ENSC 470/894
Optical Engineering and Laser Applications
Lab 1 – Basic Optics

Group 12

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1 Introduction

The purpose of this lab is to give us a basic experience with optics. We will set up lenses on an optical table, use an LCD screen pattern as our object, and then record the images using a digital camera. First, we will be doing a single lens experiment. Next, we will do a two lenses experiment and finally, we will replace one of the two lenses in the previous part with an unknown lens. The goal of these experiments is for us to use the images to calculate magnification, orientation, and light intensity changes in the system.

2 Methods

2.1 Single Lens

Using a single lens with focal length of 75 mm we put it on a lens holder, onto a post and then on the rail mount. The post aligns with the camera (Thorlabs DCC1545M) and the LCD screen because of the rail mount. For this single lens part, the lens was put onto the edge of the rail mount while we moved the camera to get a focused image.

For the next step, we moved the lens 30 mm away from the screen. Essentially, we moved it 30 mm down the rail mount. Then we moved the camera again to find the focused image.

We then set the exposure time for the images that result in an image not too dark and not too bright.

2.2 Two Lens

We then set up another 75 mm focal length lens. This second one was placed on the edge of the rail mount. Then we moved the old lens that was previously 30 mm away from the edge of the rail mount to be as close as possible to the lens at the edge of the rail mount. This distance was the distance that was physically possible when pressing two posts as close as possible. We then moved the camera to get a focused image.

The next step was then to separate the two lenses 30 mm away from each other. We kept the lens at the edge of the rail mount to stay there and moved only the old lens. The camera was then adjusted to find a focused image.

Again, we set the exposure time for the images that result in an image not too dark and not too bright.

2.3 Unknown Lens

We removed the old lens and replaced it with an unknown lens we were given. We kept the 75 mm focal length lens at the edge of the rail mount on the same spot. We then moved the unknown lens and the camera to find a focused image. Then set the exposure time for the images that result in an image not too dark and not too bright.

3 Single Lens Measurements

When setting up the single lens, we chose 159.4 mm to be the object distance. This is the distance from the screen to the lens. We adjusted the exposure time to be 29.036 ms to get the image Figure 1 below.

Figure 1: Image captured from single lens before being moved 30 mm

After moving the lens 30 mm away from the screen we adjusted the exposure time again, but found that the same exposure time of 29.036 ms was the best fit. So for *Figure 2* the exposure time was also 29.036 ms.

Figure 2: Image captured from single lens after being moved 30 mm

Table 1: Values for single lens measurements

Movement of lens 30 mm away from screen	Object Distance, *s* (mm)	Image Distance, *s'* (mm)	Exposure Time (ms)
Before	159.4 ± 0.02	135 ± 0.02	29.036
After	189.4 ± 0.02	115.5 ± 0.02	15.353

3.1 Image Distance

We know that the focal length for the lens is *f = 75 mm* and we also have the object distance length from Table 1 above. Then we can calculate for the image distance using the formula:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

$$s' = \frac{f * s}{s - f}$$

Before we move the single lens 30 mm, our calculated image distance is

$$s'_{before} = \frac{75 * 159.4}{159.4 - 75} = 141.6 \pm 0.02\ mm$$

and after we move the single lens our calculated image distance is

$$s'_{after} = \frac{75 * 189.4}{189.4 - 75} = 124.2 \pm 0.02\ mm$$

3.2 Magnification

Now for the measured magnification of the images before and after we get.

$$m = -\frac{number\ of\ pixels\ of\ the\ image\ x\ LCD\ pixel\ size}{\text{number of pixels of the camera x Camera pixel size}}$$

Measured using Paint, we got from *Figure 1* that the number of pixels of the image is 29.

$$m_{before} = -\frac{29\ x\ \sqrt{264}\ mm}{1280\ \text{x}\ \sqrt{5.2}\ mm} = -0.161$$

For *Figure 2* the number of pixels of the image is 48.

