NUMI Hadron Monitor - Calibration Stand

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Abstract

The objective of the project is to develop a calibration stand for the NuMI Hadron Monitor. This monitor consists of a 5x5 grid of ionization chambers and is positioned downstream of the target system to detect charged particles that are extracted from the target. The monitor plays a crucial role in accurately aligning the target on the beamline. The calibration stand is made to calibrate the signal of individual grid of a brand-new hadron monitor by using a radioactive source. We will develop the motion control system which reads a position of the radioactive source with respect to the individual grid location from the position sensor and feedbacks to the motor driver to position the source to the desired location.

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Acknowledgements

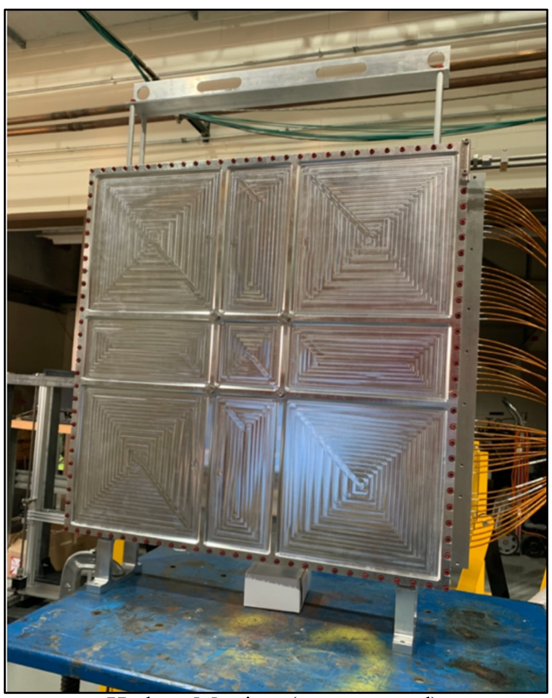
I would like to express my wholehearted gratitude to Carol Johnstone for accepting me into the CCI Fermilab internship. I'd also like to express my gratitude towards Katsuya Yonehara, my supervisor, who provided me with invaluable guidance and the freedom to tackle my project in the most creative way possible. I'd also like to express my gratitude to George Lolov and George Maniatis, both of which helped me with the electrical and mechanical knowledge needed to work on the Hadron Monitor.

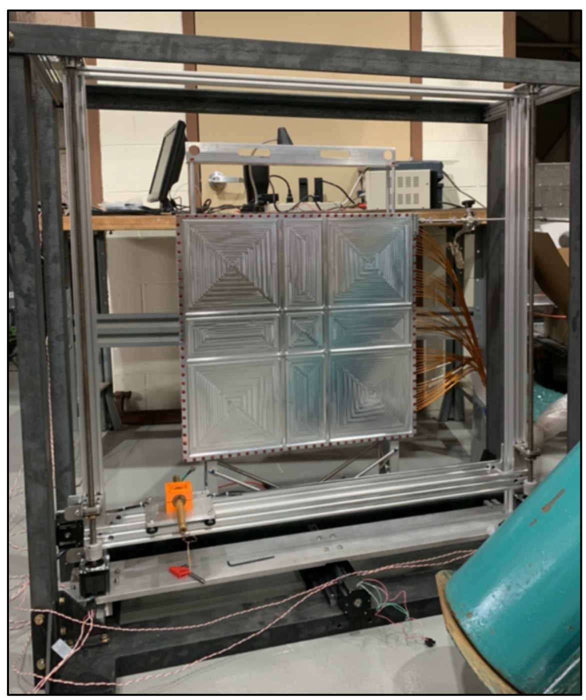
1 Introduction

The Hadron Monitor is a helium-based ionization chamber used to detect Meson particles. It consists of twenty-five helium chambers arranged in a 5x5 grid. The monitor will be placed in front of the beamline to detect the area with the highest concentration of charged particles so the target can be positioned in front of the beamline.

Previously, when the location of charged particles was found, it was necessary to manually align the target with the beamline, which was inefficient and time-consuming. The Monitor stand was designed and fabricated to align the target automatically, removing the need to manually align the target and making the process much faster. The stand contains multiple motors and a platform (which will hold the desired target) that will move in the X, Y, and Z axes using the location provided by the Hadron Monitor. The computers will then take that data from the Hadron Monitor and align the target in front of the beamline.

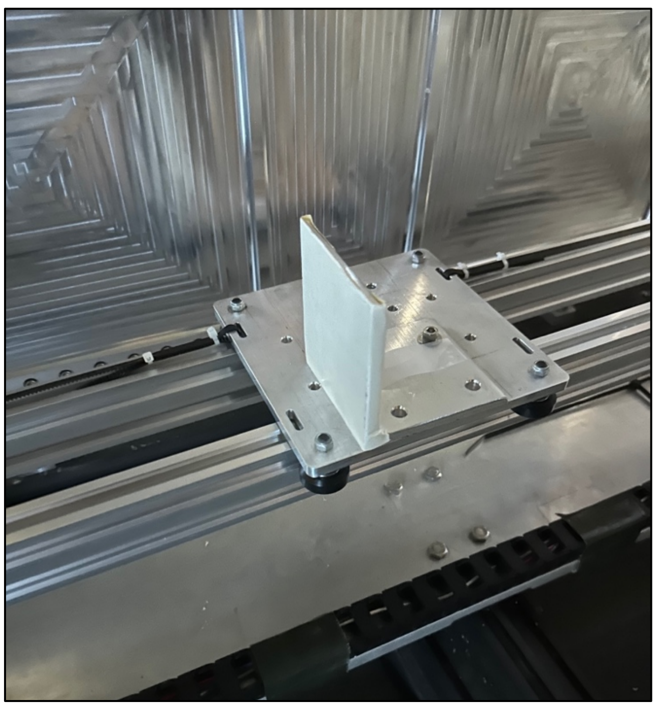
To accurately move the motors, it is necessary to use IR sensors to detect if the target is in the correct position. There were four sensors used on stand, xLeft (xL) and xRight (xR) along with yTop (yT) and yBottom (yB). There will not be any calibration for the IR sensors on the Z-axis since there are no Z-axis IR sensors. Two sensors per axis is necessary to cover the other sensor's blind spot. It will continuously adjust the platform using the distances from the IR sensors until it reaches the desired location. However, the current IR sensors provide inaccurate distance readings. The purpose of this internship is to calibrate the sensors to have an accuracy of ± 3mm so they can be used to accurately align the target with the beamline.


Hadron Monitor (not mounted)

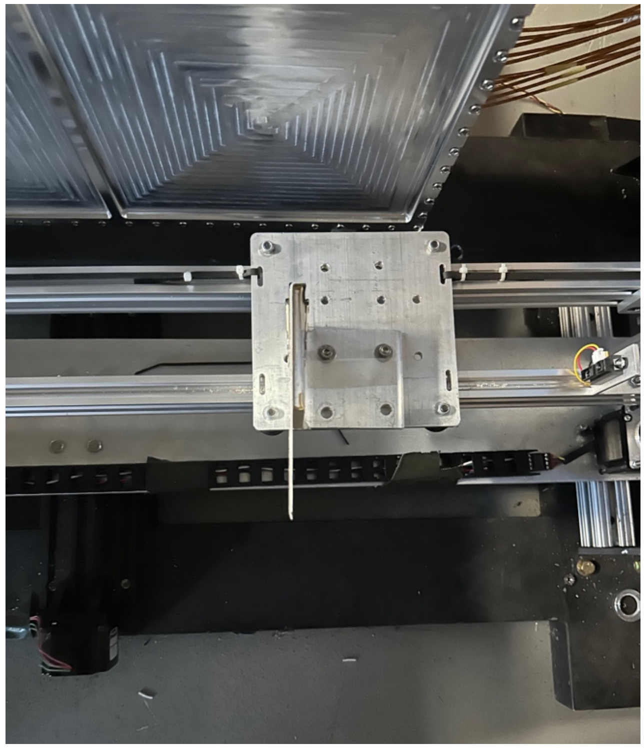

Hadron Monitor mounted in its respective stand

2 Procedure and tools used

To calibrate the IR sensors, it's crucial to identify how and where the IR sensors' outputs begin to drift. To do that, a reflector will be mounted on the moving platform and will be placed in the line of sight of the reflector. The platform will be moved in centimeter increments using the ruler and the distance output will be recorded on an excel sheet. The reflector is an aluminum bracket with four ¼" screw holes fabricated by the machinist working in MI8. However, when the reflector was fabricated, it was slightly off alignment from the sensor's line of sight, so a piece of aluminum was attached with two binder clips to the front of the reflector to extend the "reflecting surface". A 90cm aluminum ruler was placed right next the IR sensors and reflector to move the platform the correct distances. A flashlight was shined directly above piece of aluminum (the piece that extended the reflecting surface) that cast a very slim shadow which acted a marker on the ruler.



