ME 103 Experimentation and Measurements
Lab 1 - Ping Pong Ball Calibration

Introduction and Objectives

The primary focus of this lab is the calibration of the ping pong ball tower measurement system. You will continue to familiarize yourself with laboratory equipment, their limitations, and how to quantify and account for those limitations in practice. Most modern measurements rely on electronic instrumentation, where a transducer produces a voltage signal that must be converted into a physical quantity of interest. By completing this lab, you should be comfortable using the data acquisition (DAQ) system and waveform generator, constructing basic circuits, performing uncertainty calculations, and developing a calibration curve that relates sensor voltage to the position of the levitating ping pong ball.

Lab Objectives:
- Get experience with research quality signal generation, DAQ equipment, and AC circuits.
- Understand measurement uncertainty. Uncertainty analysis and quantification will be necessary throughout the semester, so make sure to learn this material in practice.
- Understanding calibration, IR sensors, and more sophisticated data analysis.

Equipment

All equipment will be provided in the lab, which include:

- DC power supply
- DG1022 Analog waveform generator
- DDM3058 Digital multimeter
- DS1102E Oscilloscope
- National Instruments USB-6211 DAQ Extension
- Vertical Wind Tube with ping pong ball and Sharp GP2Y0A41SK0F IR sensor
- Breadboard
- Coaxial cables + Banana plugs
- Resistors of various values

Datasheets/manuals for these pieces of measurement equipment are provided in bCourses under Files > Datasheets and Manuals.

Deliverables

It is to *your benefit* to look at the questions *in advance* to know what you are measuring and why. With your group follow the steps below to complete the lab. You **must** typeset your answers in LaTeX(We recommend using Overleaf with the template provided, but you can also edit locally if you prefer). Upload a single pdf file to Gradescope per team. Everyone should be contributing equally and writing on the document equally.

The lab is due 1 minute before your next lab section i.e the week of October 13th. For example, if you have lab on Monday at 8:00 AM, it is due the following Monday at 7:59 AM.

Part 1: Laboratory Facility Tours

We'll begin by familiarizing you with some of the resources available for your experimentation. The lab will split up into three groups and will be met in Hesse 122 by the shop staff, Daniel, Mike and Tom, who will show you some of the facilities in Hesse Hall that you can include in your project proposals. You'll rotate between the three staff and see the equipment listed below:

- An Instron materials testing machine for tensile and compressive loading of materials.
- A wind tunnel for testing, e.g., drag coefficients of components and structures up to about 150 mm in size.
- A stripped-down internal combustion engine that is instrumented to monitor cam and valve motion, and which has the capability to exchange the springs that close the valves. Accompanying this apparatus is a test rig for measuring the stiffness of available springs.
- A custom track, called GRADE, for logging the motion of small model vehicles: this can be used to study, e.g., effects of wheel and tire material on rolling friction, and of mass distribution in rolling bodies.

Tom will also run you through some of the sensing components available to you, many of which are ideal for integration with your microkit for automated data logging

- A 5 kg load cell that converts strain to a voltage that can be read in through a dedicated amplifier and I2C connection to the ESP32 microcontroller.
- An 6-axis inertial measurement unit with accelerometers and gyroscopes.
- A thermocouple with amplifier to send temperature signals to the ESP32 for logging.
- Photodiodes for sensing light levels with an appropriate amplifier circuit.
- Ultrasonic distance sensor for measuring distances in the cm to meter range using time of flight of 40 kHz ultrasound pulses.
- A Peltier (thermoelectric) cell sandwiched between a fan and an aluminum cap. Thermoelectic elements convert an electrical current to a temperature gradient and vice versa. Could be used in conjunction with a thermocouple to control the temperature of an experimental sample.
- A number of load cells with hand vices that could be used for bending tests of materials
- A Flir thermal imaging camera with associated data capture software.
- Thermal Rocket (More to come in Lab 4!)
- Vibrating Beam (More to come in Lab 3!)
- Inverted Pendulum (Hesse 50B) identify system parameters, evaluate dynamic response, and test control strategies.