$$m_{after} = -\frac{48\ x\ \sqrt{264}\ mm}{1280\ \text{x}\ \sqrt{5.2}\ mm} = -0.267$$

Now for the calculated magnification:

$$m = -\frac{s'}{s}$$

Before,

$$m_{before} = -\frac{135\ \pm\ 0.02\ mm}{159.4\ \pm\ 0.02\ mm} = -0.847$$

After,

$$m_{after} = -\frac{115.5\ \pm\ 0.02}{189.4\ \pm\ 0.02\ mm} = -0.607$$

3.3 Light Intensity

We already got from *Figure 1* that *dQ = 29* and we have the exposure *time dT = 29.036 ms*.

$$\Phi_{before} = \frac{dQ}{dT} = \frac{29}{29.036} = 0.998$$

And for *Figure 2* the *dQ = 48* with the same exposure time of *dT* = 29.036 ms.

$$\Phi_{after} = \frac{dQ}{dT} = \frac{48}{29.036} = 1.653$$

3.4 Discussion

We could expect the image distances to have differences between the calculated and measured results. This is because there would be errors made when measuring the distances using tools. With our results we see that the calculated image distance had a larger difference from the measure image distance after moving the lens 30 mm. This makes sense because after moving the lens by 30 mm, the measurements should not be as exact as when we just add 30 mm on paper.

For the magnification we can see from the calculations that the image should be inverted. We can also see that the image is smaller because the magnification is less than 1. The calculated magnification for calculates that after the lens is moved 30 mm, the image becomes smaller. However, from our measured magnification, the image actually became bigger after moving the lens 30 mm.

For the light intensity, this was hard to conclude because we arbitrarily chose the exposure time. The exposure time chosen was within our educated guess to create an image that was not too bright and not too dark. Our results show that the light intensity increased after the lens was moved 30 mm.

4 Two Lens Measurements

In this part, we set the exposure time to be 29.036 ms. Also the object distance is still 159.4 mm. The distance between lens 1 and lens 2 was 25.0 mm. Then we set the exposure time to be 15.353 ms. While kept the object distance constant, we changed the distance from lens 1 to lens 2 to be 30 mm. Table 2 below shows the following measurement values with those conditions added.

Table 2: Values for two lens measurements

Movement of lens 1 30 mm away from lens 2	Object Distance, *s* (mm)	Lens 1 to Lens 2 Distance, *d* (mm)	Image Distance, *s'* (mm)	Exposure Time (ms)
Before	159.4 ± 0.02	25.0 ± 0.02	43.6 ± 0.02	22.762
After	159.4 ± 0.02	30.0 ± 0.02	43.2 ± 0.02	15.353

We know that the two lenses both have a focal length of *f = 75 mm*. We assume that the lenses are thick lenses. Now with the measured value, we calculated the expected values. Before moving the second lens (*d = 25.0 mm*).

4.1 Before Moving the Second Lens

Firstly, we can get the measured magnification:

$$m_e = -\frac{8 * \sqrt{264}}{159 * \sqrt{5.2}} = -0.359$$

4.1.1 Matrix Method

Since we are using the matrix method, we have the equation:

$$\begin{bmatrix} As & Bs \\ Cs & Ds \end{bmatrix} = \begin{bmatrix} 1 & s' \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f2 & 1 \end{bmatrix} \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f1 & 1 \end{bmatrix} \begin{bmatrix} 1 & s \\ 0 & 1 \end{bmatrix}$$

Then we plug in the values we measured before we change the distance from lens 1 to lens 2 (*d = 25.0 mm*):

$$\begin{bmatrix} As & Bs \\ Cs & Ds \end{bmatrix} = \begin{bmatrix} 1 & s' \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/75 & 1 \end{bmatrix} \begin{bmatrix} 1 & 25 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/75 & 1 \end{bmatrix} \begin{bmatrix} 1 & 159.4 \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} As & Bs \\ Cs & Ds \end{bmatrix} = \begin{bmatrix} 1 & s' \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0.667 & 131.267 \\ -0.022 & -2.876 \end{bmatrix}$$

$$\begin{bmatrix} As & Bs \\ Cs & Ds \end{bmatrix} = \begin{bmatrix} 0.667 - 0.022s' & 131.267 - 2.876s' \\ -0.022 & -2.876 \end{bmatrix}$$

$$\mathrm{Bs} = 131.267 - 2.876s' = 0$$

$$\mathrm{s}' = 45.642$$

The image distance is 45.642 mm.