The aluminum bracket (reflector) attached to the platform



The aluminum piece is attached to the left side of the reflector. A Flashlight was shined from this angle, casting a slim shadow on the ruler acting as a makeshift marker.

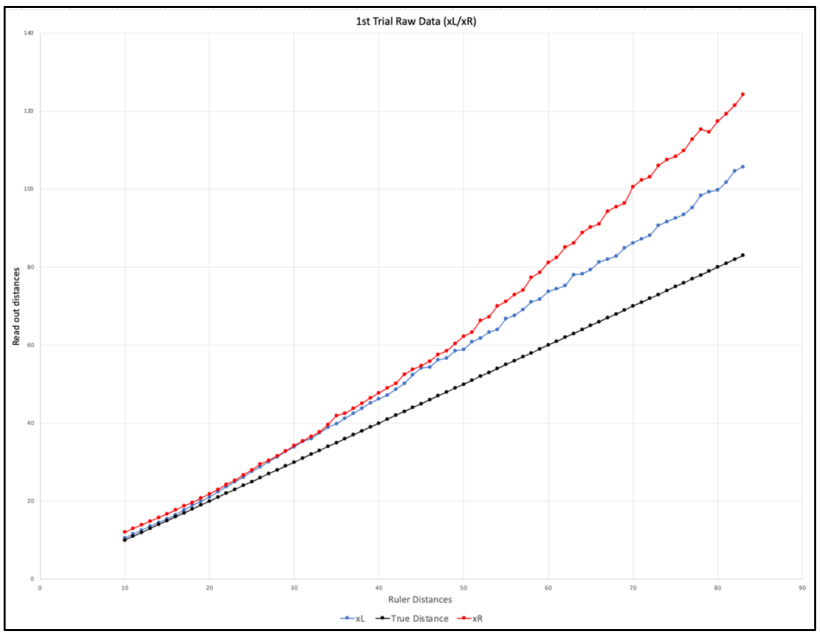
The sensors were connected to a voltage to distance converter (MCP3008 microchip). The purpose of this chip was to take the output of the IR sensor (which is in volts) and convert this voltage into a signal that the computer can properly process.[1] This converter was then connected to a breadboard, wired to its respective sensors, and hooked up to a Raspberry Pi 4 Model B. A previous intern had programmed a Python program that took the signals output by the microchip and converted them into distances, which the program would then output. It's important to note that the Python program takes in thousands of inputs from the IR sensor. The program then averages all inputs one thousand times and outputs distances few times per second. The reason for this is to reduce the fluctuation of the sensor's outputs. It is possible to increase the amount of times the program averages the IR sensor's data. This helps smooth out some of the fluctuations but reduces the number of the distance outputs that the program produces per second.

3 Gathering raw data of sensors xL and xR (Trial 1)

[1] *2.7V 4-channel/8-channel 10-bit a/D converters ... - adafruit industries*. Available at: https://cdn-shop.adafruit.com/datasheets/MCP3008.pdf (Accessed: 9 August 2023).

The first trial tested the horizontal sensors xR and xL. For each sensor, the data from the first 10 cm was not collected since the manufacturer had rated the sensors from 10-80 cm. If data was collected within the first 10cm, the sensors would output absurdly inaccurate data. [2] Unfortunately, this range cannot be calibrated so the sensors must be shifted backwards to take this unusable sensing range into account.

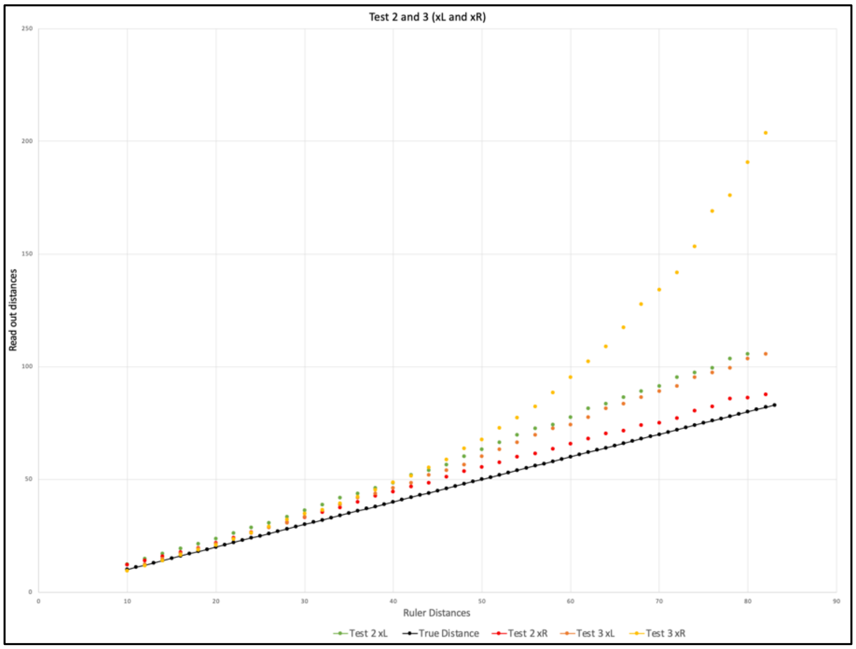
The first setup had the IR sensors flush with the motor's steel supports. The ruler origin begins at the brackets that mount the IR sensors. Data collection also began at the 10cm mark. A flashlight was shined at the extending surface creating a slim shadow tracker, which acted a marker on the ruler, greatly reducing the possibility of human error. The IR read out data was recorded in 1 cm intervals from 10 cm to 80 cm. The outputs recorded from the program were the most commonly occurring distances from the program. Raw data is shown below.



The black line refers to the correct distances that the sensors *should* output. The blue plot represents distances *actually* output by sensor xL. Similarly, the red plot represents the distances output by the sensor xR. Results show that from the 10cm to 40cm range, outputs are stable and appear to be linear. However, in distances beyond 45 cm, the read-out distances seem to fluctuate quite a bit. Distances also increase exponentially rather than being offset by a consistent amount.

Two more tests were performed that took IR distances every 2cm rather than 1. Results have shown that the not only are readings from xL and xR constantly fluctuating, but they are not reproducible.

[2] *Gp2y0a21yk E - sharp global*. Available at: https://global.sharp/products/device/lineup/data/pdf/datasheet/gp2y0a21yk_e.pdf (Accessed: 9 August 2023).



However, when analyzing the current measuring method, we speculated that the piece of aluminum attached to the reflector may be experiencing some unwanted vibrations. The reason for this could be because of the thinness of the metal and the aluminum piece only being attached using two binder clips. The aluminum piece was then removed, and reflector was bolted directly in front of the sensor's line of sight (which only allowed for two bolts to be bolted since there was not enough space for all four bolts). A few distance points were selected to quickly test if that may have been the issue and it resulted in much more consistent data points and less fluctuations. Now that the issues with stability and reproducibility fixed, a second data collection trial was planned for gathering the raw data.

