Optical Distance Sensor Investigation

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Contribution Summary.

1. **Hiromu Yamamoto:** Responsible for hardware implementation and experimental data collection through LabVIEW interface development.
2. **Eshwar Pamula:** Responsible for static and dynamic calibration analysis using MATLAB, including uncertainty quantification.
3. **Walker Blevins:** Responsible for validating experimental results against theoretical models and synthesizing project findings into comprehensive documentation.

Finally, we would like to thank the following people for their help throughout our project:

- Mark Wolf (Lab Teaching Assistant for ME 3870).
- Professor Matthew Detrick.
- Chris Adams (Lab Co-ordinator).

Project Objectives.

What did we want to achieve?

- Build a functional optical distance sensor measurement system.
- Develop and conduct experiments to characterize the distance sensor's static and dynamic response behavior.
- Conduct an uncertainty analysis to compare experimental results to theoretical expectations.
- Construct an experimental datasheet for the SHARP GP2Y0A41SK0F.

The image on the right highlights the setup and a minimum measurement depth (4 cm).

Sensor Introduction.

Working Principle:
Optical distance sensors utilize IR light reflection and triangulation methods to measure distances, converting reflected light intensity into precise voltage outputs independent of surface properties.

Features & Specifications:
The SHARP GP2Y0A41SK0F sensor offers a compact solution with 4-30 cm detection range, 16.5ms response time, and integrated signal processing, making it ideal for accurate distance measurements.

Applications:
Widely implemented in robotics navigation, automated dispensing systems, and proximity detection where reliable, non-contact distance measurement is crucial. Our project explores its potential for precise distance monitoring and calibration.

Background & Operational Physics.

Operational Principle:

An infrared LED (IRLED) emits a focused beam of light which reflects off the target surface. The reflected light is then captured by a Position-Sensitive Detector (PSD) and the distribution of IR light intensity is encoded as a voltage signal using a Lateral Effect Photodiode (LEP).

$$R_A = \frac{\rho}{A}\left(\frac{L}{2} - x\right) \qquad i_A = i\left(\frac{1}{2} + \frac{x}{L}\right)$$

$$R_C = \frac{\rho}{A}\left(\frac{L}{2} + x\right) \qquad i_C = i\left(\frac{1}{2} - \frac{x}{L}\right)$$

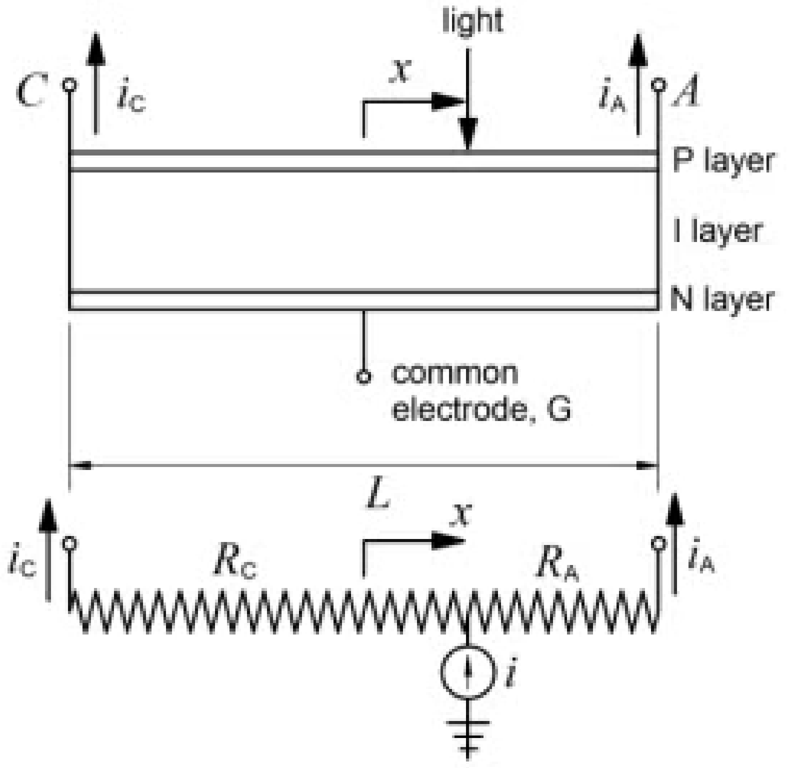


Figure 5. Position sensing diode

Position-Sensitive Detector (PSD):

- Phototransistor composed of semiconductive material
- Two independent resistance regions separated by a junction at the centroid of the PSD
- Relative resistances are inversely proportional to the intensity of distributed light across each region
- Source current is divided in parallel configuration