We encourage you to refer to the Microkit website that lists many (not all) of the components available for use with the ESP microcontroller in the kit. There are also applications pages describing how to apply the various sensors. We would also like to draw your attention to the powerful sensing capabilities in most smartphones. These typically include:

- Lidar imaging, which can be used to measure distances and create depth maps
- Intertial measurement: accelerometers and gyroscopes
- Pressure sensor: to detect changes in air pressure
- Magnetometer: to detect subtle changes in surrounding magnetic field

The free app Phyphox allows data from these sensors to be logged at high temporal resolution. **NOTE: these are not standalone projects themselves, combine them with one of the main testing stations**

Part 2: Ping Pong Tower Calibration

Having tinkered around with all the equipment at your disposal, we feel you are ready to begin your first measurements assignment! Imagine we task you with designing a lightweight levitation system—something that only uses air flow to suspend and stabilize an object at a controllable height—for a hovercraft.

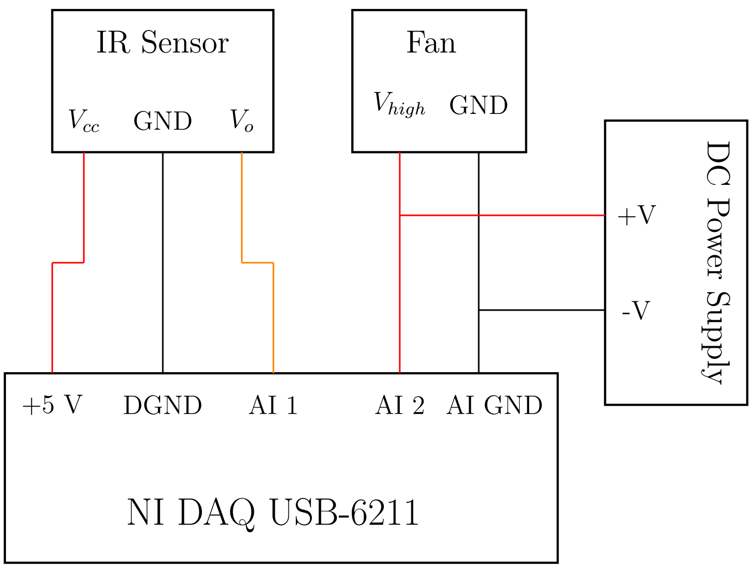
You will use a PC fan that flows a ping pong ball up a vertical tower to simulate this. By adjusting the voltage delivered to the fan, we can change the airflow and, in turn, the height of the ping pong ball. To measure this motion, an infrared (IR) sensor (Sharp GP2Y0A41SK0F) is mounted to detect the ball's position.

Your challenge is twofold:

1. **Calibration**: You will systematically record how the IR sensor's voltage output relates to the ball's actual position, and use this data to generate a calibration curve. This turns raw voltage signals into meaningful distance measurements.
2. **Experimentation**: Once calibrated, you will study how fan voltage, current, and power relate to the ball's levitated height. This process ties together measurement, calibration, and analysis—the same workflow engineers use when validating real-world systems.

By the end of this section of the lab, you'll have modeled the physics of the ping pong tower, built a calibration curve, and gained insight into how sensors and actuators work together in a dynamic system. Below is a schematic of the circuit diagram.

Warning: The output of the power supply should be off while adjusting the voltage delivered to the fan. YOU MUST HAVE A COMMON GROUND between `AI GND` and `DGND`.



1. Connect the power supply probes to the input and ground of the PC fan. Note the colours.
2. Set the power supply limit to **10 volts** and **0.75 amps**. Do not set the values higher than this or else the PC fan will get fried and so will your grade!
3. Turn the power supply on, this should blow the ping pong ball up the tower (it should get relatively close to the top of the tower, if not talk to a GSI/tutor). This can visually be seen below in **Figure 3**.