4 Gathering raw data for sensors xL and xR (Trial 2)

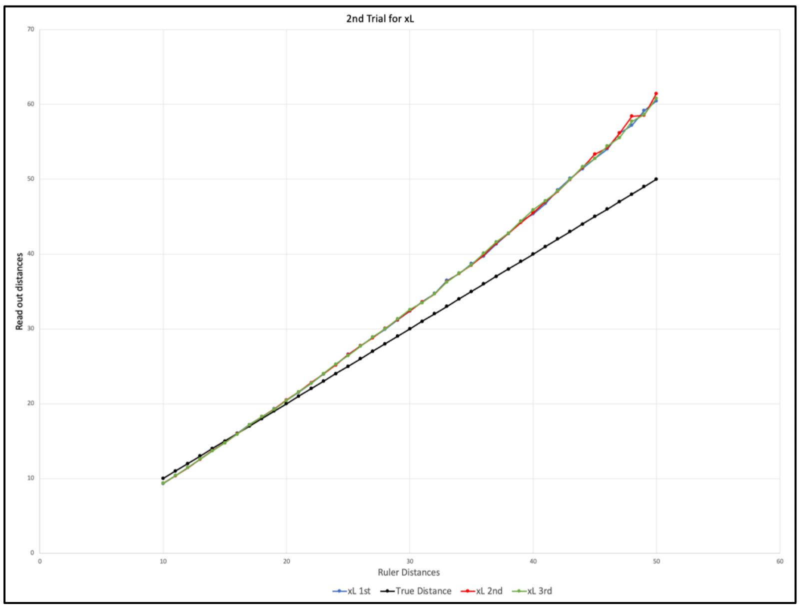
Before beginning the second trial, the sensor manual had tested the sensors results based on a white reflective object.[3] While this isn't strictly necessary for the sensor's operations, the reflector had a light-colored tape attached to the reflector to reduce any potential issues with the data collections.

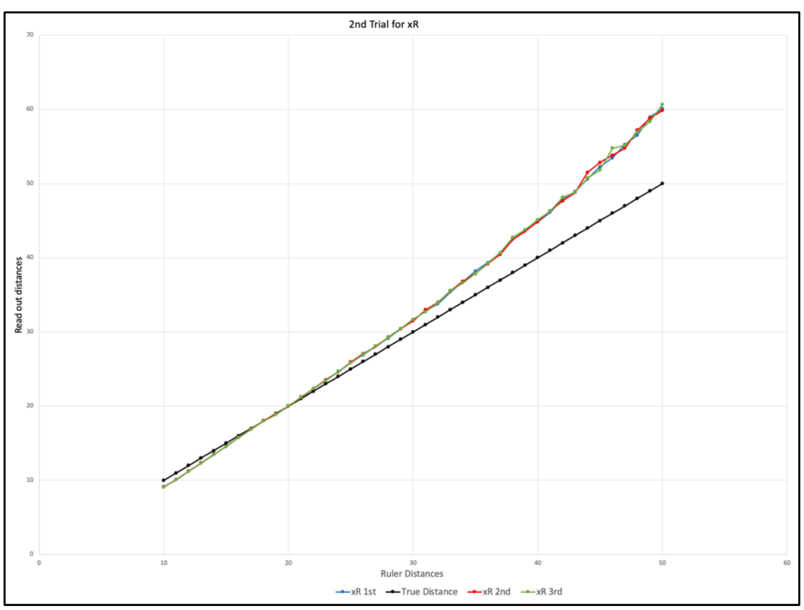
Data collection for the second trial was also improved. The previous method of collecting data was taking the most commonly occurring distance output by the program and recording it once

[3] *Gp2y0a21yk E - sharp global*. Available at: https://global.sharp/products/device/lineup/data/pdf/datasheet/gp2y0a21yk_e.pdf (Accessed: 9 August 2023).

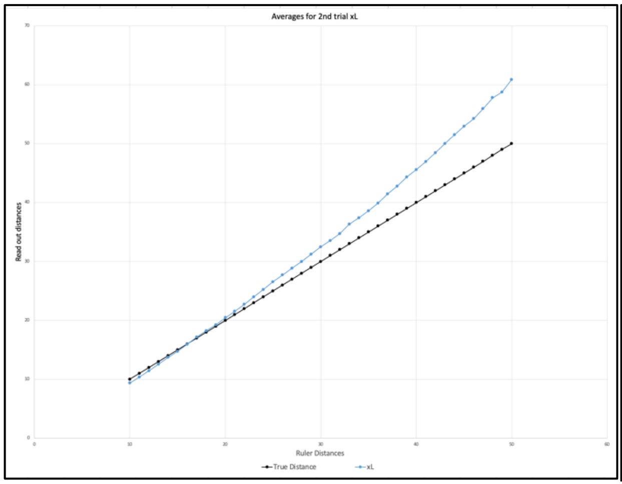
for each centimeter interval. The new method takes commonly occurring distances output by the program three times and averages them for a more accurate measurement.

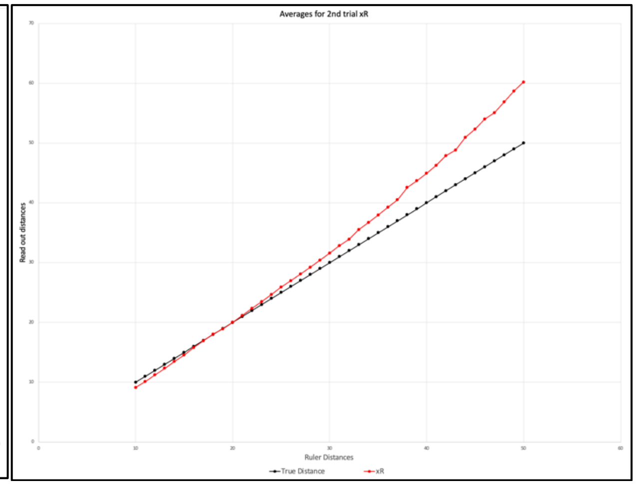
With the new setup in place and the new data collection method, recordings were taken again. However, the distance range was shortened to 10-50cm. This is because the Hadron Monitor is around 50cm wide and 50cm tall. The data from the Trial 1 revealed that the 10-40cm range was the most stable. Ranges 40-50cm are still stable enough, so the goal calibration range was changed to 10-50cm. This allows for 40cm of calibrated data per sensor. With each sensor covering 40cm on their own sides, it will be more than enough to cover the entire width and height of the Hadron Monitor. Results below are the raw data for three data points (without averaging them).



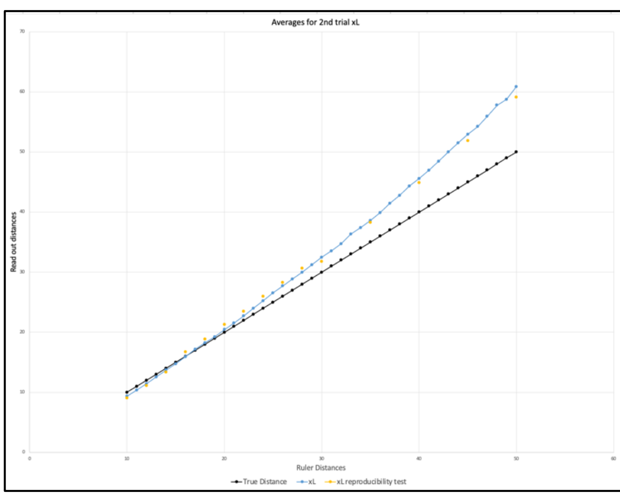


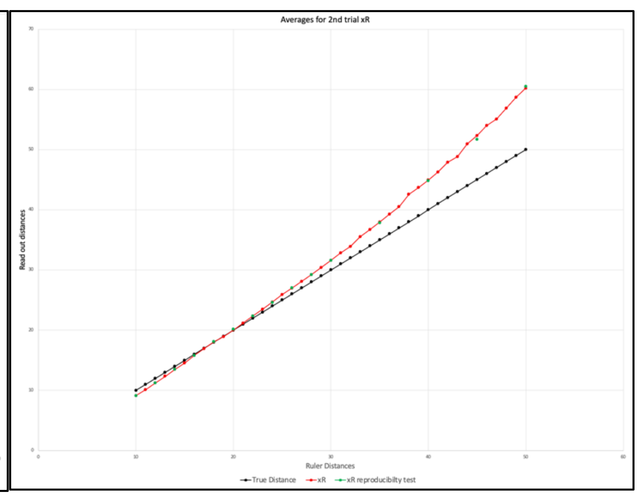
These plots show that the minimal fluctuations in distance when compared to one another, reaffirming that the new measuring procedure is much more stable. The average of each graphs' three plots is shown below.





