Report on Imaging Instructional Materials being worked on November 2002

The attached materials are lecture and laboratory modules that are being developed to enhance the imaging content of our electro-optic sequence. These materials were used last semester [Spring 2002]. Modifications and additional laboratory experiences are being developed this semester.

Original Files are being developed in "Mathcad" a "MathSoft" product. It was decided to use "Mathcad" as a laboratory analysis tool for these modules because it allows the student to see both the image result and the numerical manipulations performed upon the image matrix.

All of the attachments have been printed as adobe PDF files so that the contents of these instructional files can be accessed by individuals not having the Mathcad software.

To prepare students for this portion of the course sequence the course structure introduces Mathcad early in the semester this insures proficiency with the software's basic functions prior to encountering these modules.

These attached modules are:

Lecture Materials Chapter Nine which is one of two "Chapters" that form part of the text materials used throughout the Electro Optics course:

Chapter 9 Image Detectors
Chapter 10 Color Images

Laboratory Materials Laboratory One which is one of five laboratory exercises

Laboratory Exercise One Explores the structure and modification of a Gray Scale image. Files are:
L1
L1_Theory
L1_Example

Laboratory exercises that are under development include:

Laboratory Exercise Two Used in spring of 2002 and being modified. Drills concepts developed in Laboratory One and introduces the structure and modification of an RGB color image. Files are:
L2
L2_Theory
L2_Example

Laboratory Exercise Three Used in spring of 2002 and being modified. Drills concepts developed in exercises one and two and introduces ASCII code. Files are:
L3
L3_Theory
L3_Example
L3_Example_Decode

Laboratory Exercises Four and Five use cameras and materials purchased during the late spring and summer of 2002. These exercises are under development, both will involve the use of a CCD camera to acquire and analyze images. Accuracy of measurement and the comparison of pre-laboratory predictions to observed and measured results will be the skills developed. Laboratory Four will demonstrate the measurement of a diffraction pattern formed on a "bare" CCD sensor. Laboratory Five will be a more conventional camera with lens measurement of a physical object.

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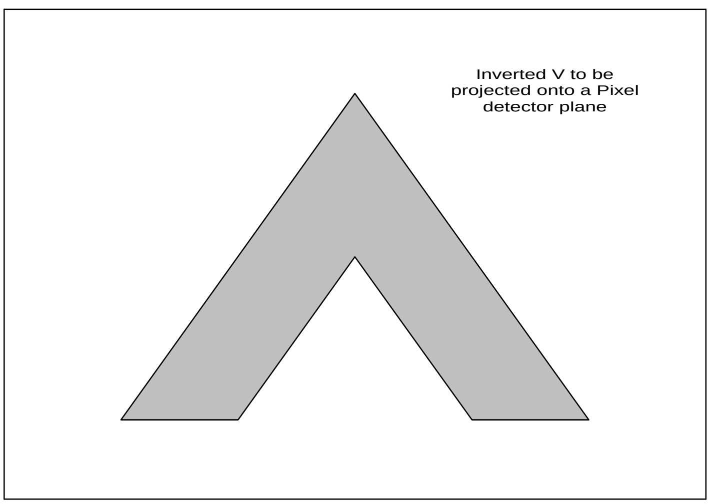
Chapter 9 Image Detectors

Introduction:

An image detector is an array of detectors that are similar in many respects to a simple radiation detectors. These detectors are generally quantum detectors with a quantum efficiency less than one and a limited line width. Each individual detector will produce a signal that is proportional to the total radiation that is incident on it within its line width. One detector represents the smallest resolvable feature of the image that falls on the array. This smallest element is called a pixel. The examples below are intended to help you develop a sense of what a pixel is, and how pixel size relative to image size affects the fidelity of the rendered image. In all cases below we will assume that the display device has infinite resolution, and pixels of zero physical dimension! All distortions will be due to the resolution of the image detector.

Example Images:

A simple inverted V will be used as the illustrative image. The inverted V being opaque and the surrounding area transparent.



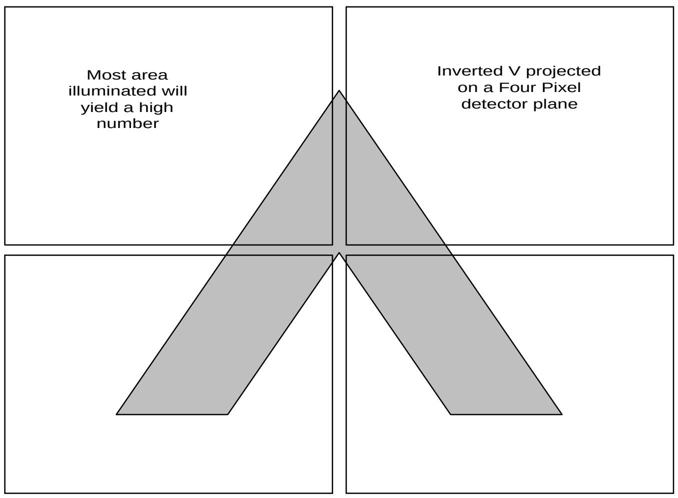
The first image will be the result of projecting the inverted V onto an image detector which has four detecting elements. Notice in the image below that the image is optically formed on the image plane with great fidelity. Problems in fidelity of reproduction will arise not from the optical system but rather from the pixel limitations.