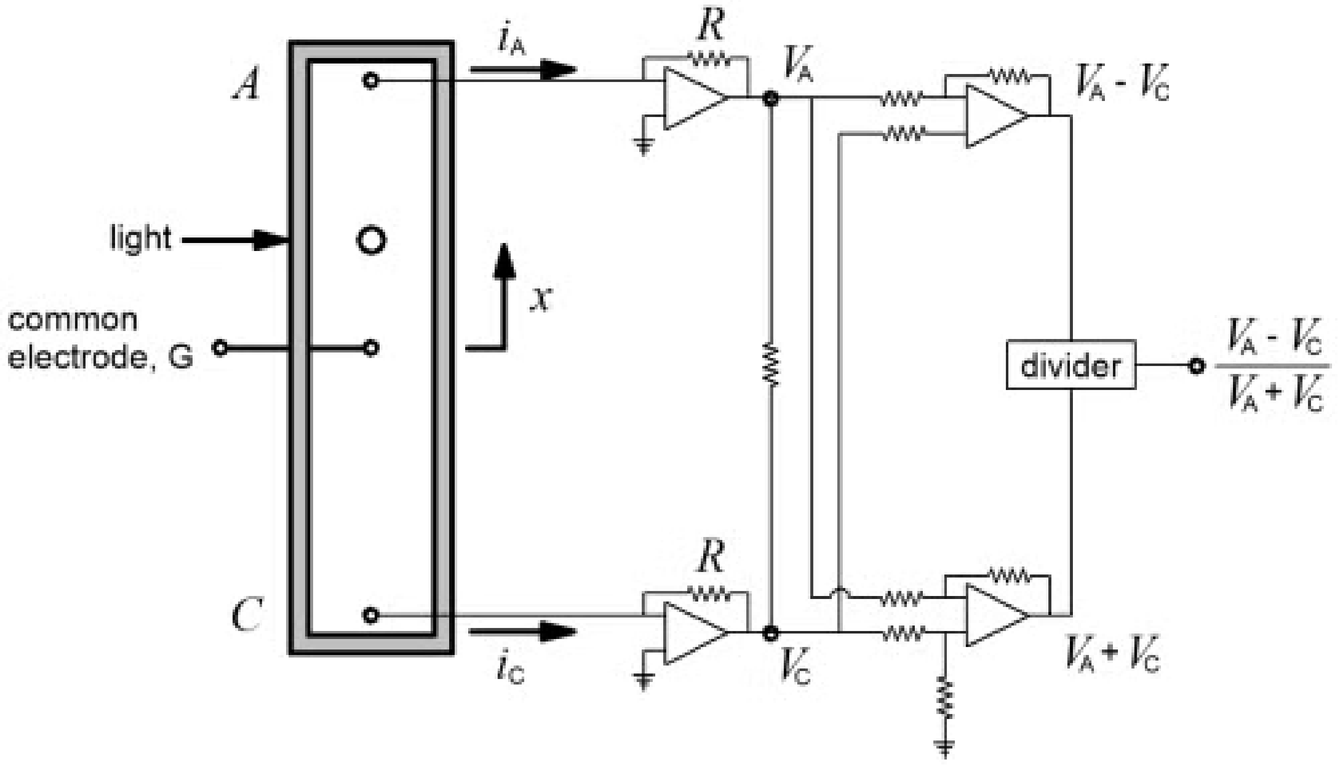


Figure 6. Lateral effect photodiode

Background & Operational Physics (cont.)

Lateral Effect Photodiode (LEP):

- Parallel currents are converted to voltages via voltage follower op-amps.
- Additional stage of op amps add and subtract the voltages.
- Divider Chip outputs voltage proportional to centroidal displacement of PSD detected light, normalized by the total light intensity.

$$V_o = \frac{V_A - V_C}{V_A + V_C} = \frac{Ri_A - Ri_C}{Ri_A + Ri_C} = \frac{i_A - i_C}{i_A + i_C} = \frac{i\left(\frac{1}{2}+\frac{x}{L}\right) - i\left(\frac{1}{2}-\frac{x}{L}\right)}{i\left(\frac{1}{2}+\frac{x}{L}\right) + i\left(\frac{1}{2}-\frac{x}{L}\right)} = \frac{\frac{2x}{L}}{1} = \frac{2}{L}x$$

$$w = \frac{f x_s}{x_s - f} \frac{y \sin\theta}{x_s - y\cos\theta}$$

Principle of Triangulation:

- Remaining internal circuitry further normalizes LEP output signal to produce a signal proportional to the normal distance.
- Pre-calibrated parameters account for fixed sensor geometry, and similar triangles are used to relate the reflected light's displacement to the normal distance of the target.