However, the important question is whether the results are reproducable. A reproducibility test was performed using the same methods as in Trial 2, but data points were taken in larger increments. For the range of 10-30cm, data points were collected every 2cm. For the range of 30-50cm, data was collected every 5cm. This was done to reduce the amount of time spent collecting data. These were then compared with the earlier averages of the xL and xR.



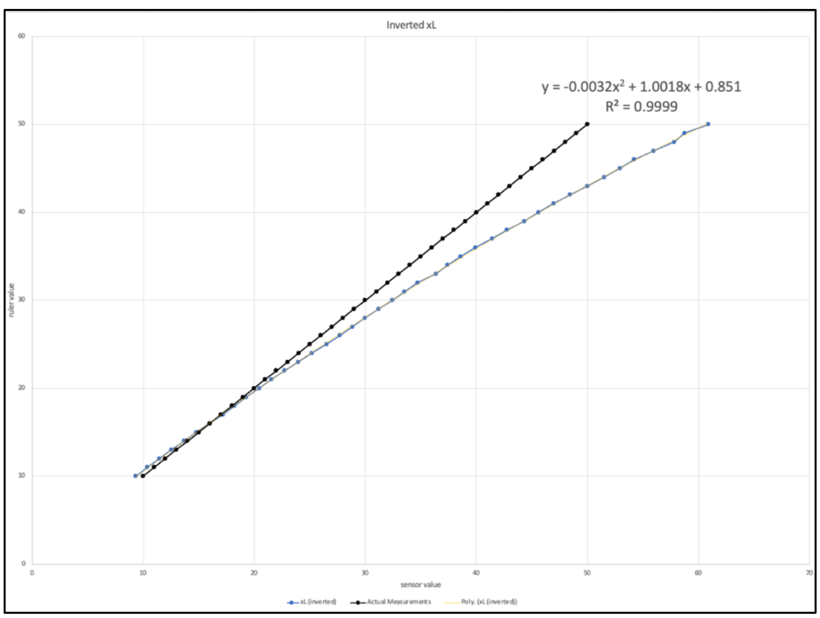


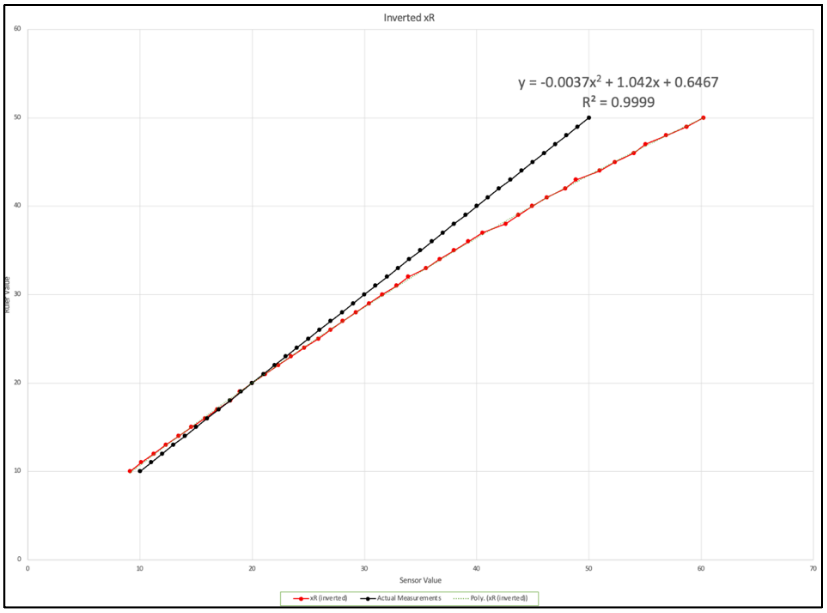
When comparing the data from Trial 1 and Trial 2, removing the aluminum piece improved the sensors reproducibility. A reason for this improvement was possibly because the vibrations that aluminum piece experienced were not visible to the naked eye. The distance outputs from the

Python also had less fluctuations and more stability by removing the aluminum piece. Now that data is stable and reproducible, we can apply a fitting curve and begin calibrating the sensors.

5 Calibrating sensors' xL and xR

To calibrate the sensors, it is first necessary to apply a fitting curve to the data. The fitting curves were applied on Trial 2's data as they have proven to be stable and reproducible. The fitting curves were only applied to the data plot with 1cm intervals as this gave us the most comprehensive graph of the IR sensor. It's important that the graphs are inverted before applying a fitting curve, as it helps reduce and simplify the equation for retrieving calibrated data. The fitting curve is a polynomial due to the plot's exponential growth pattern. If we were to create the fitting curve without inverting the graph, we'd need to solve for X since that represents the calibrated data we want the program to output. To do that we'd need to use the quadratic equation which would take more time than if we just inverted the graph. Since the inverted graph would have the ruler measurements on the Y-axis and the sensor outputs on the X-axis, the equation for the fitting curve would spit out the calibrated data without needing to solve for X since Y would already be the calibrated data. The graphs were inverted and a fitting curve was applied to each of the sensors' plot.





The equations for the fitting curve are listed below.

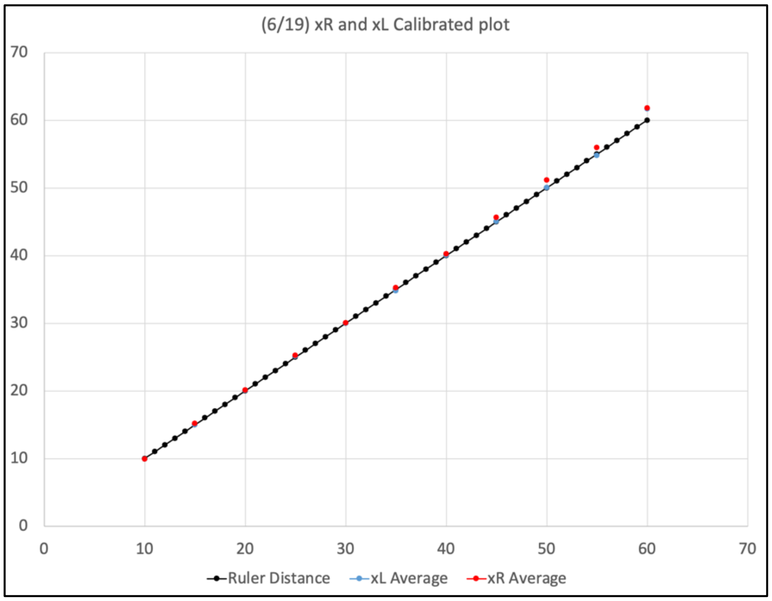
xL fitting curve equation:

$$y = -0.0032x^2 + 1.0018x + 0.851$$

xR fitting curve equation:

$$y = -0.0037x^2 + 1.042x + 0.6467$$

Using these two equations, we can plug them into the Python program and the IR sensors should output calibrated data. After plugging the equations into the program, we performed a calibration test on the sensors to ensure that the calibration was successful. The calibration test was performed with the same measuring setup used to gather the uncalibrated data from Trial 2. However, instead of gathering output data every 1cm or 2cm, the intervals were every 5cm from the range 10-60cm. While the goal was to calibrate the sensors from 10cm to 50cm, we wanted to see how well the calibration would do beyond the goal calibration range. Graphs were not inverted since we are not extracting an equation and are only looking at results. Data collection was the same method used in Trial 2, which was collecting three of the most recurring distances output by the Python program, averaging all three, and plotting them on a scatter plot.

