Sensor Calibration Lab

The lab is organized with an introductory background on calibration and the LED speed sensors. This is followed by three sections describing the three calibration techniques which include a short background section followed by the procedure for that particular technique. Before coming to class, please prepare for the lab by reading the background and procedure for each technique. Post-lab analysis is found at the end of the lab along with the memo requirements.

I. Background on Calibration: Calibration ensures that measurement devices yield precise, accurate readings. A device is calibrated by comparing the measured values obtained from the device to the measured values obtained from a “known” or standard device.

There are often numerous methods for calibrating a single device. For instance, to calibrate the 0°C temperature reading of a thermometer, the thermometer can be placed in a mixture of ice and liquid water. Another method would be to place the thermometer in a thermo controlled room that is set to 0°C. In this method, the room’s thermostat acts as the “known” value and in the first method the phase change temperature of water, 0°C, acts as the “known” value.

In this lab, you will be calibrating the roller coaster speed sensors using three different techniques. The techniques are as follows:

1. Physics Calculation Calibration Technique
2. Laser Calibration Technique
3. Camera Calibration Technique

The lab will be organized into super groups of three teams each, as shown in Table 1. Each lab table will only have the setup for one calibration technique. Each group will complete the procedure for that particular technique, and then rotate to the next table until all three techniques have been completed. The table below shows the “Super Groups” that will rotate together. For instance, upon completion of a technique, A rotates to B, B rotates to C, and C rotates to A.

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Each group will collect the data for a particular technique and record it on the spreadsheet provided at their table. The electronic copy of the spreadsheet will then be emailed out to the class upon completion of the lab.

II. Objectives: The objectives of this lab are:

- To obtain an understanding of the importance of calibration and why it is necessary to calibrate sensors
- To calibrate the roller coaster speed sensors using three different techniques
- To compare the effectiveness and accuracy of the calibration techniques in terms of their limitations and ease of application
- To understand the influence of measurement system errors and production errors when calibrating the sensors
III. LED Speed Sensors: The LED speed sensors used for the roller coaster have a correction factor built into the Coaster App software. This lab will be using three different techniques for determining the correction factor to be used in the Coaster App software. Therefore, the correction factor within the software must be set equal to one for each technique.

Part 1: Physics Calculation Calibration Technique

1. 1 Background: For this part of the lab, simple physics calculations will be used to calculate the correction factor for the LED speed sensor. As a review, the potential energy of the ball at the top of the ramp is equal to:

\[ PE = mgh_1 \]  

(1)

Where \( m \) is the mass of the ball, \( g \) is gravity (9.81 m/s\(^2\)), and \( h_1 \) is the starting height of the ball. In an “ideal” world, the potential energy stored in the system when the ball is at the top of the ramp directly equals the kinetic energy of the system when the ball reaches the bottom of the ramp. The formula for kinetic energy of the ball at the bottom of the ramp is:

\[ KE = \frac{1}{2}mv_2^2 + \frac{1}{2}I\omega_2^2 \]  

(2)

Where \( v_2 \) is the speed of the ball at the bottom of the ramp, \( I \) is the moment of inertia of the ball, and \( \omega_2 \) is the angular speed of the ball at the bottom of the ramp. In the above equation, the first term is the kinetic energy of the ball associated with translation (\((1/2)mv^2\)) and the second term is the kinetic energy of the ball associated with rotation (\((1/2)I\omega^2\)). The following equation shows \( I \), the moment of inertia of the ball, where \( m \) is the mass of the ball and \( r \) is the radius of the ball.

\[ I = \frac{2}{5}mr^2 \]  

(3)

In reality, there is energy lost due to rolling friction and air resistance. Air resistance can be assumed to be negligible at the slow speeds tested today. Therefore, the conservation of energy equation becomes:

\[ mgh_1 = \frac{1}{2}mv_2^2 + \frac{1}{2}I\omega_2^2 + \mu_{rolling}l_{ramp} \]  

where

\[ v_2 = \omega_2r' = \omega_2\frac{4}{5}r \]

\( \mu_{rolling} \) is the coefficient of rolling friction, \( l_{ramp} \) is the length of the ramp, and \( r' \) is the effective radius of the ball. \( \mu_{rolling} \) can be assumed to be 0.0007 J/m based on previous experiments, and the length of the ramp is to be measured. It is important to note that the ball starts at rest, thus there are no kinetic energy terms on the left side of the equation. When the ball reaches the bottom of the ramp, there are no potential energy terms because we consider the end of the ramp to have a height of zero. Thus the above equation satisfies the law of the conservation of energy.