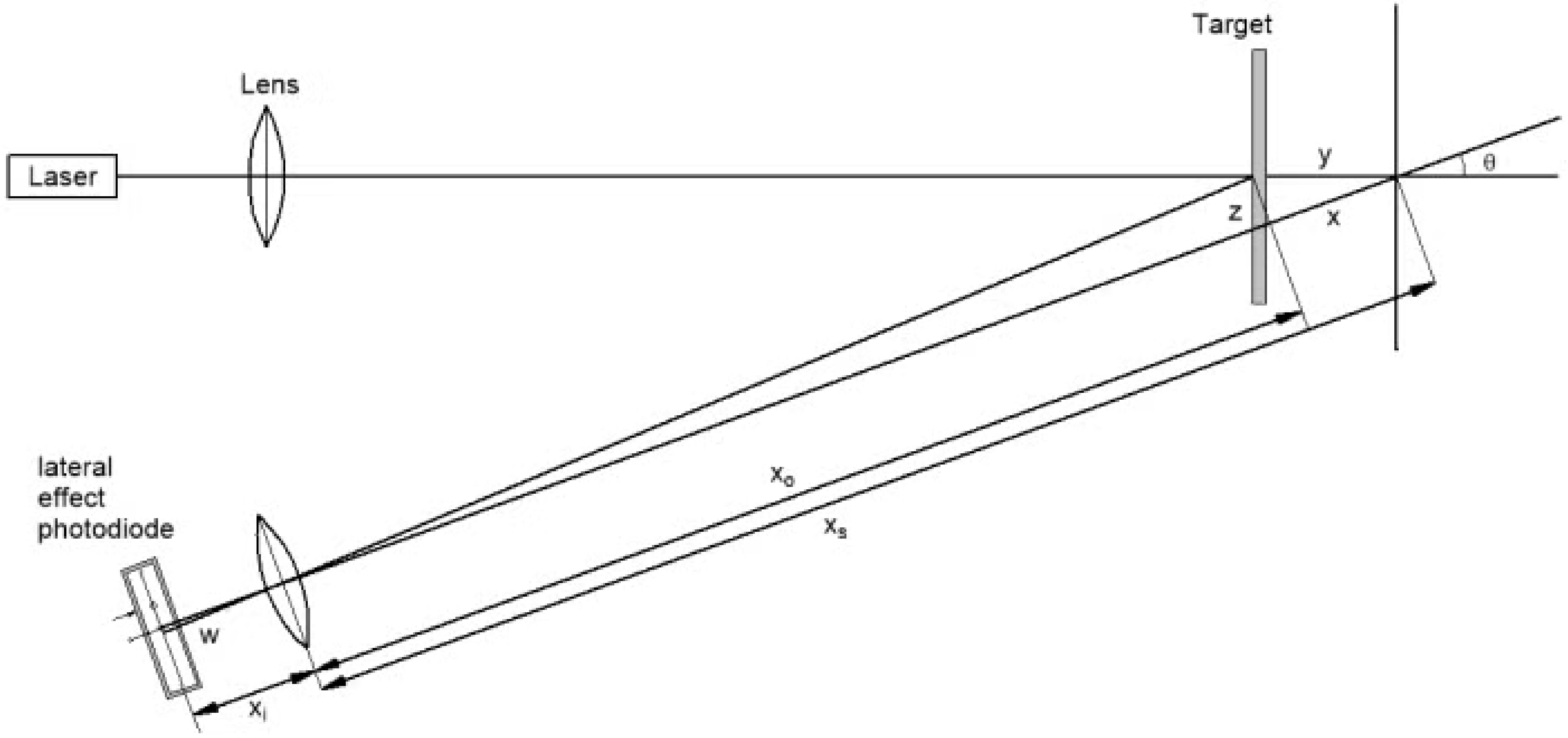
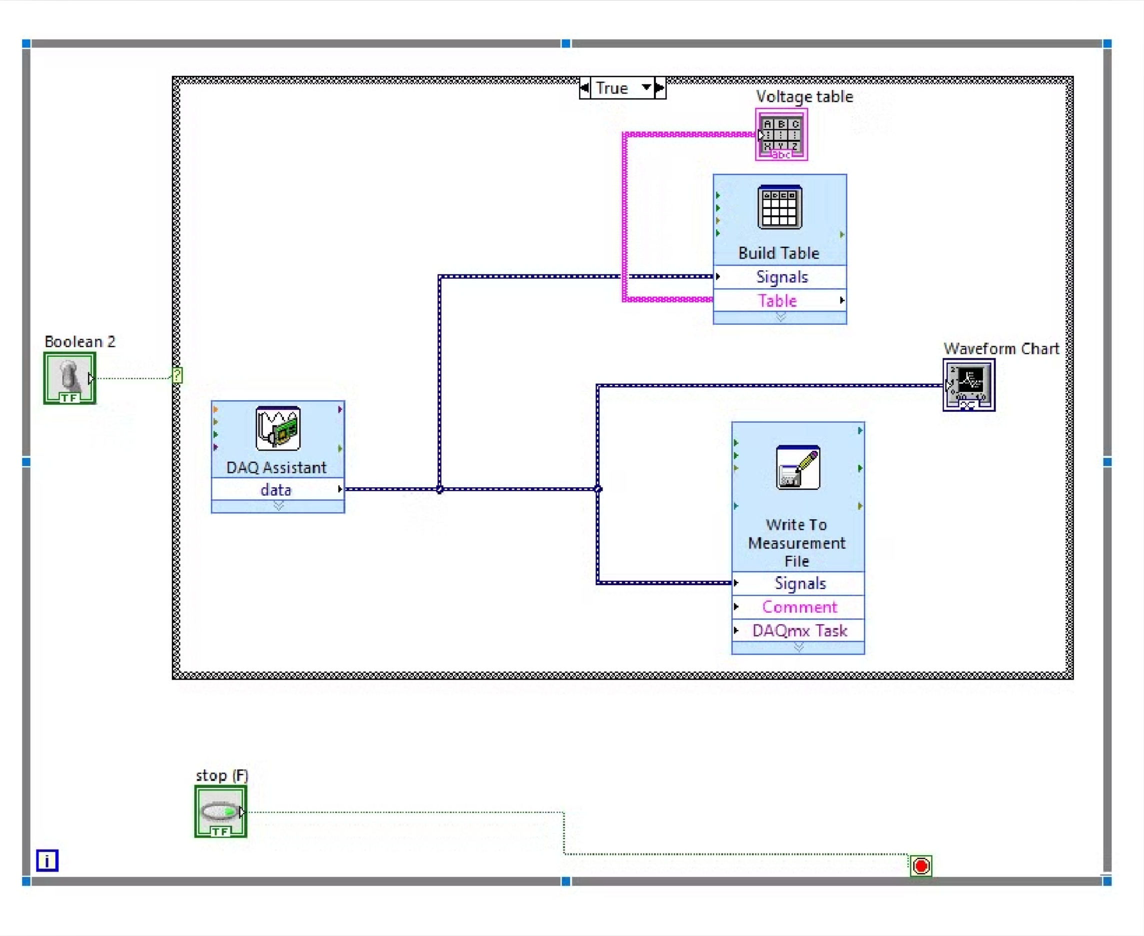