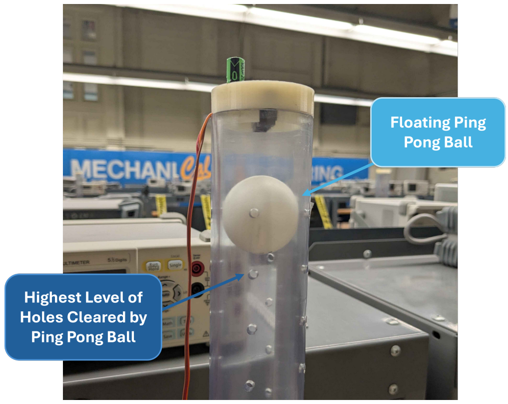


Figure 1: Ping Pong ball levitating in the tower, with the highest cleared hole level marked

4. Slide a wooden stick through the highest set of holes that the ping pong ball clears and the next set underneath. Afterwards turn off the power supply. **Figure 4** below shows what it should look like

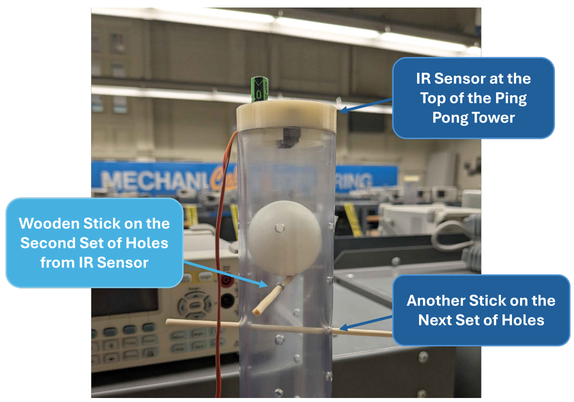


Figure 2: Ping Pong tower with IR sensor and wooden sticks marking the cleared height.

If the ping pong ball clears the highest set of holes, pick the second highest set of holes instead. Objects closer than 4 cm of the IR sensor are beyond its rated measurement range.

5. Write down the distance measurement **between the IR sensor to the ping pong ball** using a ruler. Keep in mind the resolution of your ruler.
6. Open the `Lab1A` VI found on bCourses.
7. Press run to start the measurement process (right arrow beneath Edit in the left corner). Press "MEASURE" to record the voltage reading from the IR sensor.
8. Take the highest stick and move it down two levels.
9. Repeat steps 5 through 8 until you have **at least 10** different measurements of various distances from the sensor. The trials index from 0, so you will go until you have up to Trial #9. Right click the graph and press Export to save your 10 plots on one graph to a .csv file. *Note: Be sure to name the file properly to avoid confusion*
   - Note: If you want to clear the graph, press the stop sign in the top left and then the run arrow.
10. Then create a graph of the IR sensor voltage versus distance measurement (between the IR sensor to the ping pong ball) with error bars.

11. Create a best fit curve through the points to create a calibration curve with a corresponding equation with the corresponding R^2.
12. Compare your calibration curve to the distance characteristics graph in the IR sensor's datasheet. What are some differences that you spot?

Part 3: Ping Pong Tower Experimentation

With your calibration curve now, you are now ready to explore and characterize the system and sensor under different operating conditions. In this section, you will power the fan continuously and measure how changes in fan voltage and current affect the height of the levitating ping pong ball. Using your calibration results, the raw IR sensor outputs can be translated into distance measurements, allowing you to create meaningful plots of fan voltage, current, and power versus ball position.