The top two detectors or pixels have a much larger portion of their surface illuminated than do the bottom two detectors. We can expect that the top two detectors will produce a larger signal. This signal will be reproduced as a digital number in binary format.

A common image format is *.bmp. In this format each pixel in a two dimensional array is assigned an eight bit binary number. The largest decimal number possible in this format that starts at zero is 255.

$2^7 + 2^6 + 2^5 + 2^4 + 2^3 + 2^2 + 2^1 + 2^0 = 255.000$ Or $2^8 = 256.000$

In this system 255 represents white and 000 represents black. All other numbers represent successive shades of gray. There are 256 possible levels.



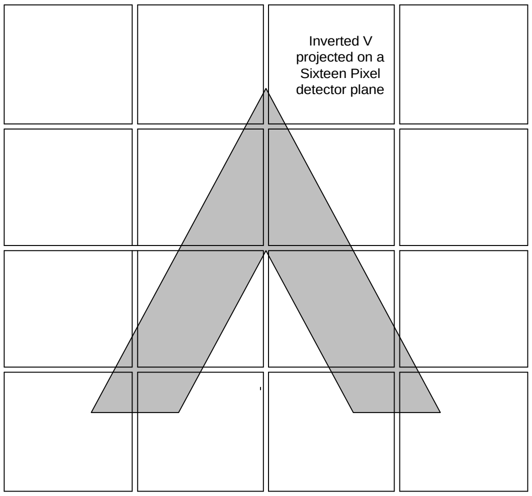
The image when projected on a four pixel array causes the matrix d1x illustrated below.

$$d1x = \begin{pmatrix} 230 & 230 \\ 198 & 198 \end{pmatrix}$$

When this matrix is reproduced on an image display device it looks like this: Note the inactive areas between detectors have been ignored in creating the displayed image.

Not a very good rendition of the original image, even though the optically formed image was perfect.

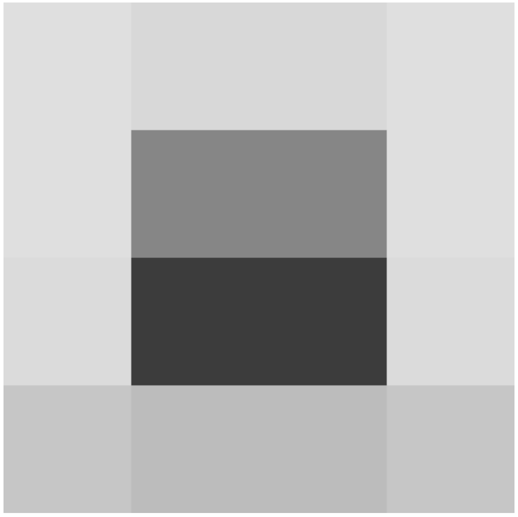
We can try and improve the image fidelity by creating a detector with more and smaller pixels. If we divide each of the original four in half, both horizontally and vertically, we will have a sixteen pixel array.



The sixteen pixel array will produce the matrix d2x below.

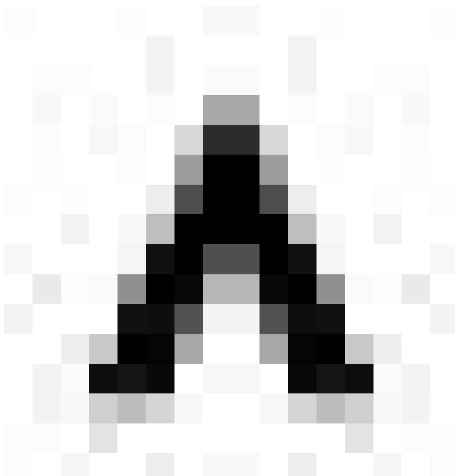
$$d2x = \begin{pmatrix} 255 & 248 & 248 & 255 \\ 255 & 166 & 166 & 255 \\ 251 & 92 & 92 & 251 \\ 230 & 220 & 220 & 230 \end{pmatrix}$$

This matrix will result in the image shown below. Fully illuminated pixels yield a value of 255 partially shaded pixels yield lower numbers representing different shades of gray



We are still clearly a long ways from having enough resolution to produce a good rendition of the original shape.

If we again divide all pixels in half, both vertically and horizontally, we will have an array with 256 pixels, 16 per side. This will result in the improved, but far from perfect, rendition below. The problem is not the total number of pixels but rather the total number of pixels available to reproduce the image of interest. In this case somewhat less than 144 of the 256 pixels are involved in actually detecting image information. The remainder are empty white space. In any imaging application the real issue is the number of pixels needed to reproduce the primary features of the image formed on the plane of the detector.