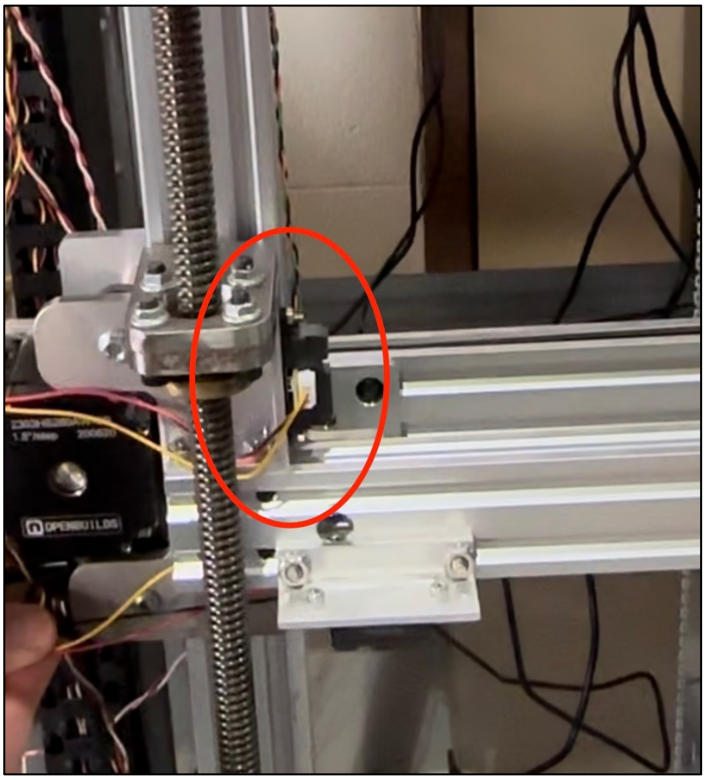


(X-axis is Ruler distance; Y-axis is Sensor Output)

The calibration for both sensors resulted in quite accurate distances in the 10-50cm range, with the distance outputs within ± 3mm of the correct distances. Looking at the data at the 55cm mark, the average of the three data points is 54.763cm for xL and 55.960cm for xR. When looking at the data at the 60cm mark, the average of the outputs is 61.687cm for xL and 61.790cm for xR. It seems that the calibration equation will not guarantee accurate data beyond 50cm, which was the expectation. Most of the outputs beyond 50cm were outside of the desired ± 3mm accuracy range. While yes, xL still output an average 54.763cm when at the 55cm mark, the fluctuation between the three of the most common outputs was too large to be relied on for accurate measurements. This means that the guaranteed accuracy range will remain at 10-50cm.

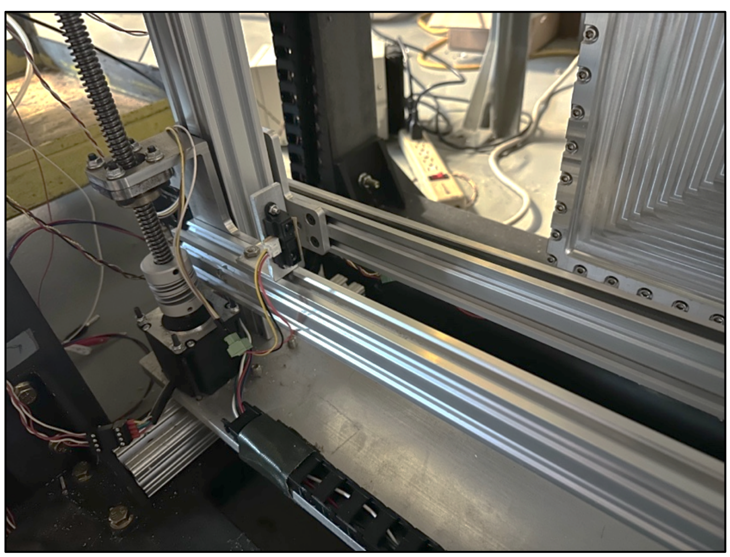
6 Unusual calibration issues with xL and xR

When performing Trials 1 and 2 along with the calibration test for xL and xR, both sensors were positioned to be flush with the steel supports of the motors.

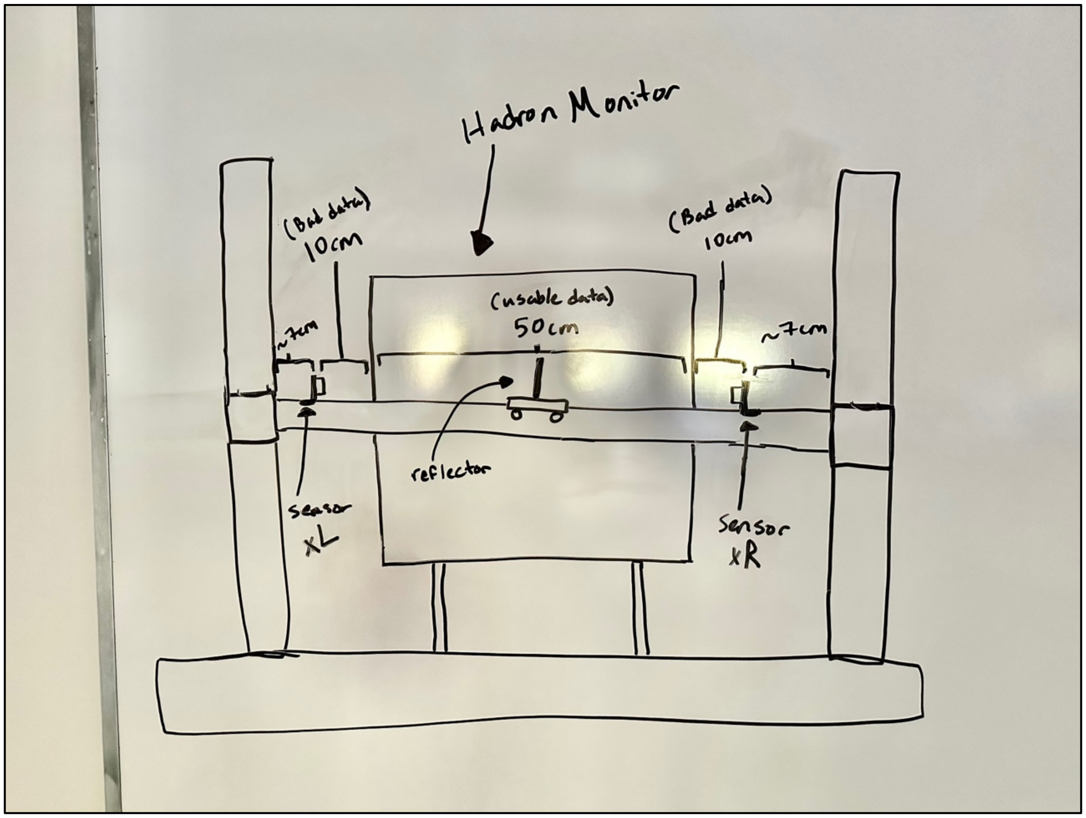


Sensor xL flush with the steel supports.

The sensors were then shifted ~7cm closer to the Hadron monitor. This is because we have a range of 40cm of calibrated data (Hadron Monitor is 50cm wide) so it's necessary to move the sensors as close as possible to cover the entirety of the Hadron Monitor. Both sensors were moved closer to the monitor while taking account the first 10cm of each sensor's unusable sensing range. Refer to the diagram below for a visual representation of the sensor positions.

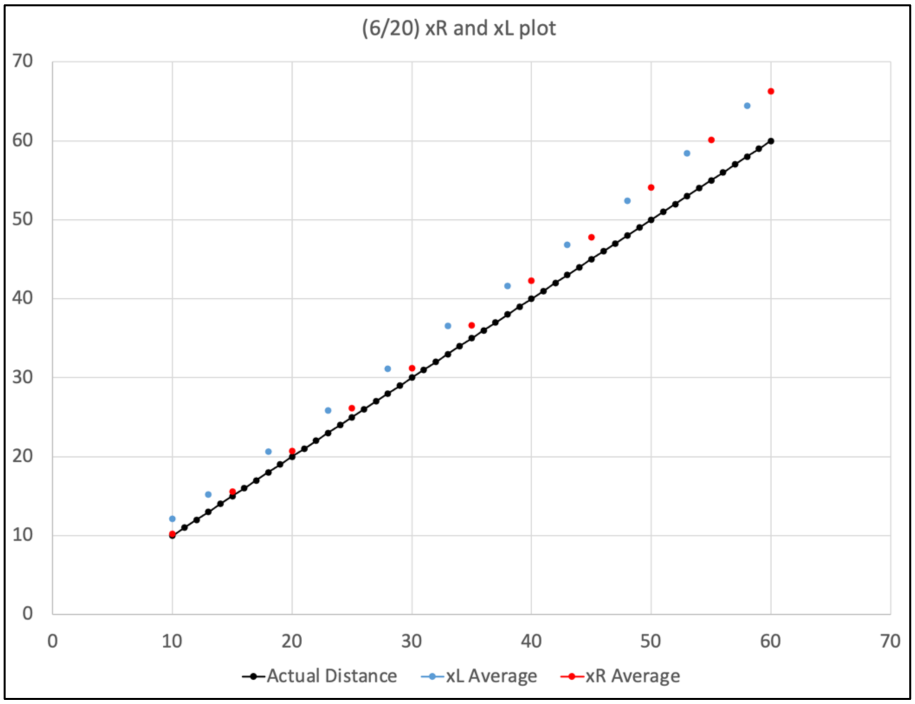


New position of sensor xL (moved 7cm to the right)