1. Run the `Lab1B` VI found on bCourses which will make it easier to stream and record data from both the IR sensor and the fan voltage simultaneously.
2. Run the fan continuously using the power supply with the same limits as Part 2 (10V and 0.75A). *Note: as a result, the ping pong ball will fluctuate within the tower.*
3. Set the Digital Multimeter to record current through the fan. Consult the Lab 0 current measurement schematic for reference and remember to measure current in series!!!!
4. Collect your data. Record **fan voltage, fan current, and IR sensor output.** For at least 10 different positions. *Hint: increasing fan voltage past 10V will still display 10V, why?*
5. Using your calibration curve from the previous section, convert the IR sensor voltages into distances and create the following plots:
   (a) Fan Voltage vs. IR-to-Ping Pong Ball Distance
   (b) Fan Current vs. IR-to-Ping Pong Ball Distance
   (c) Fan Power vs. IR-to-Ping Pong Ball Distance
6. Run the `Lab1C` VI found on bCourses which will graph the IR sensor voltage and the fan voltage.
7. While the VI is running, *slowly* increase the fan voltage in small steps, then decrease the voltage through the same steps while continuing to record data. Download the `.csv` file to examine hysteresis effects.

Hysteresis
Hysteresis occurs when the output of a system depends not only on its current input but also on the history of how that input was changed. In the ping pong ball tower experiment, this means that the ball may not return to the same height at a given fan voltage when the voltage is decreased after being increased. For example, the ball might reach a certain height at 7 V while the voltage is increasing, but settle at a slightly different height at the same voltage when the voltage is decreasing.

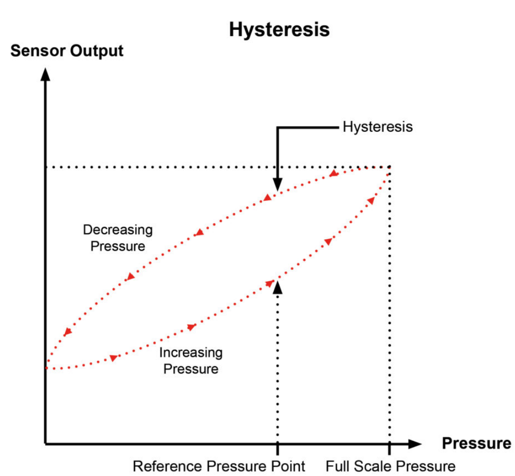


Figure 3: Hysteresis Loop of a Pressure Sensor

1 Questions

Section 1 Questions

1. Fill out the Hesse Equipment Interest survey. You can find the survey linked here. Please submit a screenshot of your completed Google Form (one submission per group).

Section 2 Questions

2. Why is it necessary to limit the fan's input to 0.75 A and 12 V, and what might happen if the DAQ is exposed to voltages above 10 V? What could you add to protect the circuit?
3. Using your repeated IR sensor measurements at a single ball position, calculate a 95% confidence interval for the mean voltage reading. What does this confidence interval tell you about the reliability of your sensor measurements?
4. If two confidence intervals (from different ball positions) overlap, what does that imply about how well the IR sensor can distinguish between those positions?
5. You want to make sure you are not using a faulty sensor, hence, you decide to do some hypothesis testing as a sanity check. After creating your calibration curve, compare two sets of IR sensor voltage measurements (for example, one taken when the ping pong ball is near the top of the tower and another when it is near the bottom), and decide at a significance level of 0.05, whether or not the IR can reliably distinguish between these 2 distances. Clearly state your null and alternative hypotheses, justify your choice of test statistic, and state your conclusion.
6. Plot your calibration curve. Be sure to label all axes with units, including appropriate titles, and appropriate number of sig figs, a curve of best fit with an **equation** and R^2 and vertical **error bars**.
7. Compare your calibration curve to the distance characteristics graph in the IR sensor datasheet. How well does your curve compare to the one on the datasheet? Why might it be different or similar?

Section 3 Questions

8. When you were streaming fan voltage data using the DAQ in conjunction with the VI, you may have noticed that if you increased the fan voltage above 10V to get the ball to go higher, the DAQ would still read 10V. Why is this?
9. For question 8, what could we add to the circuit to reduce the measured voltage? Draw a circuit diagram. What would we have to do to the VI to compensate? What are potential limitations or additional steps we need to consider using this measurement method?
10. Submit your plots. Be sure to label all axes with units, include appropriate titles, an appropriate number of sig figs, a curve of best fit with an equation. Comment on any observed trends in your analysis.
    (a) Fan Voltage vs. IR-to-Ping Pong Ball Distance
    (b) Fan Current vs. IR-to-Ping Pong Ball Distance
    (c) Fan Power vs. IR-to-Ping Pong Ball Distance
11. How does increasing fan voltage affect the levitation height of the ping pong ball?
12. Does the relationship between **fan current** and ball height appear linear or nonlinear? Explain your reasoning.
13. Which variable—fan voltage, current, or power—shows the clearest correlation with ball distance? Why might this be the case? Compare the general trends in your plots to your expectations before the experiment. Did anything surprise you?