For high fidelity rendition, a pixel should be no larger than one percent of the smallest horizontal or vertical dimension of the major features of the projected images.

The original inverted V image was designed so that the base of each leg is one sixth of the total image width. Good rendition would require a width of 600 pixels or an array with: 360, 000 pixels.

The *.bmp image used at the top of this document has a resolution of 728 by 728 pixels or 530 ,000 total pixels.

The smaller the image detail is the greater the number of sub detectors required on an image plane to resolve the detail.

Suppose you had a satellite in an orbit 5 km (3.1 mi) above the surface of the earth with an angle of view of 10 deg. This system would resolve a field of view of about 437 meters radius, an area of 0.6 km^2. If you wanted to resolve objects of one meter you would need a detector with more than $7.6 * 10^9$ elements! Spy satellites can be effective but they will not be cheap!

Calculations to verify the above assertions:

$r := 5 \cdot km \cdot \tan\left(\frac{10 \cdot deg}{2}\right)$ $r = 437\,m$ projected radius

$area := \pi \cdot r^2$ $area = 0.601\,km^2$ field of view

$N := \left(2 \cdot r \cdot \frac{100}{m}\right)^2$ $N = 7.654 \times 10^9$ number of detector elements

Note: 100 elements per meter

Image detectors are built in multiples of 256 elements for practical reasons having to do with digital coding. This leads to the sizes listed below:

$256 \cdot 256 = 6.553600 \times 10^4\,pixel$

$512 \cdot 512 = 2.621440 \times 10^5\,pixel$

$1024 \cdot 1024 = 1.048576 \times 10^6\,pixel$

$2048 \cdot 2048 = 4.194 \times 10^6\,pixel$

$4096 \cdot 4096 = 1.678 \times 10^7\,pixel$

As detector size increases the time required to read the pixel values also increases. This controls the "frame rate" of the detector. The frame rate is the total time required to obtain the image and includes exposing the detector long enough for it to respond and then reading the pixel values out into the attached digital system. A 512 x 512 array with a 2 MHz readout rate can only run about eight frames per second.

The frame rate problem is quite similar to the rate at which you can take pictures with a conventional photographic film based camera. You have some finite exposure time and then a time to wind exposed film out and new film in. The frame rate is similar, you must "expose" the detector, readout the values and reset the detector to zero.

The readout and reset time generally far exceed the required exposure time and numerous schemes are used to try and speed up read outs. Unfortunately many of these schemes use up surface area on the image plain and so degrade the image. In the drawings above you will note that there are spaces between the pixel elements and any information that falls on these spaces is lost. The "fill factor" is an important parameter of a detector array. Fill factor is the percentage of the array area given over to active detector surface. Fill factors of above 90% can be obtained at the expense of readout time. Very fast arrays often have fill factors less than 45% and so there is a trade off between frame rate and image fidelity.

Detector types:

The most common type of detector is the Charged Coupled Device CCD. The pixels on these devices are quantum detectors that convert incident photons to electrons and store them as an electric charge. The pixels are capacitors and the have quantum efficiencies that approach 100%. This of course means that incident power at long wavelengths causes a much bigger response that will incident short wavelenght energy. Like diode radiation detectors some sort of filtering is needed if a "flat" color response is desired. When the image is read out the capacitors are "discharged" to prepare for the next exposure. A shutter is used during the charge readout stage.

The material used determines effective detector line width with the same types of materials being used for CCD arrays as are used for diode detectors. Silicon is most common and used for the range 380 nm to 1100 nm which includes the visible.

Near IR detectors are fabricated out of platinum silicide PtSi, indium antimonide InSb. Some of these detectors are CCD arrays while others use diode arrays. With the arrays available, images can be acquired between 1500 nm and 30000 nm; just not with the same array! Arrays have also been constructed using microbolometers; where the readout circuitry reads the change in resistance, very wide spectral line widths and flat responses can be obtained with this technology.

Every sort of optical detector known has been tried in an array but by far the most common are CCD detectors. The CMOS process (complementary metal oxide semiconductor) is also being used to build array detectors out of silicon. These arrays tend to have all the necessary preliminary circuitry on the same chip as the array. CMOS devices have a smaller dynamic range than CCD detectors but they have the potential of being cheaper than CCD devices. It is expected that CMOS arrays will become the dominant type in applications that do not require the dynamic range available in the CCD technology. Other array types are being used primarily for long wavelenght IR work, where silicon's spectral characteristics are deficient.

Practical Considerations:

A representative CCD pixel would be 20 μm or less on a side; so a common 512 x 512 array would have an active area with a side dimension slightly larger than 1 cm and an area of about 105 mm^2.

Problem: Estimate the smallest object that can be resolved with high fidelity if the optical system has an angle of view of 30 deg and the focused field of view is at a distance of 3 m.