From the above equation, the theoretical speed of the ball can be calculated. This value will be compared against the measured speed from the LED sensor to find the correction factor for the sensor. It is easiest to find \( v_2 \) by rearranging the above equation, as seen below:
\[ v_2 = 4 \left( \frac{mgh_1 - \mu_{\text{rolling}} l_{\text{ramp}}}{13m} \right)^{0.5} \] (5)

1.2 Procedure:

Place the ramp at the bottom rung of the tower, as seen in the figure below:

![Figure 1: Ramp placed on bottom rung of tower](image)

Open the LED speed sensor lab app by double clicking “Lab Apps” on the desktop and selection “Roller Coaster.” The user interface should look like the image below:

![Figure 2: LED Sensor Interface](image)
Ensure that the first three windows are set to “active”, the time division is set to 0.1s, and that the *Geometry Correction (the Correction Factor) is set to one!*

Press Begin and release the ball three times with the ramp on the lowest rung of the tower to obtain the speed at the bottom of the ramp. Each time the ball is released from the ramp, it must be done with a buck id (or other thin plastic item) to ensure consistency. The release point is the first standalone snapfit, as seen in the figure below.

![Figure 3: Release Point](image)

Record the measured velocities from the LED sensor on the spreadsheet at your table, under your group’s name. Also record the height of the ramp (subtract the height of the sensor) in meters on the spreadsheet by measuring the height from the table to the bottom of the ramp underneath the snapfit where the ball was released. The height is measured in this way so that height difference between the release point and the sensor is obtained. Repeat the above steps with the ramp resting on the middle rung of the tower, and again with the ramp on the highest rung of the tower. These two setups can be seen in the figures below.

Therefore, the correction factor using the physics calculation calibration technique is:

\[
\text{correction factor} = \frac{v_{LED, \text{oscope}}}{v_{\text{calculated}}}
\]

where \(v_{LED, \text{oscope}}\) is the measured speed obtained from “Coaster App” (when the geometry correction is set to one), \(v_{\text{calculated}}\) is the calculated speed using equation (5).
Figure 4: Setup with ramp on the middle rung

Figure 5: Setup with ramp on the highest rung
PART 2: Laser Calibration Technique

2.1 Background: Begin the Laser Calibration portion of the lab with the setup as shown below. In this setup, two small beam lasers and phototransistors are located an equal distance before and after the LED speed sensor.

![Laser Calibration Setup](image)

As seen in the diagram, there are two lasers, boxed in red, and two laser beam receptors, circled in yellow. A beam receptor consists of a phototransistor behind a small hole that is 0.039 inches in diameter. The lasers are spaced at 1.975 inches apart. This can be seen more clearly in the figure below.

![Close-up of Laser/Receptors and LED Sensor](image)

The lasers provide the light intensity necessary to change the output voltage of the phototransistor even with the very small sensing area. As the ball rolls passed the first laser/receptor, the output voltage of the
first beam receptor spikes because it no longer receives light from the laser. This occurs again as the ball rolls passed the second laser/receptor.

2.2 Procedure

Verify the setup. The USB DAQ (data acquisition) module will be setup as shown below with the lasers plugged in CH 1 and the LED Sensor plugged in CH 2. Verify that the BNC cables are plugged in the correct locations on the DAQ module and in the back of the computer (USB connection).

![USB DAQ Module](image)

Figure 8: USB DAQ Module

Also verify that the sensors are working properly by passing a finger between the red LED and the phototransistor to ensure that the green LED lights up. Do the same for the lasers and receptors.

Double click the Matlab icon on the desktop. This will open up a Matlab application and present you with the command window. Type “run calibration4mce” in the command window after the “ >> ”. Give the output file a name with no spaces or characters, and an extension of .txt (Ex: test1.txt). As soon as the filename is entered, the program will begin! Release the ball from release point 1, the first standalone snapfit, as seen below.

![Release Point along Ramp for Laser Calibration](image)

Figure 9: Release Point along Ramp for Laser Calibration
After running the calibration m-file, you will see a plot like the one below:

![Plot of Laser (top) and LED Speed Sensor (bottom)](image)

**Figure 10: Plot of Laser (top) and LED Speed Sensor (bottom)**

*If the plot does not look like the figure above, rerun the calibration file!*

Next, run the pulseAnalysisStudent.m file by typing "run pulseAnalysisStudent" in the command window. Type the name of the data file with the extension .txt (Ex: test1.txt). This outputs two plots that look like the figures below:

![Sample Plot from pulseAnalysisStudent Script](image)

**Figure 11: Sample Plot from pulseAnalysisStudent Script**
As seen above, Figure 11 is a close-up view of the pulses in Figure 10. In both figures, the plot on top refers to the ball passing between the two lasers. The first pulse occurs when the ball passes the first laser and the second pulse occurs when the ball passes the second laser. The plot on the bottom refers to the ball passing the LED sensor. The distance between the leading edge of one pulse and the trailing edge of the same pulse is the diameter of the ball, since the pulse represents the length of time that the light (laser or LED) is blocked from the phototransistor. The speed of the ball is therefore the diameter of the ball divided by the time width of the pulse.