14. In addition to your plots, perform a hypothesis test at a significance level of 0.05 to determine whether changes in fan voltage significantly affect the ping pong ball's levitation height. Clearly state your null and alternative hypotheses, justify your choice of test statistic, and state your conclusion.

15. Investigate whether hysteresis is present in the ping pong tower system by plotting ball height as fan voltage is increased and then decreased.

    (a) Using the dataset collected while sweeping fan voltage upward and then downward, convert IR sensor voltage measurements into distance using your calibration curve.

    (b) In Excel, create a scatter plot with **fan voltage on the horizontal axis** and **ball distance on the vertical axis**. Ensure the data is plotted in time order so that the increasing and decreasing voltage sweeps appear as separate paths.

    (c) Label the portions of the curve corresponding to increasing and decreasing voltage, and determine whether a hysteresis loop is visible.

    (d) Briefly explain possible physical reasons why hysteresis may or may not appear in this system.

2 Solutions

Section 1 Questions

1. Fill out the Hesse Equipment Interest survey. You can find the survey linked here. Please submit a screenshot of your completed Google Form (one submission per group).

   SOLUTION: Hesse Equipment Survey image should be present for points.

Section 2 Questions

2. Why is it necessary to limit the fan's input to 0.75 A and 12 V, and what might happen if the DAQ is exposed to voltages above 10 V? What could you add to protect the circuit?

   SOLUTION: Limiting the fan input protects the fan from getting fried and protects the DAQ from receiving too much voltage.

   Since the DAQ input range is $\pm 10\ V$, anything higher will lead to clipping in your readout.

   A voltage divider, RC circuit, OP Amp buffer, or 10 V zener diode could all protect the circuit.

3. Using your repeated IR sensor measurements at a single ball position, calculate a 95% confidence interval for the mean voltage reading. What does this confidence interval tell you about the reliability of your sensor measurements?

   SOLUTION: At a single ball position, they should find the mean voltage $\bar{V}$ and sample std. dev s. 10 measurements indicate t-distribution:

   $$\bar{V} \pm t_{0.975,n-1} * \frac{s}{\sqrt{n}}$$

   This means that we are 95% confident that the true mean voltage lies in this range.

4. If two confidence intervals (from different ball positions) overlap, what does that imply about how well the IR sensor can distinguish between those positions?

   SOLUTION: If two intervals overlap, this means that the sensor cannot reliably distinguish between these two positions, and the distances between these positions is not larger than the resolution of the sensor.

5. You want to make sure you are not using a faulty sensor, hence, you decide to do some hypothesis testing as a sanity check. After creating your calibration curve, compare two sets of IR sensor voltage measurements (for example, one taken when the ping pong ball is near the top of the tower and another when it is near the bottom), and decide at a significance level of 0.05, whether or not the IR can reliably distinguish between these 2 distances. Clearly state your null and alternative hypotheses, justify your choice of test statistic, and state your conclusion.