$$\mathrm{m} = \frac{1}{Ds} = \frac{1}{-2.876} = -0.348$$

The image magnification is -0.348. since the magnification is negative, the image is upside-down.

4.1.2 Combined Lens Formulas

Then we use the combined lens formulas:

$$f_e = \frac{f1 * f2}{f1 + f2 - d}$$

With the values we measured, we can get:

$$f_e = \frac{75 * 75}{75 + 75 - 25}$$

$$f_e = 45$$

Distance from first lens primary principal point to combined lens primary principal point:

$$\mathrm{D} = -\frac{df_e}{f2}$$

$$\mathrm{D} = -\frac{25 * 45}{75}$$

$$\mathrm{D} = -15$$

Distance from second lens secondary principal point to combined lens secondary principal point:

$$\mathrm{D}' = -\frac{df_e}{f2}$$

$$\mathrm{D} = -\frac{25 * 45}{75}$$

$$\mathrm{D} = -15$$

Combined object distance:

$$s_e = s1 - D$$

$$s_e = 159.4 + 15$$

$$s_e = 174.4$$

Combined image distance:

$$\frac{1}{s_e} + \frac{1}{s_e{}'} = \frac{1}{f_e}$$

$$\frac{1}{s_e{}'} = \frac{1}{45} - \frac{1}{174.4}$$

$$s_e{}' = 60.649$$

Then we can get the magnification by the equation:

$$m_e = -\frac{s_e{}'}{s_e}$$

$$m_e = -0.348$$

Which is exactly the value we got using matrix method.

4.1.3 Light Intensity

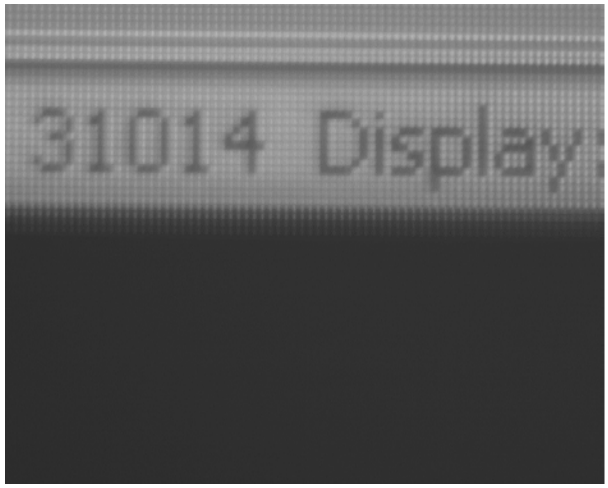

Figure 3: Image captured before moving lens 1 and lens 2 30 mm apart

Measured using Paint, we got *dQ = 170*, and we have the exposure *time dT = 22.762 ms*. So:

$$\Phi = \frac{dQ}{dT} = \frac{170}{22.762} = 7.469$$

4.1.4 Discussion

The measured magnification is -0.359, and the calculated magnification is -0.348. The measured magnification is 1.030 times comparing with the calculated value, which is close. And since the light intensity from Part 1 is 0.998 the light intensity is 7.484 times brighter than the light intensity in Part 1. This difference in the light intensity can easily be seen when comparing *Figure 1* and *Figure 3*.