$\Theta v := 35 \cdot deg$ $\quad$ $Z := 3.5 \cdot m$

$$S := \pi \cdot \left(Z \cdot \tan\left(\frac{\Theta v}{2} \right) \right)^2 \qquad S = 3.826\,m^2$$

$$dia := 2 \cdot Z \cdot \tan\left(\frac{\Theta v}{2} \right) \qquad dia = 2.207\,m$$

A target with a diameter of 2.207 will fill the entire 512 pixel dimension, therefore:

$$\delta L := \frac{2.207 \cdot m}{512 \cdot pixel} \qquad \delta L = 4.311 \frac{mm}{pixel}$$

Following the argument we used above we need more than one pixel to represent an object with fidelity. If we chose a one percent rule. This would mean that the smallest object from this scene we would expect to be distinct would have a dimension of about.

$L := 100 \cdot pixel \cdot \delta L$ $\quad$ $L = 431.055\,mm$ $\quad$ nearly half a meter!

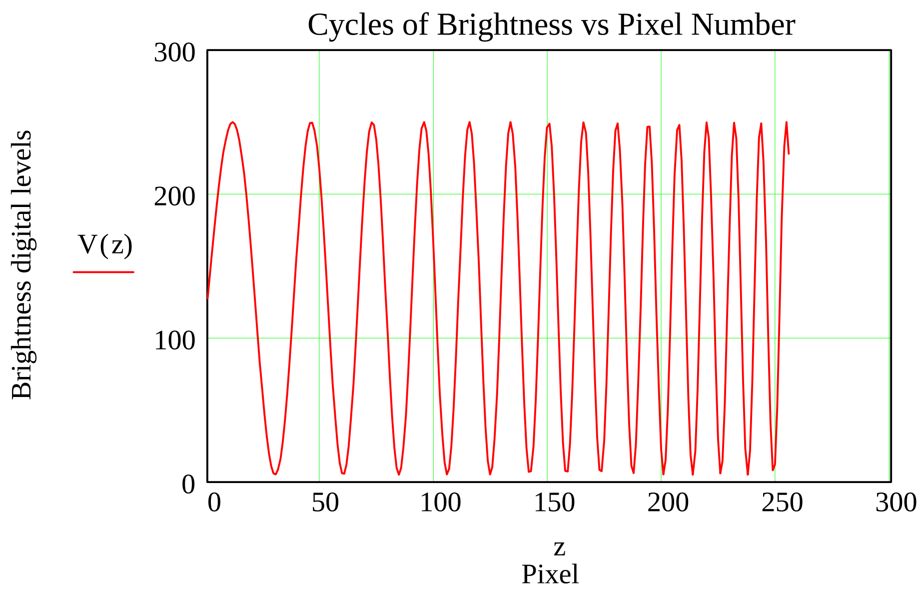
If we chose a 10% criteria we would end up with a dimension of 43 mm or a little more than an inch and one half. The truth would lie somewhere in between. The point being the pixel size ultimately limits the resolution of the detail of any image.

Spatial Frequency

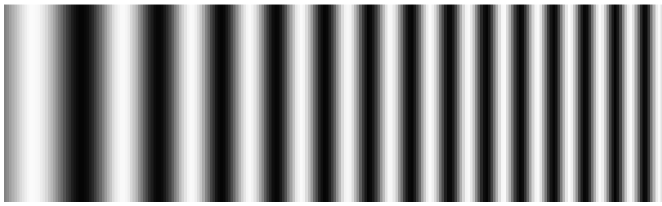
The term spatial frequency is used as a way to characterize the complexity of an image or the potential for fidelity of a detector or reproduction technique.

Your probably more familiar with the idea of electrical frequency; cycles per second of voltage or current. Spatial frequency is similar except the cycles are not measured per unit time but rather per unit distance. Lines per mm is a common unit of spatial frequency.

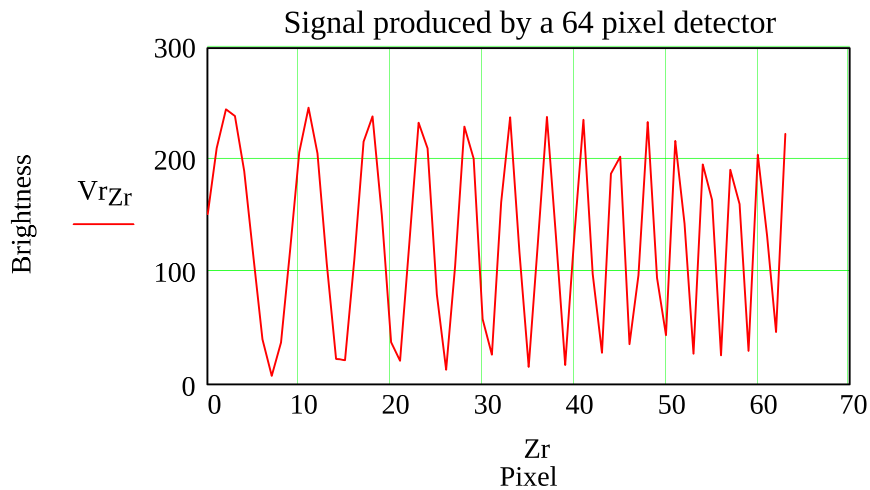
A complex image with many changes from dark to light over a short distance will have high spatial frequency content. Where as an image of a uniformly illuminated flat surface will have zero (dc) frequency content. Most images have regions of high and low spatial frequency content. A detector with a large pixel density will reproduce high spatial frequency with greater fidelity than will a detector with fewer pixels per unit area. This is illustrated by the images below.

