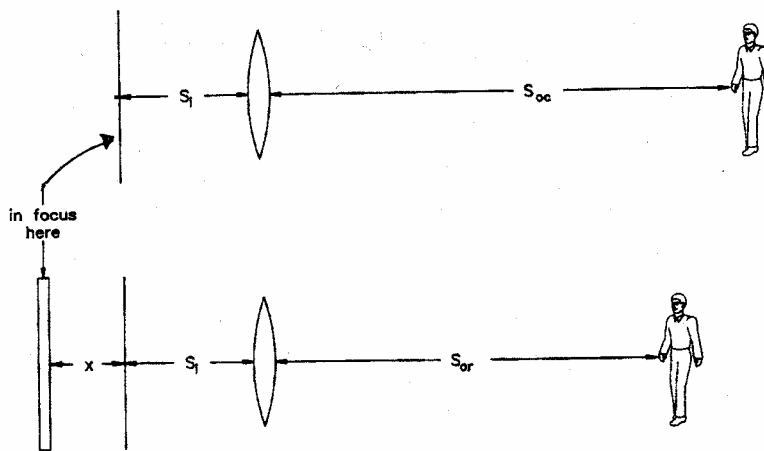


Figure 1. Description of experimental parameters.

Experimental Procedure:

Set up the camera with $f = 50$ mm at one end of a raised optical bench with a target (see Figure 2). Set the focusing ring to one of the calibrated points and start snapping away. Move the target back and forth until it is in focus. In this way you can plot S_{or} versus S_{oc} [or $1/(S_{or} - f)$ vs. $1/(S_{oc} - f)$]. Two notes:

- 1) Use as small an f-number as possible, and explain why you should.
- 2) Try to get data up to about $S_{or} = 2$ m.

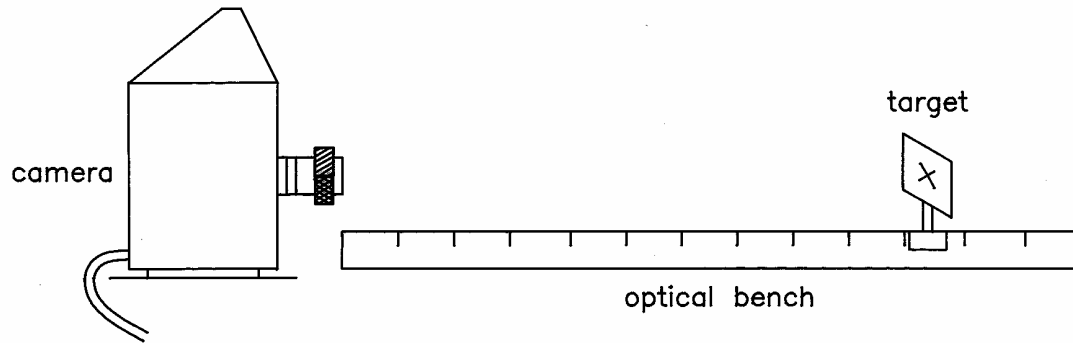


Figure 2. "Focusing the Camera" set-up.

Now by trying different values of x you can fit the equation you derived to your data. Now you can answer: Where is the CCD array with respect to the film plane? What is the uncertainty? How must the focusing ring be set to focus an object at infinity? If f were changed to 80 mm, how must the focusing ring be set to focus an object at 1 meter? Test your result.

Part III. Dark Current

The CCD array is sensitive to heat as well as light. For normal use the camera will be cooled to -150°C to reduce the temperature sensitivity. In this experiment, however, we are interested in these effects.

The CCD array is zeroed most of the time, so there is no dark current. When the shutter opens the dark current begins to flow. The shutter closes and the computer begins to read out the CCD array, starting at the top. By the time it gets to reading out the bottom of the array, the dark current has increased the charge in those pixels. This is why the image is brighter at the bottom.

Experimental Procedure:

By using the exposure time box you can specify the exposure. Leave the lens cap on. Take pictures at different exposure times up to about 2 seconds. Read the absolute pixel count at different rows of the image. Plot the absolute pixel counts versus row number. Do not take any data from the top few rows or the left few columns. There are transient effects.

The number of counts at row zero (extrapolated - remember: do not use the top few rows) should be directly proportional to the exposure time. In addition, the slope of the line gives you a relation between the number of counts

and the row number. From this information, calculate the time needed for the computer to read out and image (576 rows).

Notice that there is an absolute maximum number of counts. This is the saturation level. It will give you how many bits each pixel value is composed of (Note: counts = 2^n , where n is the number of bits of resolution of the image card). Find this n.

Optional: Investigate the variation of dark current with temperature. The blue box on the camera tripod has a digital display for the temperature of the CCD array. It also has a potentiometer that can control the temperature. Start to cool the camera by pouring in liquid nitrogen and plot counts versus temperature for a given pixel.

Part IV. f/# and Intensity

You know the relation between f/# and intensity. Now you can test it experimentally. Cool the camera with liquid nitrogen until it reaches about $-150\text{ }^\circ\text{C}$. Take pictures of a blank wall using different f/#s. Plot f/# versus absolute pixel counts to get a straight line. Change the lighting and plot another line. Do the two lines intersect where you expect them to?