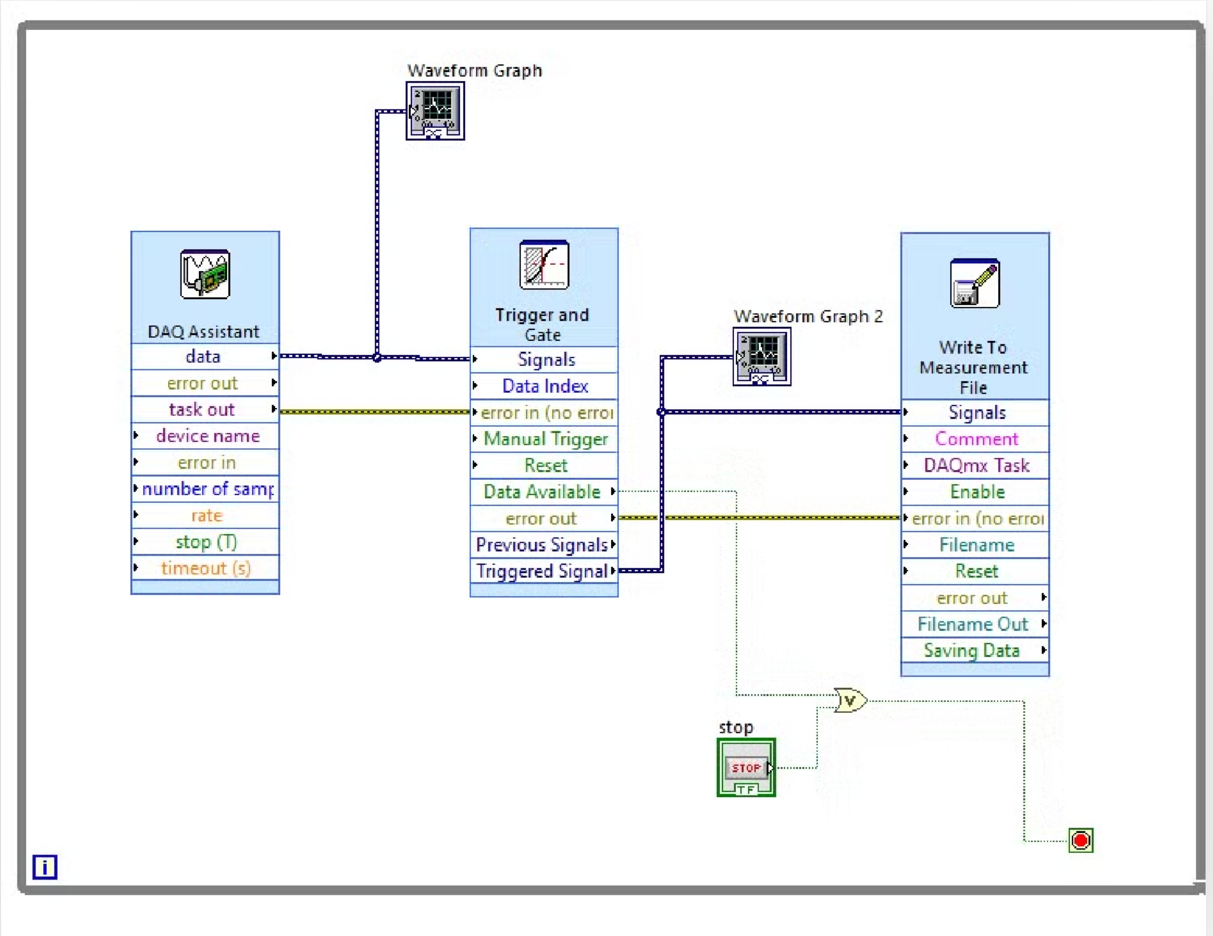
Figure 7. Triangulation

Experimental Setup - LabView.



Primary Configuration (Static Testing)

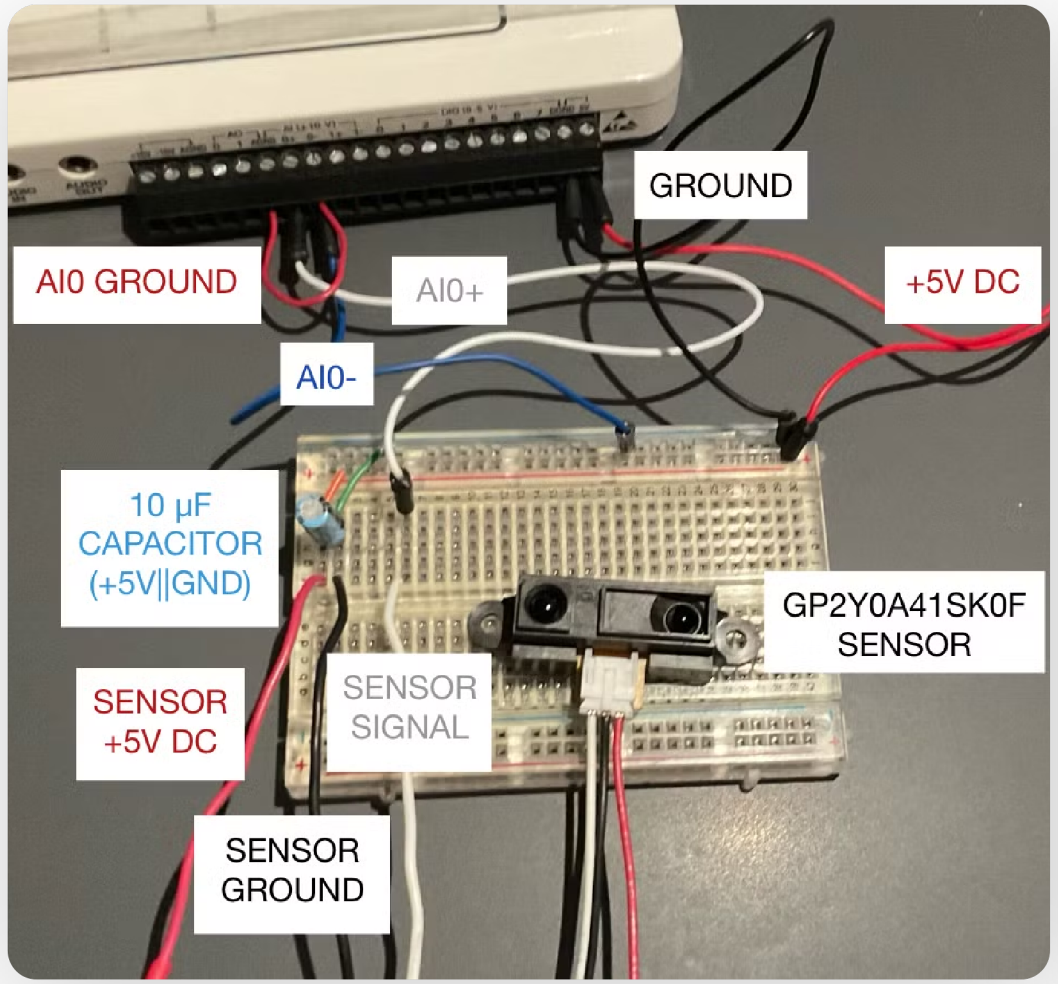
Basic VI architecture with DAQ Assistant connected to waveform chart and voltage table for recording static measurements at fixed distances. Includes data logging capability and user controls.

