Optics Laboratory #1

Session #1: Geometrical Optics and Calibration of the CCD Camera

Goals

- Reinforce geometrical optics of image formation.

- Learn image processing basics in MatLab.

- Calibrate the spatial scale of the CCD camera.

- Observe the Gaussian intensity profile of a laser beam

I. Intensity Profile of Unexpanded Beam

1. Open the "FlashBus MV" image acquisition software in "live" mode and maximize the window to get a window size of 640 x 480 pixels. If you have problems with the image refresh, go to "Tools", "Configure" and make sure "Offscreen" is unchecked. Point the HeNe laser into the CCD camera. Increase the attenuation with OD (optical density) filters, in combination with the variable attenuator, until the spot no longer saturates the CCD camera. (An OD=1 filter attenuates the beam by a factor of 10. An OD=2 filter attenuates the beam by a factor of 10^2.)

2. Save a bitmap of the image using the Flash Bus MV software by clicking "Grab", then "File", then "Save image". (Use descriptive filenames as you will be recording several images in each session of the optics labs.)

3. Load the image into MatLab. `imread` is part of the image processing toolbox and reads a grayscale or color image from the file specified by the string filename. The return value `I` is an array containing the image data. If the file contains a grayscale image like ours, `I` is an M-by-N array. The semicolon at the end suppresses the output of the array on the screen. Also remember, if you don't know the full path of the saved file, make sure the file opened in the 'Current Directory' window.

   ```
   >> I = imread('imagename.bmp');
   ```

   Load the image into the current axes with `imshow`. Because we are working with a grayscale image, we can call `imshow` with the already loaded image `I` in the MatLab workspace.

   ```
   >> imshow(I)
   ```

Measure the laser spot intensity profile with `improfile` and load it into a variable, here called c.

`improfile` is also part of the image processing toolbox and computes the intensity values along a line or a multiline path in an image. `improfile` selects equally spaced points along the path you specify, and then uses interpolation to find the intensity value for each point. `improfile` works with both grayscale images and RGB images. If you call `improfile` with the following syntax, it operates interactively on the image in the current axes.

To store the profile image to a parameter c by using

```
>> c = improfile;
```

Use the mouse to draw a line profile through the center of the laser spot in Figure 1 you just loaded. Right-click to end the selection. A figure will pop up showing the profile. Make sure the center of the spot is not saturated. When you finish selecting points, `improfile` returns the interpolated data values in c. c is an n-by-1 vector if the input is a grayscale intensity image, or an n-by-1-by-3 array if the input is an RGB image.

II. Beam Expansion

1. Expand and recollimate the HeNe laser beam using a combination of lenses of 150-mm (or 160-mm) and 25-mm focal length in the configuration of an "inverted telescope". Use the black screen as an aid to convince yourself that the beam is being expanded and recollimated. Be sure to include a diagram of the optical layout in your report. Adjust the attenuation so that the signal is strong, but does not saturate the CCD.

2. Save the image and measure the intensity profile of the expanded beam, just as you did in section I.3. Do not use c to save the data again, use a different variable name.

III. Calibration of the CCD

1. Use the expanded beam to illuminate the mm markings of a transparent ruler. Make an m=1, i.e., unmagnified, image of the mm markings of the ruler using a single 80-mm lens. (Comment: Use the lens equation $1/s + 1/s" = 1/f$, where s is the position of the object relative to the lens, $s"$ is the position of the image relative to the lens, and f is the focal length, to determine the appropriate location of the 80-mm lens and the distance between the detector and the ruler). You can see the position of the CCD detector in the camera if you temporarily remove the attenuators. Adjust the attenuation so that several ruler graduations are visible.

2. Print this image for your report and determine the number of pixels per mm with the image in MatLab. This is similar to part I and II. Now you know that how many pixels corresponds to 1 mm in real space and you will use this information to determine the diameter of unexpanded and expanded laser beam next.

3. After that, think about the direction of the ruler image. Is it the same as what you expect? Try to image a number such as 5 or 7 on the ruler to clarify this.