The command window displays the time of the leading and trailing edges of all three pulses. Enter this information on the spreadsheet on your table.

**Repeat the above procedure with the ramp on the middle rung and the second to highest rung. Record all data in the spreadsheet on your table.**

![Figure 12: Ramp on Middle Rung](image1.png) ![Figure 13: Ramp on Highest Rung](image2.png)

Therefore, the correction factor using the laser calibration technique is:

\[
\text{correction factor} = \frac{v_{\text{LED}}}{\frac{v_{\text{Laser}_1} + v_{\text{Laser}_2}}{2}}
\]

and

\[
v_{\text{LED}} = \frac{D}{(T.E.\text{LED} - L.E.\text{LED})}
\]

\[
v_{\text{Laser}_1} = \frac{D}{(T.E.\text{Laser}_1 - L.E.\text{Laser}_1)}
\]

\[
v_{\text{Laser}_2} = \frac{D}{(T.E.\text{Laser}_2 - L.E.\text{Laser}_2)}
\]

where

D: diameter of the ball
T.E.: trailing edge of the pulse
L.E.: leading edge of the pulse
PART 3: Camera Calibration Technique

3.1 Background
Using a camera, the ball will be recorded rolling down the track at 30 frames per second. The camera software will allow us to examine the ball’s position each 1/30th of a second along a calibrated track. Using the ball’s change in position, each 1/30th of a second, we can calculate its speed along the track.

3.2 Procedure
Place the edge of the ramp on the edge of tower, as seen in the figure below.

![Figure 144: Ramp Placement on Coaster Tower](image)

Open the program titled “Microsoft LifeCam” which can be found on the desktop. You should now be able to see the live video feed from the camera on the screen, as seen below.

![Figure 15: LifeCam Software Interface](image)
Adjust the resolution of the screen to 960x544 in the Settings window (click on the gear icon if settings window is not visible) on the right hand side of the screen, as shown below. This also adjusts the recording frame rate to 30 frames per second.

![Figure 16: Adjusted Video Resolution](image)

Place the camera on the table such that it faces the end of the ramp, and is perpendicular to the side of the ramp, as seen below.

![Figure 17: Camera Placement](image)

Move the camera toward the end of the ramp until 6 in (150 mm) can be seen in the field of view, as seen below.
Hold a black binder (course packet) behind the visible view of the camera, as seen in the above image.

Use a BuckID to drop the ball from the snap fit closest to 2 inches just outside the field of view. The speed of the ball at the LED sensor can be recorded using the Coaster App program. Adjust the settings of “Coaster App” to the settings of Figure 2 in the Physics Calculation Setup, i.e., the Geometry Correction (the Correction Factor) is set to one.

Record the speed in Table A under the “LED Sensor Speed” column. The speed of the ball will also be recorded from the video capture. In order to do this, the image of the video camera under the live feed must be clicked to start recording before the ball is dropped.

The same button then becomes the “stop recording” button as well. Have one group member drop the ball, another group member operates the record/stop record button, and a third group member can hold the piece of black construction paper behind the track as the backdrop for the video. Once the “stop record” button is clicked, a video file appears in the lower left hand corner of the screen, as seen in the figure below. This may be clicked on to open up the recorded video in Windows Media Player.
Once Windows Media player opens, you will need to advance the frames one at a time. In order to do this, right click on the video and select “Enhancements” then “Play speed settings” as seen below.

This provides the menu options as seen in the figure below. The buttons encircled below show the options to advance the video one frame at a time. Do not maximize Windows Media Player or this will not work!

The first data point should be the first frame where the entire ball can be seen in the video. Record the placement of the ball on the spreadsheet at your table under the “Placement” column.
Finding the placement of the ball within each frame: to find the placement of the ball, refer to the image below. Move the “Play speed settings” menu box across the screen to the leading edge of the ball, such that the left hand side of the menu acts as a straight edge to provide an accurate measurement reading (82 mm(0.082 m) in this case). The “Play speed settings” menu box can be moved by left-clicking and dragging on the upper portion of the screen where the text “Play speed settings” can be seen.

Repeat this for each frame until the leading edge of the ball is no longer on the ramp above the measurement tape (2 mm in this case) as seen below.

Record the data points on the worksheet on your table. (Note: Sometimes when the back button is hit, the video skips back several frames. If this occurs, advance the video one frame at a time until the desired frame is found.)