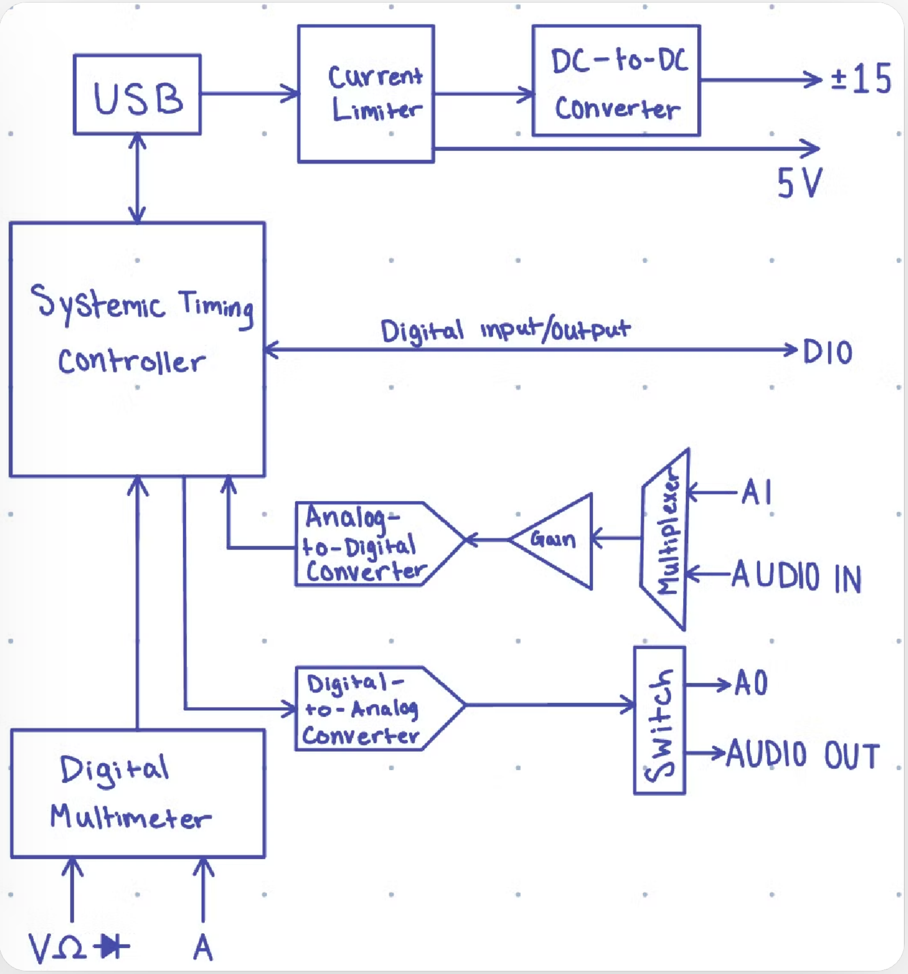


Secondary Configuration (Dynamic Testing)

Enhanced VI design with trigger control and dual waveform graphs for capturing real-time voltage changes during dynamic distance variations. Features automated data logging for step response analysis.

Experimental Setup - Circuitry.





Hardware Setup:
The GP2Y0A41SK0F IR sensor was connected to a breadboard with a 10µF decoupling capacitor between power and ground to stabilize the 5V supply. The sensor's analog output was connected to the DAQ's analog input (AI) channels for voltage measurements.

Data Collection Methodology:

- **Static Calibration:** Systematically recorded voltage outputs at 1cm increments from 4-30cm using a fixed paper target, enabling precise calibration points.
- **Dynamic Response:** Implemented trigger-based data acquisition to capture the voltage response during rapid target movement from 4-30cm.

LabVIEW provided the interface for data acquisition and storage.

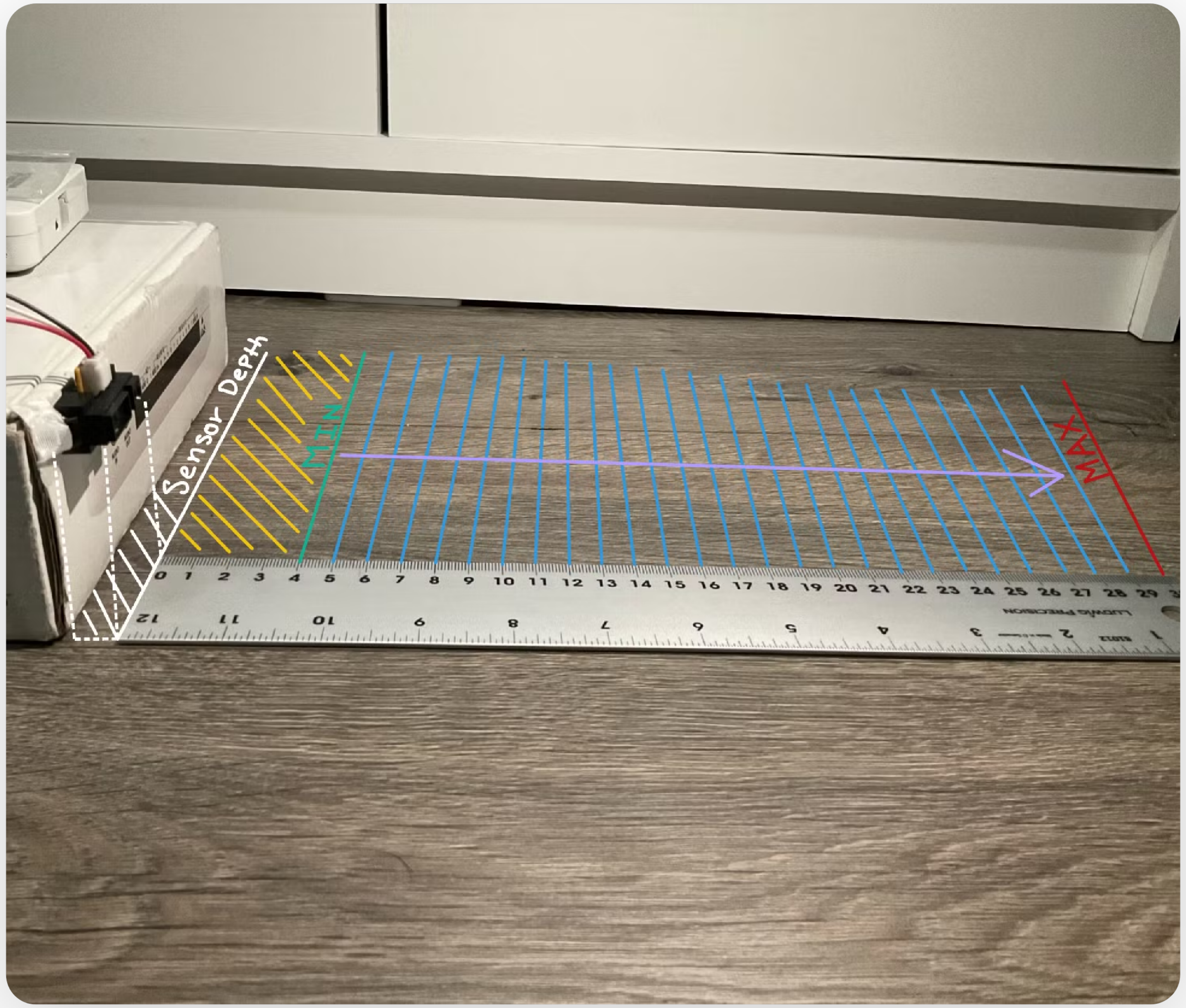
Static and Dynamic Calibration.