IV. Analysis of Beam Intensity Profile

1. `imshow` is the toolbox's fundamental image display function, optimizing figure, axes, and image object property settings for image display. `imtool` provides all the image display capabilities of `imshow` but also provides access to several other tools for navigating and exploring images, such as the Pixel Region tool, Image Information tool, and the Adjust Contrast tool. `imtool` presents an integrated environment for displaying images and performing some common image processing tasks.

   ```
   >> imtool('filename.bmp')
   ```

   The Image Tool will open your file. Place the mouse cursor over a marking on the ruler and click. A star will mark the pixel you have chosen, and its position and RGB value is displayed in the bottom left-hand corner of the image tool as (x,y) [R G B]. Write down the x and y position of your chosen pixel or right-click on it to copy the information to the Clipboard. In the same way, get the location of another pixel on another legible marking on the ruler. Calculate how many pixels per mm your image has.

2. For your report, fit the intensity profiles of both the unexpanded and expanded beams to a Gaussian function. First, find out how many points `improfile` used by looking at the size of c in the workspace or typing `whos c` at the prompt. If you use `whos`, you will see something like this:

   ```
   Name        Size              Bytes  Class     Attributes
     c         94x1x3             2256  double
   ```

   Remember that `improfile` returns an n-by-1-by-3 array, where n is the number of pixels `improfile` sampled. In this example, n is 94, meaning `improfile` sampled 94 pixels.

   Then, create a vector with the n pixels you sampled.

   ```
   >> x = 1:n  (where n is the number of points you had – in the example here, 94.)
   ```

   Then, load one of the array columns returned by `improfile` into c into a single vector.

   ```
   >> y = c(:,:,1);
   ```

   Start the MatLab Curve Fitting Tool. The Curve Fitting Tool is an interactive environment presented in the form of a graphical user interface. It allows you to
   - Import data from the MATLAB workspace

- Explore the data graphically
- Preprocess the data for fitting using exclusion rules and smoothing
- Fit a variety of library or custom models to the data
- Generate relevant regression statistics
- Post-process the fit through interpolation, extrapolation, differentiation, and integration
- Export results back to the MATLAB workspace for further analysis and visualization

Don't worry, we're just fitting a library model to the data here. However, if you ever need to do some advanced curve fitting, you know where to do it.

```
>> cftool
```

Fit a Gaussian to your data with the Curve Fitting Tool using the following menu choices.

Data…

X Data: x
Y Data: y
Weights: (none)
Data set name: Intensity Data (or whatever you prefer)

Create Data Set

Fitting…

New fit

Type of fit: Gaussian

The results are shown in the results window on the fitting tool. You can change the display name of the fit to something more descriptive than 'fit 1'. You can save the plot window contents as a MatLab figure by selecting 'Print to figure' from the File menu in the curve fitting tool menus. Include this figure in your report.

For a normalized Guassian distribution, the diameter of the beam is defined as the distance between the intersections of the Guassian curve and $y= 1/e^2$. If use y=a1*exp(-((x-b1)/c)^2), the diameter is $2\sqrt{2}$ c.

Calculate the magnification of your beam expander. Do your experimental results agree with the beam expansion you expected? (You can ignore the confidence intervals reported by MatLab.)

Homework assignment due next lab session: A partial draft of the laboratory report, showing at a minimum your diagrams, any equations used to determine the experimental setups, and any images you collected.

Session #2: Optical Diffraction in Two Dimensions

Goals

- Observe and quantify Fresnel and Fraunhoffer (far-field) 2-D diffraction from a periodic array of apertures.

- Use lenses to bring the far-field diffraction pattern to a sharp focus at a diffraction-plane to determine the lattice constant and width of the apertures.

I. Fresnel and Fraunhofer Diffraction

There are two fundamental length scales we need to consider in the position of the camera with respect to the grid. If the camera is very close to the grid, then the CCD sensor will record a projection image of the aperture in the grid. As the camera is moved farther away, diffraction from the apertures will blur the edges and light diffracted by adjacent apertures will overlap. The distance L_0 at which this happens can be calculated from the condition that the characteristic diffraction angle θ times L is comparable to the aperture size a. Since $θ ≈ λ/a$, $L_0 ≈ a^2/λ$. (a is the lattice constant of the grid and λ is the wavelength of the laser light, 633 nm in this case.)