   SOLUTION: We are going to use a Welch's two sample t-test to determine whether the distributions differ at $\alpha = 0.05$.Lets call μ_{top} and μ_{bottom} the mean voltages when the ball is at the top of the tower and the bottom, respectively.

   $$H_0 : \mu_{\text{top}} = \mu_{\text{bottom}}$$

   i.e the sensor does not distinguish between the two distances.

   $$H_a : \mu_{\text{top}} \neq \mu_{\text{bottom}}$$

   i.e. the sensor does distingush between the two distances. From your repeated measurements at each position, compute:

   $$\bar{V}_{\text{top}} = \frac{1}{n_{\text{top}}} \sum V_{\text{top},i}, \quad s^2_{\text{top}} = \frac{1}{n_{\text{top}} - 1} \sum (V_{\text{top},i} - \bar{V}_{\text{top}})^2 \tag{1}$$

   $$\bar{V}_{\text{bottom}} = \frac{1}{n_{\text{bottom}}} \sum V_{\text{bottom},i}, \quad s^2_{\text{bottom}} = \frac{1}{n_{\text{bottom}} - 1} \sum (V_{\text{bottom},i} - \bar{V}_{\text{bottom}})^2 \tag{2}$$

The test statistic is:

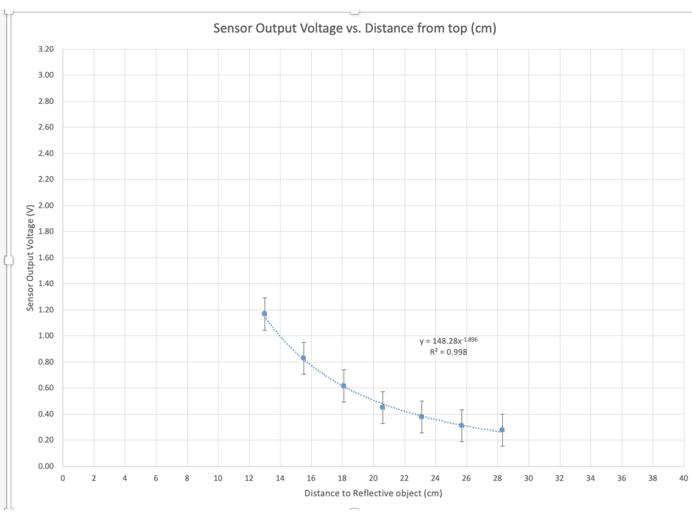
$$t = \frac{\bar{V}_{\text{top}} - \bar{V}_{\text{bottom}}}{\sqrt{\frac{s^2_{\text{top}}}{n_{\text{top}}} + \frac{s^2_{\text{bottom}}}{n_{\text{bottom}}}}}$$

with degrees of freedom:

$$\nu = \frac{\left(\frac{s^2_{\text{top}}}{n_{\text{top}}} + \frac{s^2_{\text{bottom}}}{n_{\text{bottom}}}\right)^2}{\frac{(s^2_{\text{top}}/n_{\text{top}})^2}{n_{\text{top}}-1} + \frac{(s^2_{\text{bottom}}/n_{\text{bottom}})^2}{n_{\text{bottom}}-1}}$$

Compare p-value from two-tailed t-distribution($t_{\nu,0.025}$) to $\alpha = 0.05$. If $p < 0.05$, reject H_0: sensor reliably distinguishes the positions.

6. Plot your calibration curve. Be sure to label all axes with units, including appropriate titles, and appropriate number of sig figs, a curve of best fit with an **equation** and R^2 and vertical **error bars**.
SOLUTION:



best fit equation, R^2 value and vertical error bars must be shown.

7. Compare your calibration curve to the distance characteristics graph in the IR sensor datasheet. How well does your curve compare to the one on the datasheet? Why might it be different or similar?

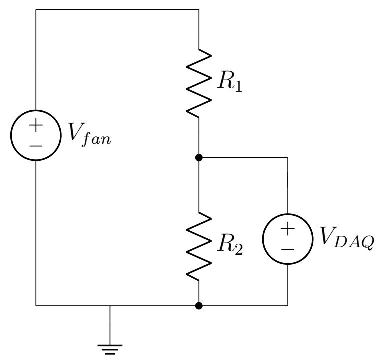
SOLUTION: The calibration curve should be generally similar in shape to the datasheet curve, but likely wont match point-for-point. Alignment of the ball, surface reflectivity, supply voltage stability, and noise in the DAQ may be reasons for this difference.