For static and dynamic calibration, we performed five independent measurement trials to characterize the sensor's voltage response to distance changes.

The collected data was analyzed to develop both linear and nonlinear calibration models, enabling us to determine the sensor's static sensitivity and assess its measurement accuracy.

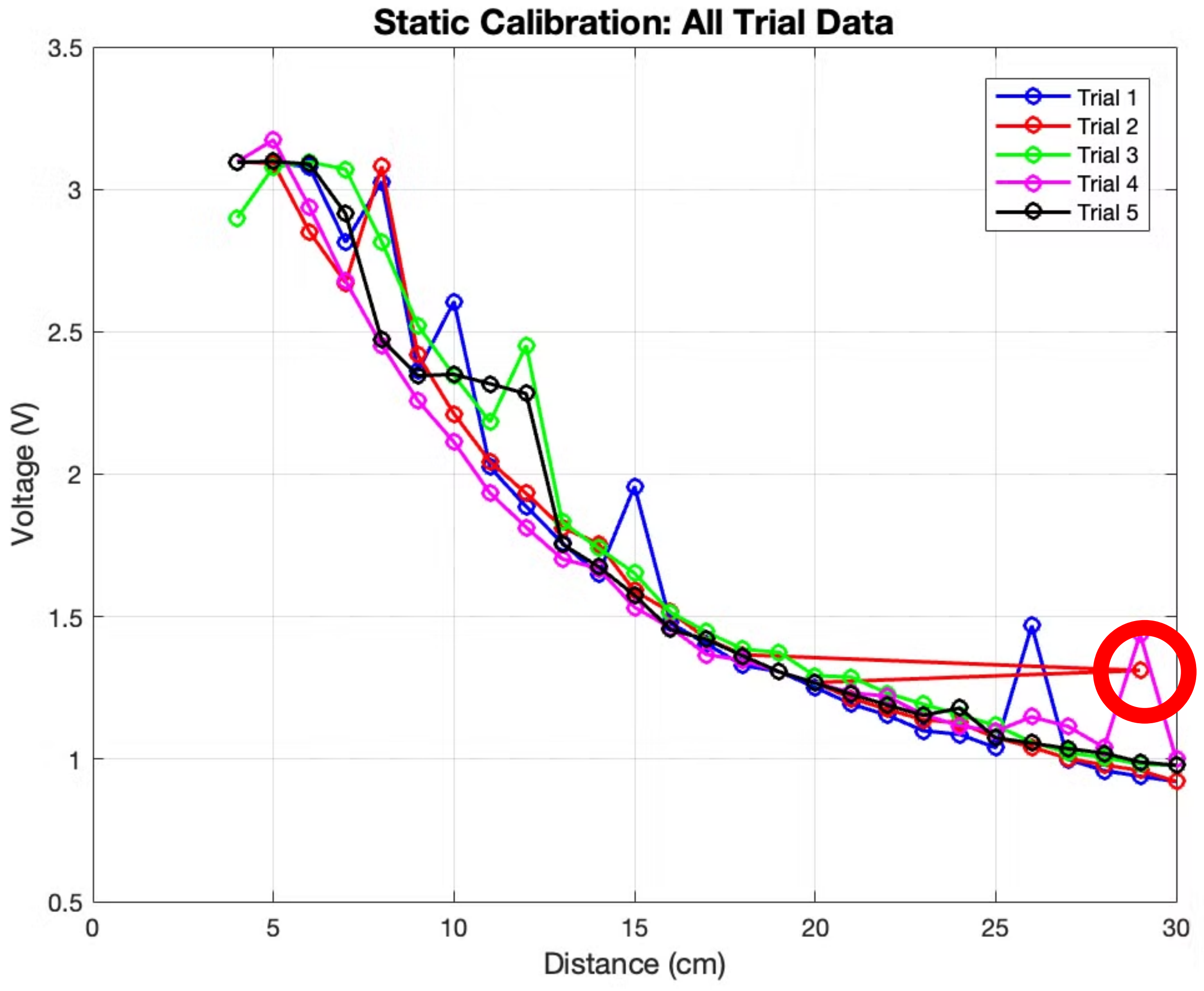
Here are a list of calculations we were looking to obtain:

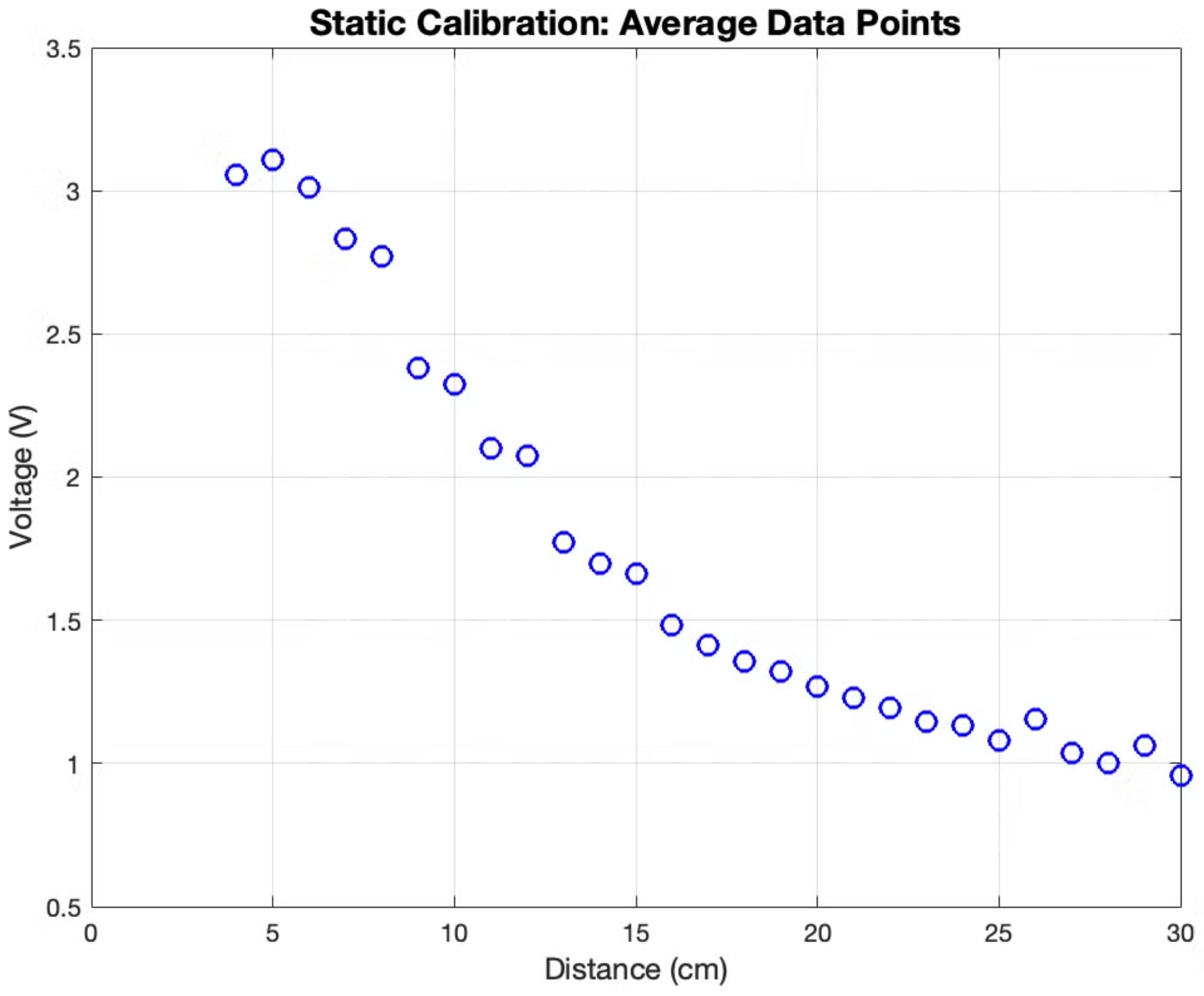
1. Static Calibration: All Trial Data
2. Static Calibration: Average Data Points
3. Static Calibration: Data with Regression Line.
4. Static Calibration: Average Data with Nonlinear Fit
5. Regression Analysis Results
6. Dynamic Calibration: Distance Quantization Error
7. Dynamic Calibration: Uncertainty and Time Constant (tau)
8. Dynamic Calibration: Temporal Step Response and Z-Plot



Static Experimental Results.

Our collected data from LabView were txt files with voltage vs distance data points. Using MATLAB, here are our findings for the data.