As the distance L between the grid and camera is increased, Fresnel diffraction evolves into Fraunhofer diffraction at a distance $L > L_1$ with $L_1 = (2w_0)^2/λ$ and $2w_0$ is the diameter of the laser beam. The physics of this was discussed in lecture but the basic idea is that Fraunhofer diffraction occurs when the distance to a point on the sensor from one side of the illuminated portion of the gird is the same as the distance from the other side of grid to within a wavelength of light.

1. Illuminate (in transmission) a 300-mesh Cu grid of square apertures with the unexpanded laser. ("300 mesh" means 300 wires per inch.). Calculate L_0 and L_1.

2. Position the CCD camera as close as you can to the diffraction grid. Because of the attenuators, you will not be able to achieve $L<L_0$, so you will observe Fresnel diffraction. Once you have the image on the CCD, observe what happens when you move the grid by a small distance perpendicular to the optical axis. In your report, describe your observations, and include an image of the diffraction pattern.

3. Repeat with the camera 10, 15, 20, and 30 cm away from the grid to observe a transition between Fresnel diffraction and Fraunhofer diffraction. Repeat the above steps using the 200-mesh grid. For your report, organize the series of images in a meaningful way. Compare and contrast what you observed for the two different grids and therefore the two different values of L_0 and L_1. Be sure to include a diagram of the setup to indicate positions and relative distances of each optical component.

II. Determine the lattice constant from the diffraction pattern.

Now use the 150-mm lens to create a sharp image of the center portion of the Fraunhofer diffraction pattern on the CCD camera. As before, avoid saturating the CCD camera. Record images for both the 200-mesh and the 300-mesh grid. Take line scans of both images using `improfile` in MatLab.

For your report, include the following:

a. A basic diagram of the setup and the images you recorded for <u>both</u> grids.

b. Intensity profiles of both images. (For how to use `improfile`, see the MatLab help or part I of the previous week's lab.) Determine the full-width-at-half-maximum (FWHM) of the individual peaks for each grid. Are they all the same?

c. A comparison of the measured peak width w_p to the expected peak width w_e for an even illumination over a diameter for both grids. $w_e = f\lambda/(2w_0)$, where $(2w_0) = 0.6$ mm and f is the focal length.

d. Calculation of the lattice constant a of each grid using the center-to-center distance x between peaks as measured from your intensity plot ($a = f\lambda/x$). Compare to the expected value of a for each grid.

III. Determine the width of the wires in each grid using the variations in diffraction spot intensity

Because the dynamic range of the CCD camera is limited (8 bits), we will need to take several images with different attenuations to accurately measure the intensities of both strong and weak diffraction spots.

1. Use an 80 mm lens to capture a wide range of diffraction angles on the CCD. Use enough optical attenuation to avoid saturation of the CCD by the central diffraction spot.

2. Take the data again with the optical density of the attenuators reduced (not increased!) by 1.0 (ten times more light getting to the camera).

3. Take the data a third time with the optical density of the attenuators reduced by 2.0 (100 times more light getting to the camera). Record the best of these images for both grids.

For your report, include the following:

a. A diagram of the setup to indicate positions and relative distances of each piece

b. Images obtained for both grids at the best level of optical attenuation.

c. A determination of the width of the apertures $d = a - l$, where a is the lattice constant of the grid and l is the width of the wires. There are two periodicities to observe in the diffraction pattern: one is the distance between diffraction spots, which you have already used to determine the lattice constant of the grid. The other

is an oscillation of the spot intensity, which will allow you to measure the width of the wires in the grid, or equivalently the width of each individual aperture. What is the ratio of these periodicities? See section 7.4 of the text. Use this information to calculate d. (Note that there is a subtlety here: using diffraction you cannot distinguish between the size of the aperture d and the width of the wire l. You need additional information. In this case, $d>l$ is the other piece of information you need to know.)