Visual Representation of new sensor positions

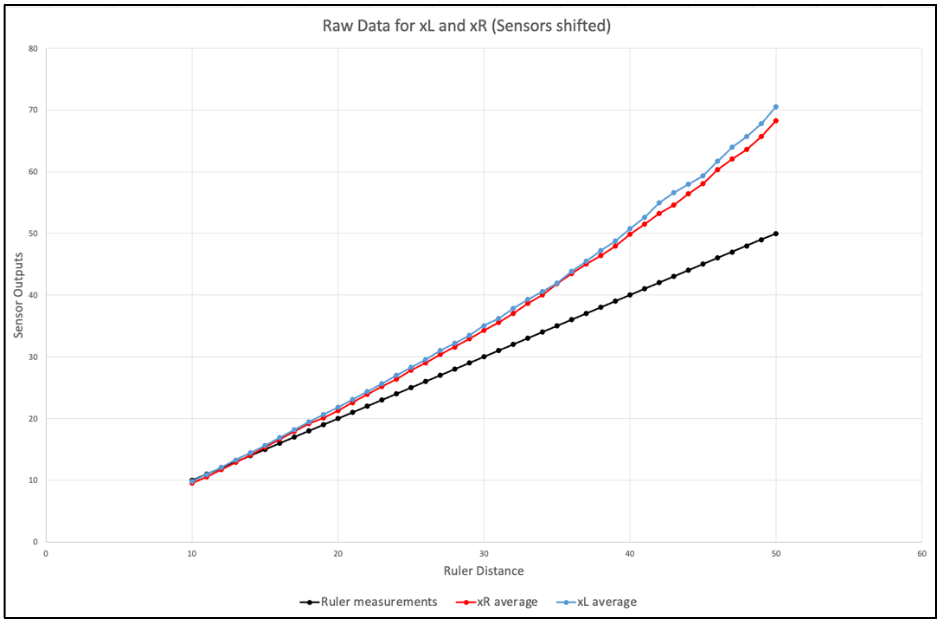
With the sensors shifted closer, a few distances points were taken to verify that the sensors operated normally. We noticed, however, that the sensors were not displaying accurate distances anymore despite using the new calibration. For example, when testing a distance point of 30cm from sensor xL, the Python program output 31.11cm, way over the acceptable ± 3mm accuracy range. Multiple distances were tested and most displayed distances that were above the ± 3mm acceptable accuracy range. When moving the sensors back to their original position (flush with the motor supports), the sensor's accuracy returned to normal. We decided to take two more tests, one for each sensor, to figure out where the sensors began outputting inaccurate data. Testing and data collection methods were the same used in Trial 2 but taken at 5cm increments. Results are shown below.



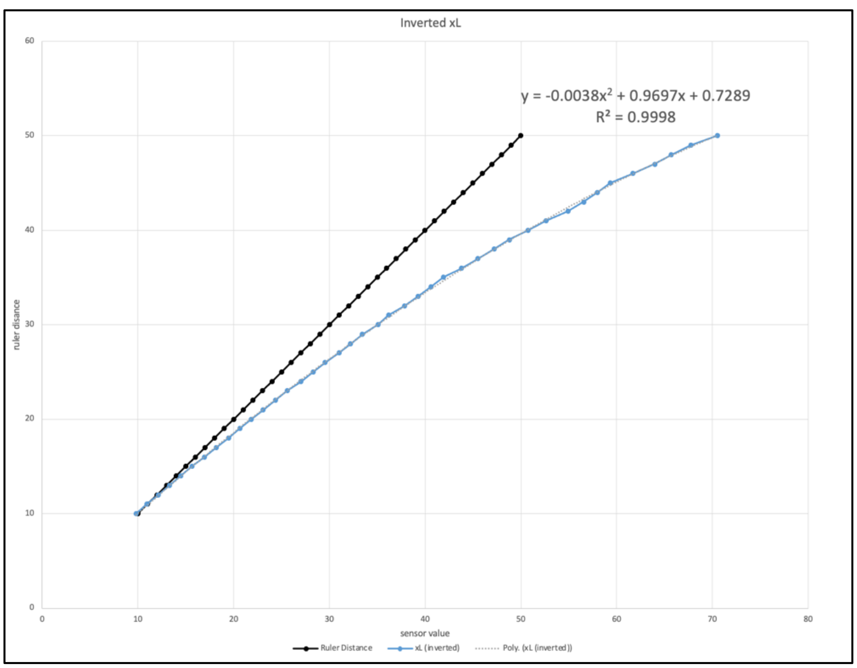
Sensor outputs after shifting 7cm (X-axis is Ruler distance; Y-axis is Sensor output)

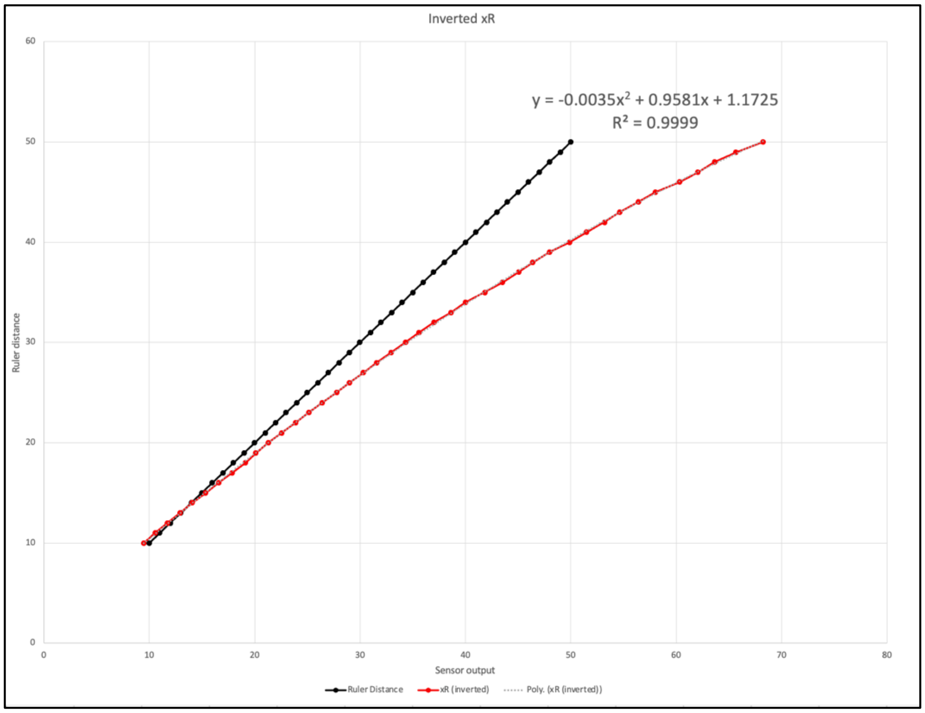
Sensor xL appears to be growing linearly but actually has a very slight exponential growth. Sensor xL output an average value of 15.180cm at 15cm but output a value of 52.420cm at 50cm. Sensor xR's exponential growth rate is more apparent. Sensor xR output an average value of 15.573 cm at 15cm but output an average value of 54.077cm at 50cm. This clearly ruined the calibration of the two horizontal sensors. We analyzed the current setup to figure out what may have caused this change, but the setup was identical to Trial 2's setup with the exception that setup was shifted 7cm for each sensor. What's strange is that sensor outputs return to normal when shifted back to their original positions (flush with steel supports).