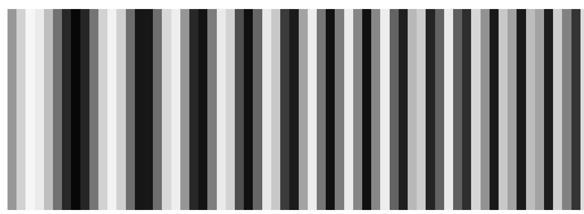


The graph above illustrates brightness cycles imaged onto a detector with 256 horizontal pixels. For illustrative purposes the signal has a varying frequency that increases from left to right. The picture below illustrates the detectors displayed output.



If the same image were focused onto a detector with 64 horizontal pixels, a 4:1 reduction, your would obtain the results illustrated below. Note the relative compression of the higher frequencies and the distortion of the wave shape.





The picture illustrates the choppy appearance of the sine wave peaks and the decreasing intensity from left to right as spatial frequency increases.

<u>Summary:</u>

The pixel is the smallest element of an image, the fidelity of reproduction is a function of the pixel size relative to the size of the feature being reproduced on the image plain. The smaller the pixel is relative to the feature the higher the fidelity of reproduction.

This fidelity is sometimes characterized in terms of the spatial frequency of the image. Low pixel counts will attenuate the higher frequency content and distort the original signal.

High fidelity comes with not only a higher economic cost but also a slower frame rate. It takes longer to extract the image data from a high pixel density detector array.

Calculation Problems:

1) A detector has 64 pixels on a side and is used with a lens system that has an angle of view of 20 deg focused at a distance of 4 m. What unit of length does one pixel encompass?

2) Your detector is 4096 x 4096 pixel array. If you want to resolve a one meter distance with at least 20 pixels from an altitude of 3 miles what focused angle of view will you use? How big will the field of view be?

3) If the dynamic range of you detector is 3000:1 and you are going to map amplitudes to an eight bit system (0 -255).
A) If each change of one represents the same change of flux how many flux units does each step represent?
B) How much greater is the average flux level at eight bit 200 than it is at eight bit 20?

4) If a detector has a quantum efficiency of 87 from 400 nm to 980 nm. How much bigger is the signal caused by one microwatt at 980 nm than the signal caused by one microwatt at 400 nm?

5) A detector and its Analog to digital conversion circuit has been set up so that the brightness area on the image will cause a digital number of 253 and the darkest area will cause a digital number 5. An white to dark edge crosses 10 pixels darkening the percent areas indicated in the list below. Determine the digital number that each pixel will generate:

Percent dark

$n := 0 .. 9$

6 On the attached Kodak data sheet Sensor # TH-7887A is specified at three different bit rates and their corresponding frame rates.

A) Convert each bit rate to the total number of gray levels.
B) Calculate the relative number of gray levels for each bit rate with respect to the eight bit rate.
C) Calculate the relative frame rate for each bit rate with respect to the eight bit rate.
D) What do you observe about the relative values?

L1 Gray Scale Image Modification:

Refer to attached documents: L1_theory and L1_example

Materials:

One faded Black and white photograph.
One Zip disk

Equipment:
Scanner
Computer terminal with Mathcad installed.

Objectives: To observe how altering the numerical values of an image's pixels can alter the perceived image. To observe how the brightness and contrast of an image change as the histogram of the image changes. To improve the appearance of an image by altering its pixel values using a linear function.

Procedure Refer to example file through out:
1) Create a folder on zip disk named L1.
1) Scan image and save a a "bmp" file in folder L1 on zip disk.
2) Open a Mathcad file and save it in folder L1 on zip disk as "L1_lastname.mcd"
3) Read image file into Mathcad using the READ_IMAGE command.
Example:

Q **:=** READ_IMAGE("Great-Grandma.bmp")