4.2 After Moving the Second Lens

Firstly, we can get the measured magnification:

$$m_e = -\frac{8 * \sqrt{264}}{185 * \sqrt{5.2}} = -0.308$$

4.2.1 Matrix Method

Similar with the previous calculation:

$$\begin{bmatrix} As & Bs \\ Cs & Ds \end{bmatrix} = \begin{bmatrix} 1 & s' \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f2 & 1 \end{bmatrix} \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f1 & 1 \end{bmatrix} \begin{bmatrix} 1 & s \\ 0 & 1 \end{bmatrix}$$

Then we plug in the values we measured before we change the distance from lens 1 to lens 2 (d=30.0 mm):

$$\begin{bmatrix} As & Bs \\ Cs & Ds \end{bmatrix} = \begin{bmatrix} 1 & s' \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/75 & 1 \end{bmatrix} \begin{bmatrix} 1 & 30 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/75 & 1 \end{bmatrix} \begin{bmatrix} 1 & 159.4 \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} As & Bs \\ Cs & Ds \end{bmatrix} = \begin{bmatrix} 1 & s' \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0.6 & 125.64 \\ -0.0213 & -2.801 \end{bmatrix}$$

$$\begin{bmatrix} As & Bs \\ Cs & Ds \end{bmatrix} = \begin{bmatrix} 0.6 - 0.0213s' & 125.64 - 2.801s' \\ -0.0213 & -2.801 \end{bmatrix}$$

$$\mathrm{Bs} = 125.64 - 2.801s' = 0$$

$$\mathrm{s}' = 44.855$$

The image distance is 44.855 mm.

$$\mathrm{ms} = \frac{1}{Ds} = \frac{1}{-2.801} = -0.357$$

The image magnification is -0.357. since the magnification is negative, the image is upside-down.

Combined lens formulas

Again, we use the combined lens formulas:

$$f_e = \frac{f1 * f2}{f1 + f2 - d}$$

With the values we measured, we can get:

$$f_e = \frac{75 * 75}{75 + 75 - 30}$$

$$f_e = 46.875$$

Distance from first lens primary principal point to combined lens primary principal point:

$$\mathrm{D} = -\frac{df_e}{f2}$$

$$\mathrm{D} = -\frac{30 * 46.875}{75}$$

$$\mathrm{D} = -18.75$$

Distance from second lens secondary principal point to combined lens secondary principal point:

$$\mathrm{D}' = -\frac{df_e}{f2}$$

$$\mathrm{D} = -\frac{30 * 46.875}{75}$$

$$\mathrm{D} = -18.75$$

Combined object distance:

$$s_e = s1 - D$$

$$s_e = 159.4 + 18.75$$

$$s_e = 178.15$$

Combined image distance:

$$\frac{1}{s_e} + \frac{1}{s_e{}'} = \frac{1}{f_e}$$

$$\frac{1}{s_e{}'} = \frac{1}{46.875} - \frac{1}{178.15}$$

$$s_e{}' = 63.613$$

Then we can get the magnification by the equation:

$$m_e = -\frac{s_e{}'}{s_e}$$

$$m_e = -0.357$$

Which is exactly the value we got using matrix method.

4.2.2 Light Intensity

Figure 4: Image captured after moving lens 1 and lens 2 30 mm apart

Measured using Paint, we got *dQ = 164*, and we have the exposure time *dT = 15.353 ms*. So:

$$\Phi = \frac{dQ}{dT} = \frac{164}{15.353} = 10.682$$

4.2.3 Discussion

The measured magnification is -0.308, and the calculated magnification is -0.357. Our measured magnification is 1.030 times compared to the calculated value, which is close.