We could not figure out the cause of this change, so a proposed solution was to add two different calibrations for each position. One calibration equation when sensors were flush with the steel supports, another calibration equation when the sensors are shifted 7cm closer to the Hadron Monitor (which is also 10cm away from the Hadron Monitor, to take the unusable data range into account). Measuring method was set up identical to Trial 2's setup. Earlier calibration equations were removed and the data points recorded were the raw, uncalibrated data. Data points were recorded at 1cm increments for the 10-50cm range. The graph for the raw data is shown below.



Calibrating the new data follows the same steps as the earlier calibration methods. Inverted graphs and calibration equations are shown below.





xL fitting curve equation (shifted):

$$y = -0.0038x^2 + 0.9697x + 0.7289$$

xR fitting curve equation (shifted):

$$y = -0.0035x^2 + 0.9581x + 1.1725$$

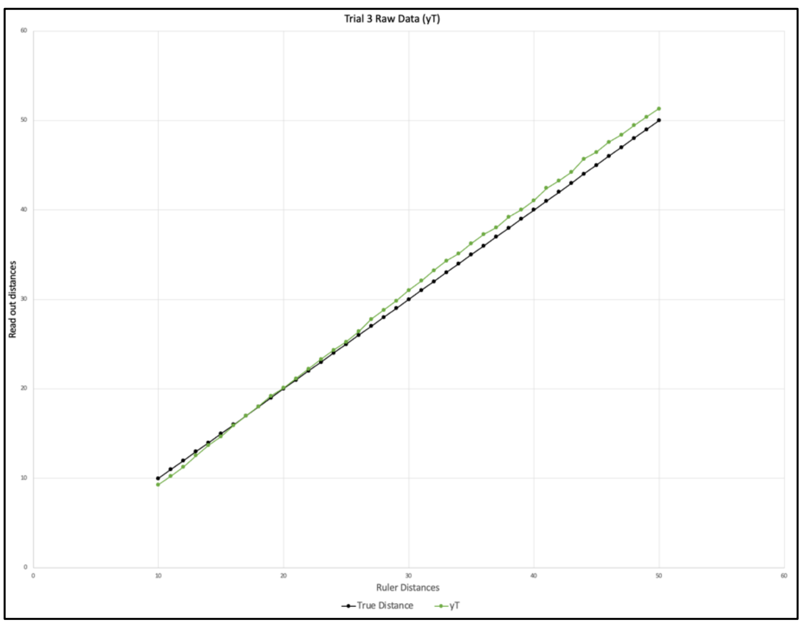
Once the equations were applied, a couple distance points were tested, and the sensors output distances within ± 3mm, which verifies that the sensors returned to the original calibrated state.

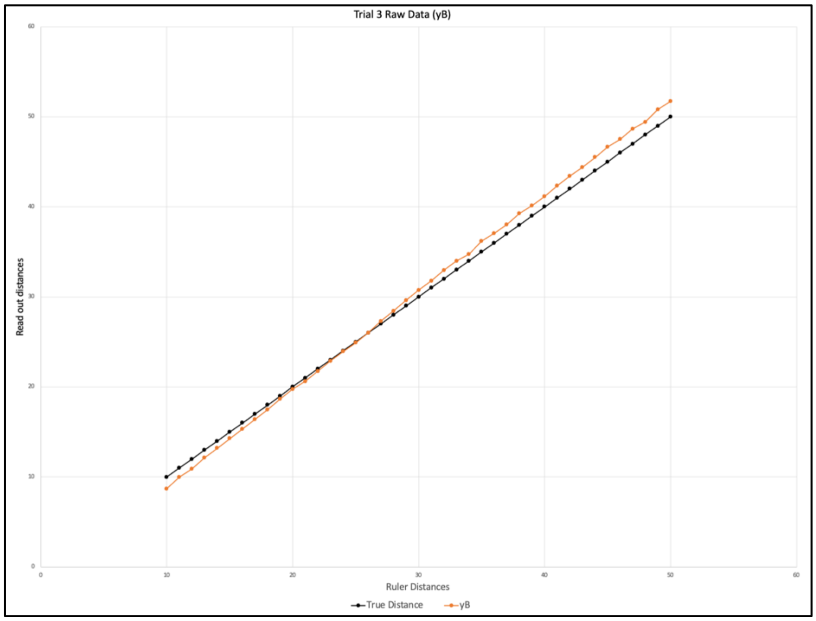
7 Gathering raw data for sensors yT and yB (Trial 3)

The methods for gathering data for the vertical sensors, yT and yB, are different than the data collection methods for the horizontal sensors. This is because the vertical sensors are not mounted on opposite sides like the horizontal sensors. Instead, sensor yB is mounted on the side of the railing (Sensor facing the ground), not at the bottom of the Hadron Monitor stand (supposed to face up). Sensor yT is mounted as expected, which is at the top of the Hadron monitor stand (facing the ground). There is also no platform that could be used to mount a reflector to, meaning that the IR sensors will be reflecting off the bottom of Hadron Monitor stand (The distance between the sensor and the bottom of the monitor is well over 80cm).

One solution was to mount a reflector on top of the rails that extended to be in sensor yT's line of sight. Since there was no platform to move, it was proposed to move the entire railing (the reflector was attached to) up and down with the help of a spirit level to ensure the railing remained level. The ruler was placed perpendicular to the railing and parallel to the sensor yT's line of sight. One concern is that the reflector being extended may create the vibrations observed in Trial 1's setup. This problem was tested with a couple distance points multiple times to test the sensor's reproducibility. To our surprise, the sensor's outputs were not only reproducible and very stable, but the outputs themselves were relatively accurate when compared to sensors' xL and xR.

With the new setup's reliability verified, we began collecting the data. While the setup for measuring had changed from Trial 2, the methods for collecting the data remained the same. Three of the most common distances outputs were collected, which were then averaged and plotted on a graph. Data points were recorded at 1cm intervals from 10-50cm. Results are shown below.