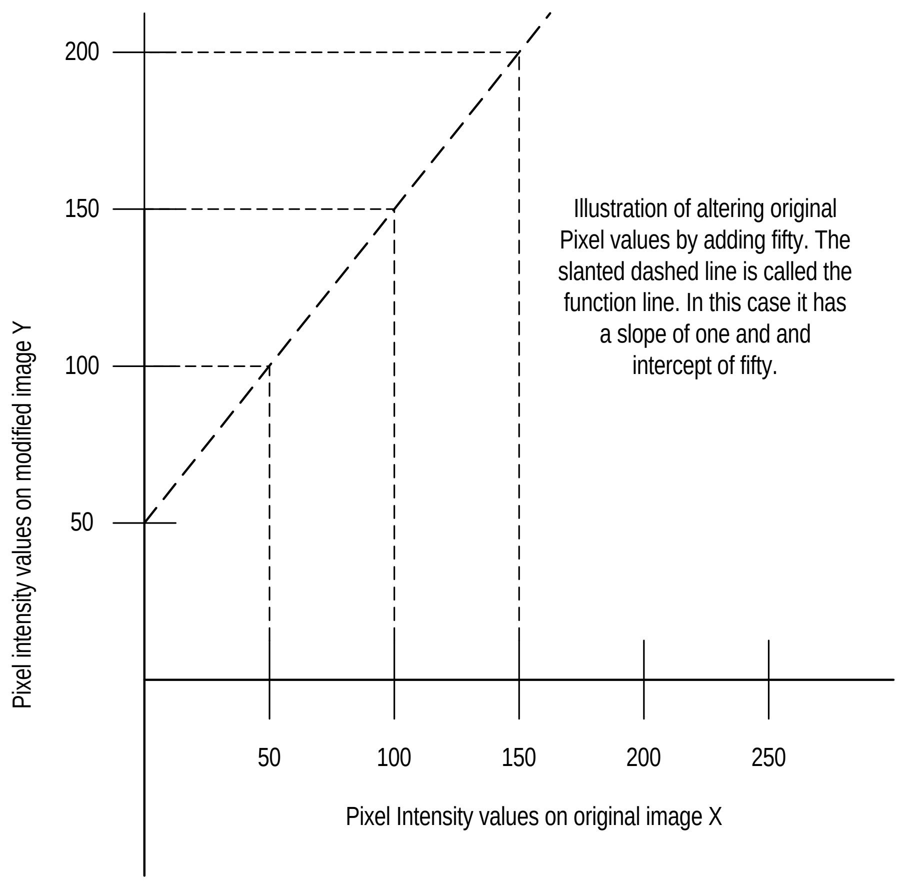
4) Use the insert Picture command to display image as a picture.
5) Determine the maximum and minimum pixel values of the image and create a histogram. Plot the histogram for the image.
6) Construct a straight line function to alter and improve brightness and contrast. Be sure your function does not cause any calculated values larger than 255 or smaller than zero.
7) Create a new image matrix using your function.
8) Use the insert Picture command to display the new image as a picture.
9) Determine the maximum and minimum pixel values of the new image and create a histogram. Plot the histogram for the new image.
10) You may have to experiment a little with the slope and intercept values of you function to optimize the final picture. An average brightness of 155 t0 165 generally yields and acceptable image. (Be sure you stay inside 0 to 255 range)
11) Hand in a print out of your work and the zip disk at the end of the period.

Key Mathcad commands you will use in this lab:
max min mean hist rows cols READ_IMAGE

Menu commands
Insert > Picture Insert > Graph File > Save As

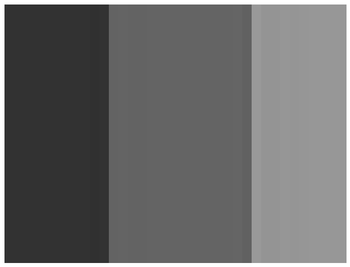
Theory for laboratory exercise L1

This document discusses and illustrates using the histogram approach to alter image brightness and contrast.

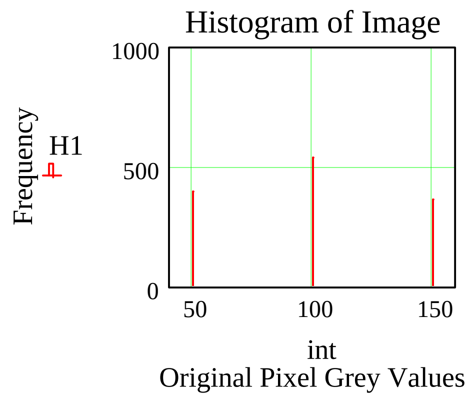


This process will be illustrated below with a simple image of vertical bars with gray scale values of 50, 100, and 150.

Original Image Pic1



Pic1

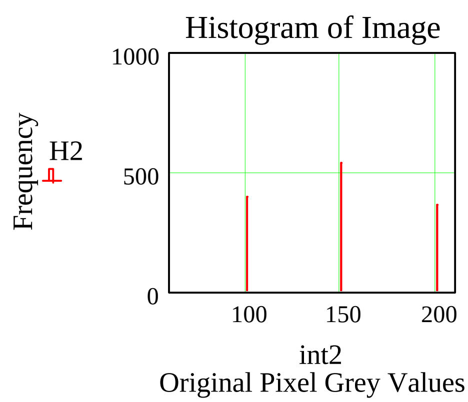


Add fifty to all image pixels

$$pic1_{i,j} = 50 + Pic1_{i,j}$$

Modified image pic1

pic1



Statistical parameters and images:

mean(Pic1) = 98.611 stdev(Pic1) = 38.163

mean(pic1) = 148.611 stdev(pic1) = 38.163

Note that adding a constant changes the average but not the standard deviation. The average brightness changes but the contrast difference between the bars remains constant. If you want to alter both brightness and contrast you must use transfer function line with a slope greater or less than one.