Section 3 Questions

8. When you were streaming fan voltage data using the DAQ in conjunction with the VI, you may have noticed that if you increased the fan voltage above 10V to get the ball to go higher, the DAQ would still read 10V. Why is this?
SOLUTION: The sensor clips at 10 V since that is the DAQ's maximum input range.

9. For question 8, what could we add to the circuit to reduce the measured voltage? Draw a circuit diagram. What would we have to do to the VI to compensate? What are potential limitations or additional steps we need to consider using this measurement method?

SOLUTION: SOLUTION: We could add a voltage divider into the circuit to reduce a fan voltage $>$ 10V to 10V.



Voltage divider will scale the fan voltage by a factor of $k = \frac{V_{\text{DAQ}}}{V_{\text{fan}}} = \frac{R_1}{R_1+R_2}$. We must multiply the measured DAQ voltage by the inverse of this factor to report the true fan voltage $V_{\text{fan}} = \frac{1}{k}V_{\text{DAQ}}$ High input impedance from the rest of the circuit attached to the divider are important to keep in mind, because the other components in the circuit could distort the voltage divider and change the actual divider ratio.

10. Submit your plots. Be sure to label all axes with units, include appropriate titles, an appropriate number of sig figs, a curve of best fit with an equation. Comment on any observed trends in your analysis.
    (a) Fan Voltage vs. IR-to-Ping Pong Ball Distance
    (b) Fan Current vs. IR-to-Ping Pong Ball Distance
    (c) Fan Power vs. IR-to-Ping Pong Ball Distance

    SOLUTION: 3 plots present, labeled with appropriate sig figs and best fit curves.

11. How does increasing fan voltage affect the levitation height of the ping pong ball?

    SOLUTION: Increasing fan voltage will increase the power of the fan, resulting in a higher ball height.

12. Does the relationship between **fan current** and ball height appear linear or nonlinear? Explain your reasoning.

    SOLUTION: Fan current and ball height are not linear. Back EMF and motor load are factors that come into play when current is increased, which will have a nonlinear impact on ball height.

13. Which variable—fan voltage, current, or power—shows the clearest correlation with ball distance? Why might this be the case? Compare the general trends in your plots to your expectations before the experiment. Did anything surprise you?

    SOLUTION: Power is the likely best linear correlation with ball distance. It represents the total energy being transfered to the ball, and is a combination of voltage and current.

14. In addition to your plots, perform a hypothesis test at a significance level of 0.05 to determine whether changes in fan voltage significantly affect the ping pong ball's levitation height. Clearly state your null and alternative hypotheses, carry out the test using your data, and state your conclusion.

    SOLUTION: Null: Ball height at a low voltage is the same as ball height at a high voltage.

$$H_0 : h_{low} = h_{high}$$

Alternative: Ball height at a low voltage is not the same as ball height at a high voltage.

$$H_a : h_{low} \neq h_{high}$$

Compute a two sample Welch's t-test statistic assuming unequal variances between fan voltages. A pooled statistic is acceptable, so long as the variance assumption is stated.

$$t = \frac{\bar{h}_1 - \bar{h}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{3}$$

$$\nu = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(s_1^2/n_1\right)^2}{n_1 - 1} + \frac{\left(s_2^2/n_2\right)^2}{n_2 - 1}} \tag{4}$$

15. Investigate whether hysteresis is present in the ping pong tower system by plotting ball height as fan voltage is increased and then decreased.
    (a) Using the dataset collected while sweeping fan voltage upward and then downward, convert IR sensor voltage measurements into distance using your calibration curve.
    (b) In Excel, create a scatter plot with **fan voltage on the horizontal axis** and **ball distance on the vertical axis**. Ensure the data is plotted in time order so that the increasing and decreasing voltage sweeps appear as separate paths.
    (c) Label the portions of the curve corresponding to increasing and decreasing voltage, and determine whether a hysteresis loop is visible.
    (d) Briefly explain possible physical reasons why hysteresis may or may not appear in this system.

SOLUTION: Plot should be included for credit, as ell as an explanation about hysteresis–this is for completion