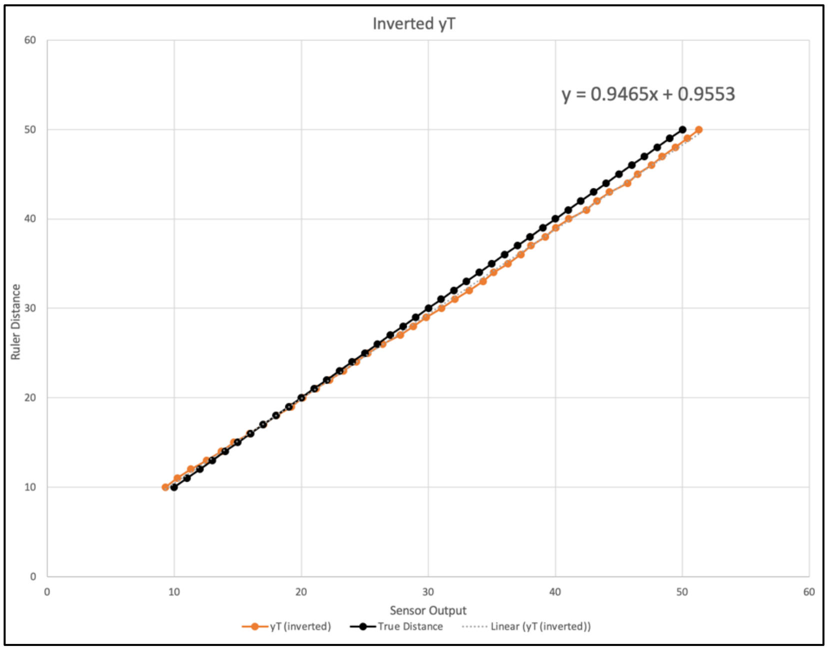


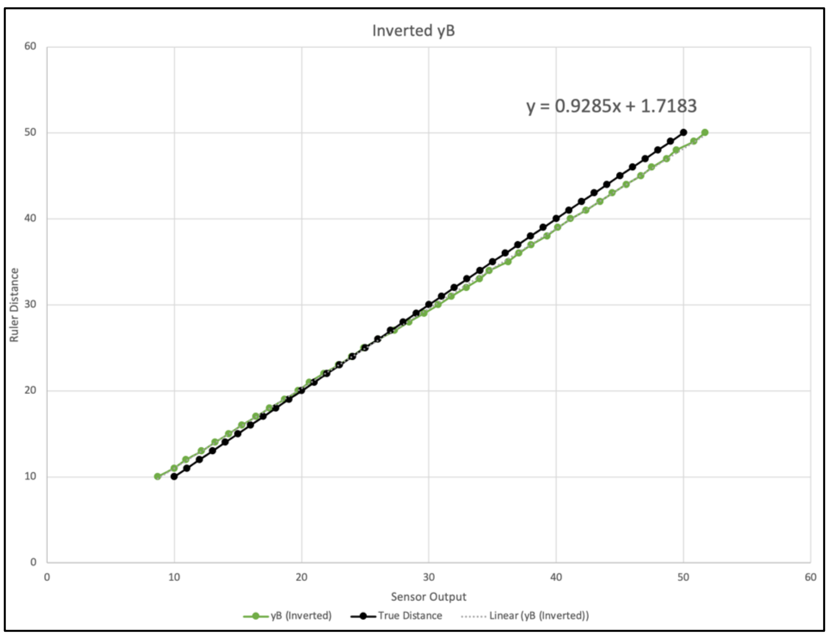


The accuracy of the data is surprisingly accurate. Unlike sensors xL and xR, these sensors have a growth pattern that is linear instead of exponential. The raw outputs were never off by more than 2cm for both yT and yB, which is significantly better than sensors xL and xR. The reason behind the differences in data between the horizontal and vertical sensors remains unclear.

8 Calibrating sensors' yT and yB

The calibration procedure for the vertical sensors is similar to the horizontal sensors. The only difference is that the fitting curve is a linear fit rather than a polynomial fit. The raw data graphs will be inverted, and a linear fitting curve will be applied. Once the curve is generated, we take the provided equation and plug this equation into the Python program. Inverted graphs and equations are provided below.





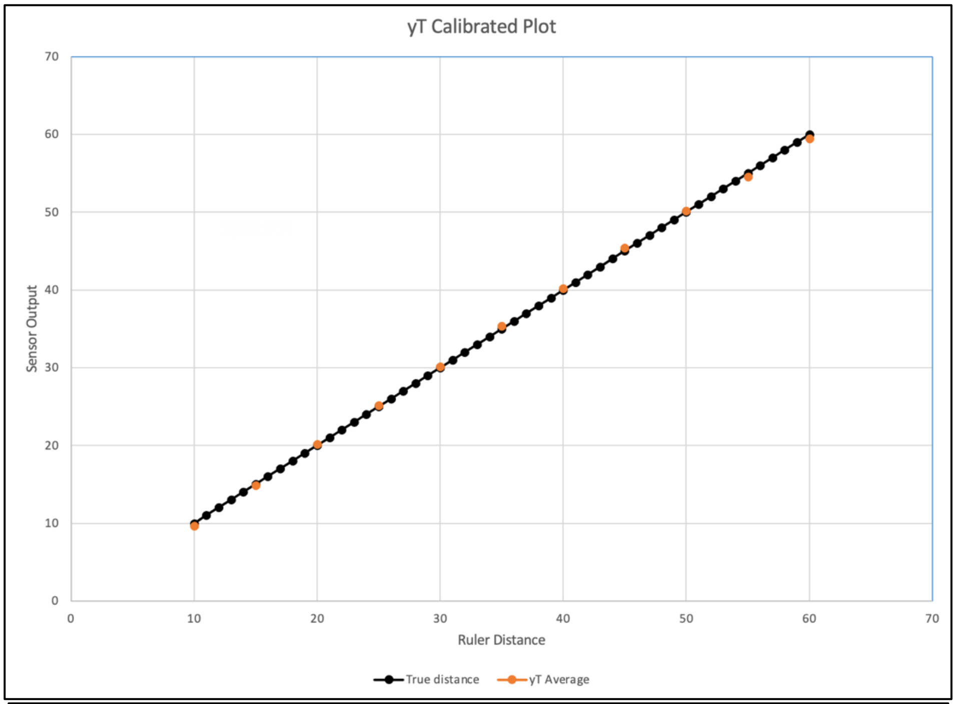
yT fitting curve equation:

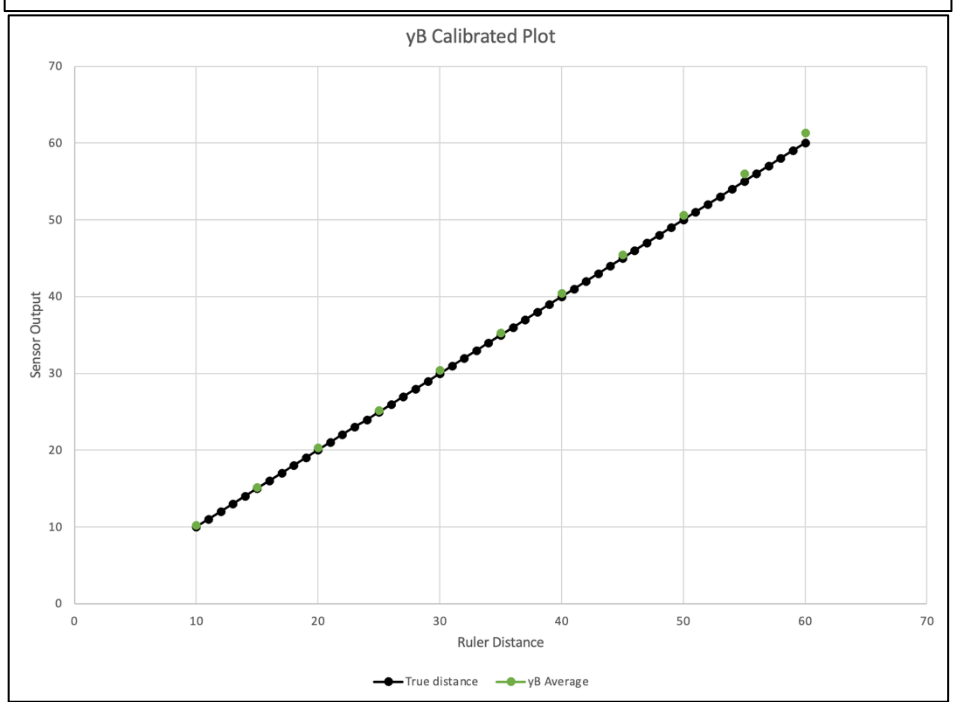
$$y = 0.9465x + 0.9553$$

yB fitting curve equation:

$$y = 0.9285x + 1.7183$$

After the equations were plugged into the Python program, a calibration test was performed for each of the sensors. The calibration test followed the same procedures used to gather the raw data from Trial 3. Data points were recorded at 5cm intervals from 10-60cm. Results are shown below.





The calibration results appear to be successful. Sensor outputs are well within the ± 3mm accuracy range in the 10-50cm range. When looking at the graphs from 50-60cm, we notice that the data points begin to drift off. Those points, however, are not necessary. The 50-60cm range was only tested to see if calibration worked beyond the goal range, which in this case, is not accurate enough to be relied on.

9 Conclusion

Calibration results for the horizontal sensors and vertical sensors appear to be a success. All four sensors display results that are not only stable and reproducible, but they are within the desired 3mm accuracy range. However, the calibration issues discussed in section 6 are still present. We do not know why the calibration was thrown off when sensors were shifted from their original calibration position. While, yes, there are two calibration equations for the horizontal sensors (one when sensors are flush with the steel supports; another when shifted ~7cm closer to the Hadron Monitor), those are the only positions that the horizontal sensors can be in if the user wants accurate results. This is not a pressing concern since the sensors are not meant to be shifted away from the intended position (that being ~7cm away from the stand or 10cm away from the Hadron Monitor), but it is an issue worth mentioning. Vertical sensors do not have this issue and can be shifted up or down freely without ruining the calibrations.

10 References

2.7V 4-channel/8-channel 10-bit a/D converters ... - adafruit industries. Available at: https://cdn-shop.adafruit.com/datasheets/MCP3008.pdf (Accessed: 9 August 2023).

Gp2y0a21yk E - sharp global. Available at: https://global.sharp/products/device/lineup/data/pdf/datasheet/gp2y0a21yk_e.pdf (Accessed: 9 August 2023).