For the brightness change illustrated above the function used was:

$Y = X + b$ where b was the added constant.

To alter both brightness and contrast you would use the function:

$Y = m \cdot X + b$ where the slope factor m alters the contrast.

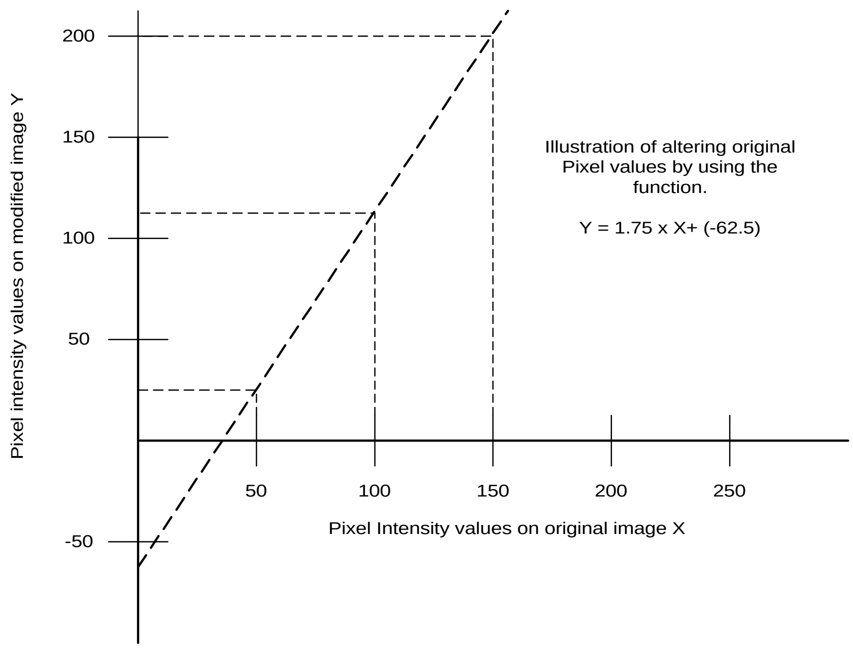
For example lets make it our goal that pixels that have a value of fifty get changed to 25 and those that have an original value of 150 get changed to 200.

$$200 = m \cdot 150 + b$$

$$25 = m \cdot 50 + b$$

therefore: $m := \frac{200 - 25}{150 - 50}$ $m = 1.75$

$b := 25 - m \cdot 50$ $b = -62.5$

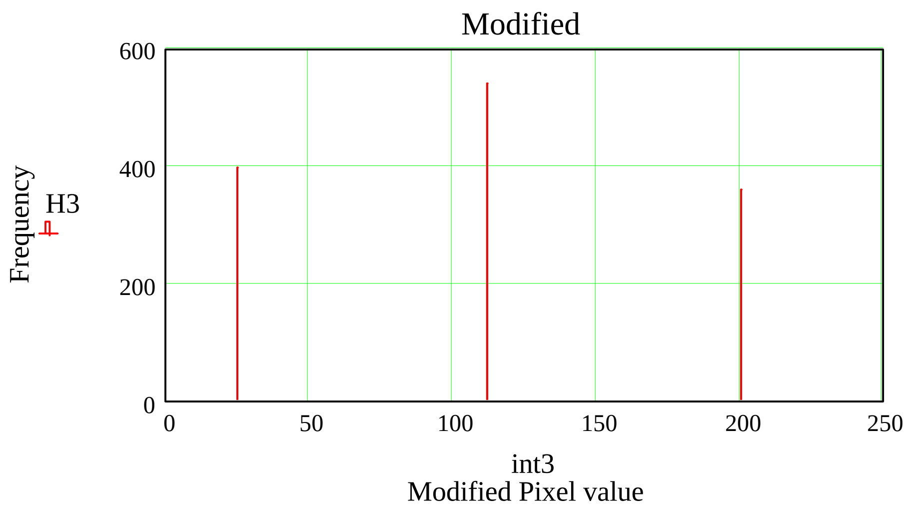


pic2

mean(pic2) = 110.069

stdev(pic2) = 66.785

Both average and standard deviation are changed by this transfer function.