When comparing the results of the first and second lens position, we have the first exposure time as 22.762 ms, the second exposure time as 15.353 ms.

$$\frac{\mathrm{T1}}{\mathrm{T2}} = 1.483$$

And we have the first magnification as -0.359, and the second magnification as -0.308.

$$\left(\frac{m1}{m2}\right)^2 = 1.359$$

5 Unknown Lens

In this part, we asked to determine the given unknown lens, which is replace by the lens positioned in part 2 that is closer to the camera

5.1 Finding Focal Length

First, using distance to calculate the focal length of the unknown lens. We have the following formulas:

$$f_e = \frac{f_{known} f_{unknown}}{f_{known} + f_{unknown} - d}$$

$$\frac{1}{f_e} = \frac{1}{s_e} + \frac{1}{s_e'}$$

Where

$$s_e = s_{known} - D$$

$$s_e' = s_{unknown}' - D'$$

$$D = -\frac{d f_e}{f_{unknown}}$$

$$D' = -\frac{d f_e}{f_{known}}$$

We measured

$$d = 25.0\ mm$$

$$f_{known} = 75\ mm$$

$$s_{known} = 159.4\ mm$$

$$s_{unknown}' = 58.5\ mm$$

After the calculations above were done, we get the values below

$$f_{unknown} = 102.967\ mm$$

$$s_e = 171.658\ mm$$

$$s_e' = 75.328\ mm$$

5.2 Magnification

To get the image from *Figure 5* below we used an exposure time of 15.253 ms.

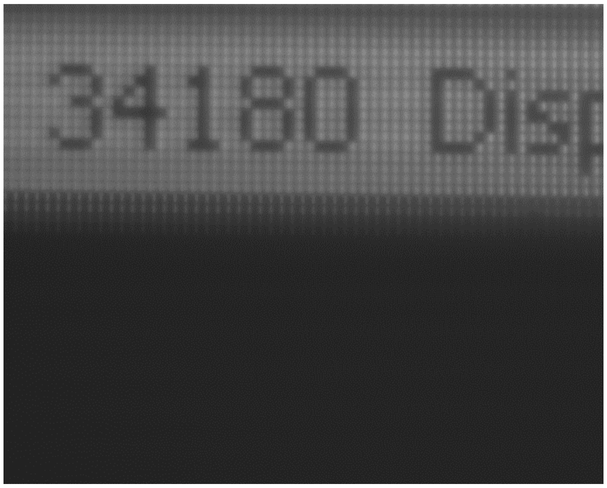

Figure 5: Image captured with the unknown lens

$$f_{unknown} \approx 100\ mm$$

$$m_e = -\frac{s_e'}{s_e} = -0.439$$

Now, using magnification to check the focal length of the unknown lens. we have following formulas:

$$m = -\frac{number\ of\ pixels\ of\ the\ image \times LCD\ pixel\ size}{number\ of\ pixels\ of\ the\ camera \times Camera\ pixel\ size}$$

Figure 5 above is our captured image for the LCD screen with the added unknown lens. From this image we are able to obtain 57 horizontal pixels. We achieved this by counting the number of horizontal pixels.

Therefore, we can calculate the magnification to be:

$$m = -\frac{57 \times \sqrt{264} mm}{1280 \times \sqrt{5.2} mm} = -0.417$$

$$m \approx m_e$$

5.3 Discussion

The focal length of the unknown lens was calculated to be *f = 102.967 mm*, since we were told that the focal lengths should only be in increments of 25 mm. We can conclude that the approximate focal length of the unknown lens is *f = 100 mm*.

For the magnification we can see that the image is real and inverted. We also see that when comparing the measured magnification with the calculated magnification they are very close to each other. Our results were very close to the expected value.

6 Conclusion

We can conclude that the image created from the single lens was inverted and smaller. Also, we knew that our measured results were off when compared to the calculated results. This was because of the errors created from the measuring of the distances of the lens to the screen and the lens to the camera.

From the one lens, we saw that the light intensity was brighter when the distance was farther (moved 30 mm).

The measured magnification measurements for the two lens system were found using the matrix method and the combined lens formulas. For the results, the two measured magnifications were almost exactly the same, which was to be expected. Also, the light intensity of the two lens system was a lot brighter when compared to the one lens system.

The unknown lens was found to have a focal length of 100 mm. Then we found the magnification of the image with the unknown lens and found that the measured magnification was almost exactly the same as the calculated magnification.