Correction factor equation for camera calibration technique is shown in the post-lab analysis.
**Post Lab Data Reduction:** (All teams are required to email the completed worksheet to instructor within two days of the completion of the lab. The excel file should be named as Eng1182_Lab4_GroupX)

**Physics Calculation Calibration Tasks:**

1. Complete the “Physics Calculation – post lab” tab in the Sensor Calibration Data Sheet workbook using the class data, which has been emailed to you upon completion of the lab by the Instructor.

2. Observe the mean sensor correction factor for your group, as compared to the other groups. The standard deviation for one group reveals the user/system error in the group’s measurements. List three user/system sources of error and explain how each one contributes to the standard deviation.

3. The standard deviations between groups reveal production differences in the speed sensors. Knowing this, is it valid to apply one sensor correction factor to every speed sensor? In other words, did any of the correction factors differ by more than one standard deviation?

4. For your group’s data, produce a scatter plot (with data points) of the correction factor vs. release point for the three heights. Include a proper caption, figure title, and axis labels.

5. Notice how the correction factor increases as the ramp is moved to the top rung. What is the dominant reason for this increase in the correction factor? (Hint: what rule of thumb is violated by placing the ramp on the top rung?)

**Laser Calibration Tasks:**

1. Complete the “Laser Calibration – post lab” tab in the Sensor Calibration Data Sheet workbook using the class data, which has been emailed to you upon completion of the lab by the Instructor.

2. Calculate the speed of the ball at the first laser by dividing the width of the ball (given on spreadsheet) by the pulse duration. Repeat this calculation for the ball at the LED sensor and second Laser. Calculate the Correction Factor.

3. For your group’s data, create a scatter plot (with data points) of laser speed vs. height (y vs. x). For height, the numerical values 1, 2, and 3 may be used rather than a measured height. Insert a linear trendline and display the equation of the trendline on the figure. On the same plot, included LED speed vs. height. Notice the vertical shift in the plot of the two velocities. This shift represents a visual representation of the correction factor.

4. For your group’s data, plot the correction factor vs. laser speed (y vs. x). Do you notice a slight increasing trend of the correction factor with speed (i.e. is the slope greater than zero)? If so, why do you think the correction factor increases as the speed of the ball increases?

**Camera Calibration Tasks:**

1. Complete the “Camera Calibration – post lab” tab in the Sensor Calibration Data Sheet workbook using your own team’s data, which has been emailed to you upon completion of the lab by the Instructor.
a. The speed of the ball at each frame is found by dividing the distance the ball has traveled between frames by the time between frames. For instance, the speed of the ball in Frame 2 is:

\[ v_{\text{frame}2} = \frac{\text{placement}_1 - \text{placement}_2}{\left(\frac{1}{30}\right)} = \frac{\text{placement}_1 - \text{placement}_2}{0.033} \]

Note: the speed of the ball in the first frame cannot be found, since the placement in the preceding frame is unknown.

b. In order to find the measured speed of the ball at the location of the sensor, the data must be extrapolated. In order to do this, plot speed at each frame vs. placement (y vs. x), for each of the frames, for your group’s data only. Insert a linear trendline and display the equation on the graph. This equation allows you to find the speed of the ball at the sensor by linear extrapolation:

\[ v_{\text{calc at sensor}} = mx + b \]

where m and b are given in your trendline equation, and x = 0 mm.

c. Why is the speed linear instead of exponential if the ball is accelerating down the track?

- The plot is linear because the speed of the ball is simply the displacement of the ball with a multiplication factor of 1/time difference = 1/(1/30) seconds) for 30 frames per second.

Therefore, the correction factor equation for camera calibration technique is:

\[ \text{correction factor} = \frac{v_{\text{LED, Oscpe}}}{v_{\text{calc at sensor}}} \]

where \( v_{\text{LED, Oscpe}} \) is the measured speed obtained from “Coaster App” (when the geometry correction is set to one) , \( v_{\text{calc at sensor}} \) is the speed estimated using the trendline when x=0 mm.

**DISCUSSION QUESTION:**

1. Compare the correction factors for the three calibration techniques (average correction factor for Physics Calc and Laser Calibration, and your group’s correction factor for camera calibration) by addressing the following:

   a. Discuss two pro’s and two con’s for each of the three techniques.
   b. Which technique do you believe is the most **accurate** and why?
   c. Based on a and b, which technique would you recommend to calibrate the LED speed sensors and why?
## Grading Guidelines: Sensor Calibration Memo (Group)

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<td>Email completed spreadsheet to instructor within two days of the completion of the lab</td>
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**Grading Guidelines – 2 points will be deducted if these guidelines are not attached to the memo.**