L1_example: Great Grandmother enhance dress detail:

Q := READ_IMAGE("Great-Grandma.bmp")

Numerical parameters of image matrix

max(Q) = 77.000   min(Q) = 31.000   rows(Q) = 356.000

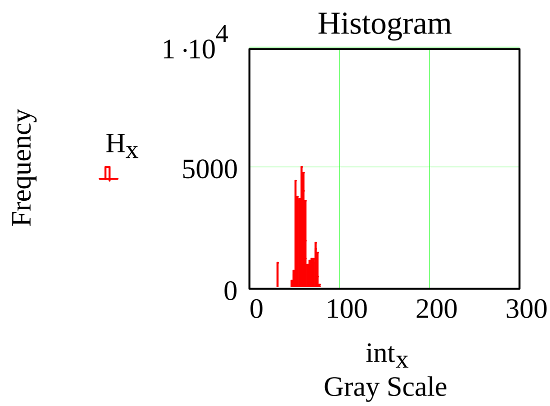
cols(Q) = 180.000   mean(Q) = 58.265

Define Histogram horizontal axis "int" and evoke Mathcad histogram function

$x := 0..255$ $int_x := x$ $H := hist(int, Q)$

Display Image and Histogram

Insert Picture Q



Q

Map original Gray Scale values to new Gray scale values using a y = mx + b function.

Line fit

$Xmin := min(Q)$ $\qquad$ $Xmax := max(Q)$

Select Desired new values of X which will be the Y values of the conversion function.

$Ymin := 30$ $\qquad$ $Ymax := 250$

Solve for slope coefficent "m" and intercept coefficent "b".

$$Ymax = m \cdot Xmax + b$$

$$Ymin = m \cdot Xmin + b$$

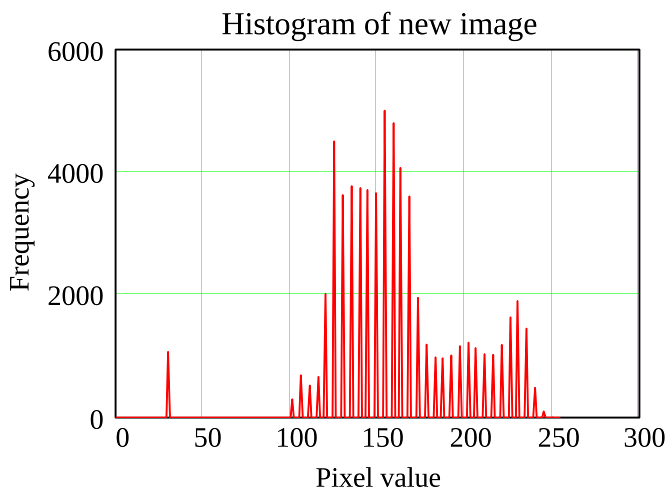
$$\Delta Y = m \cdot \Delta X + 0 \qquad m := \frac{Ymax - Ymin}{Xmax - Xmin} \qquad m = 4.783$$

$$b := Ymax - m \cdot Xmax \qquad b = -118.261$$

$$b := Ymin - m \cdot Xmin \qquad b = -118.261$$

Use function to create new image Q1.

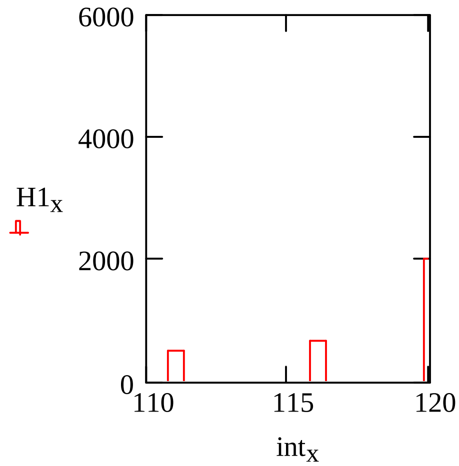
$$Q1 := m \cdot Q + b \qquad mean(Q1) = 160.400 \qquad H1 := hist(int, Q1)$$



New Image

Q1

Note that the slope of 4.783 causes empty spaces about 5 Gray Scale levels wide.



An **optional** "improvement" to the image is to fill in these gaps. This is done by adding random numbers in the range negative four to plus four to each pixel.

$i := 0 .. rows(Q1) - 1 \quad j := 0 .. cols(Q1) - 1$

$Max := rows(Q1) \qquad Max = 356.000$

$cols(Q1) = 180.000$

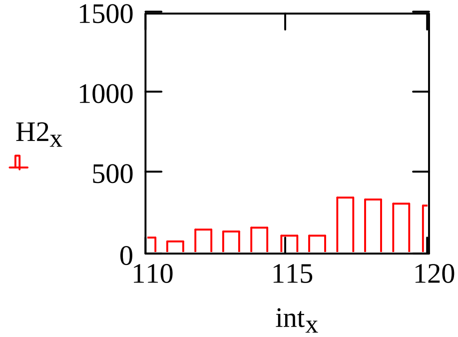
$A_{i,j} := rnd(4) \cdot (-1)^{ceil(rnd(4))}$ Create a matrix of random numbers using the rnd function and the ceil function.

$min(A) = -4.000 \qquad max(A) = 4.000$

Create new image Q2 by adding random number matrix to image Q1.

$Q2_{i,j} := Q1_{i,j} + A_{i,j} \qquad H2 := hist(int, Q2)$

Final image and histogram



Q2