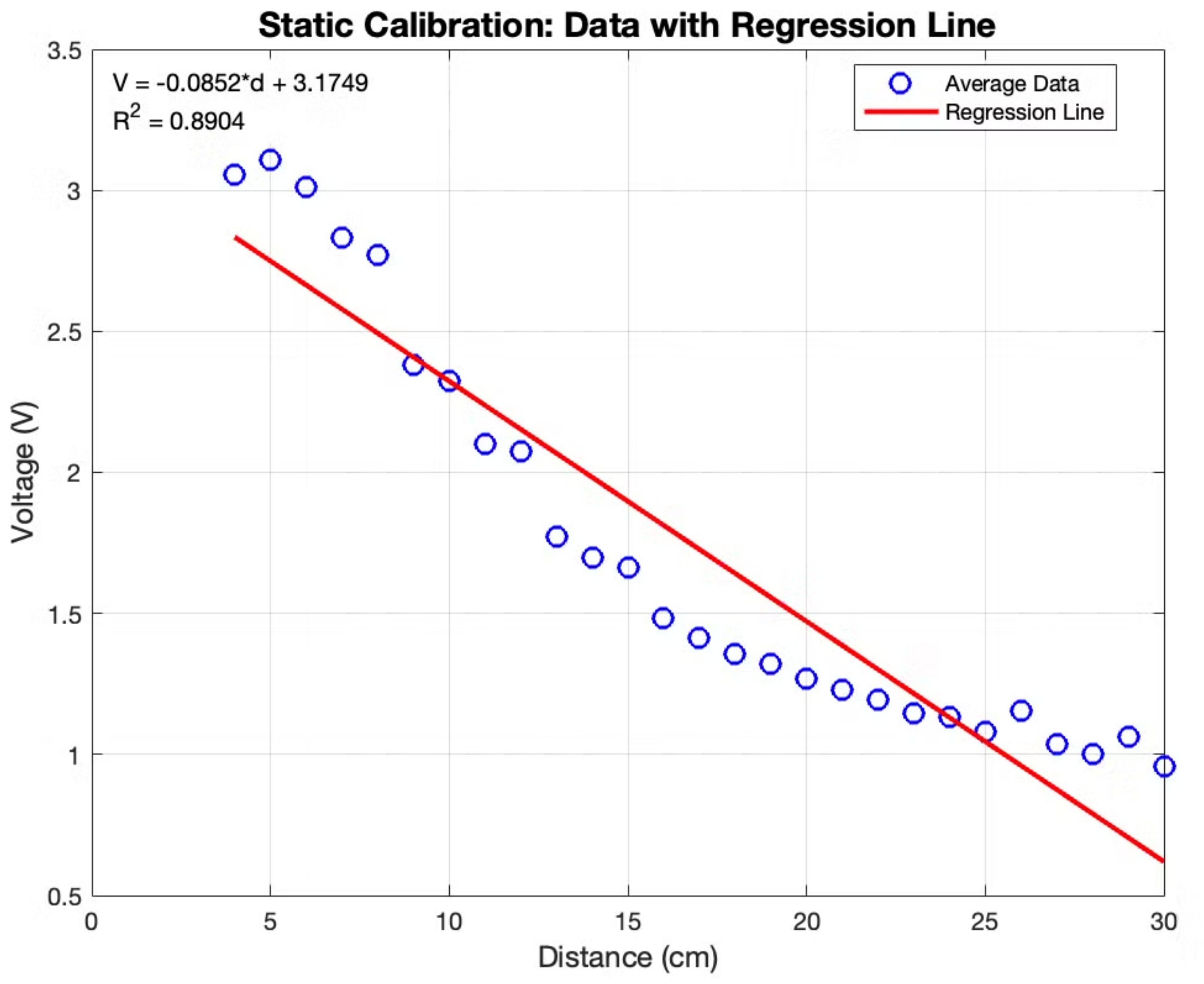


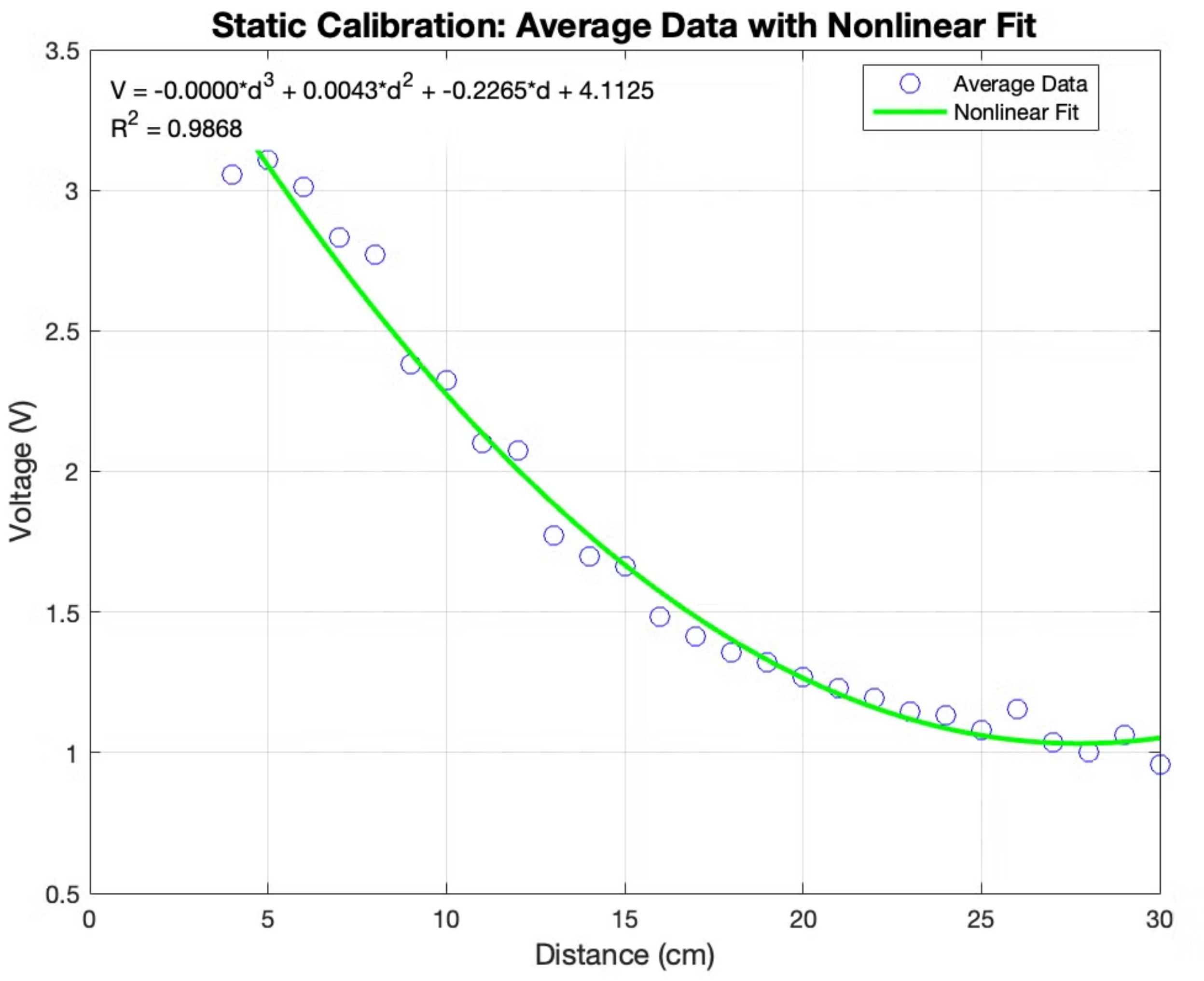


As we can see during our trial 2 of collecting static data, there was a huge spike in distance that is out of the ordinary and hence can be discarded as a data point due to calibration error. The remaining data follows the normal curve plot for an optical distance-measuring sensor.

Static Experimental Results.

As a part of static data, we also performed Regression Analysis for the collected data.





As we can see, the third-degree polynomial provides a much better fit for the calibrated data. Our findings were as follows:

1. Slope (V/cm): -0.08516
2. Y Intercept: 3.1749
3. R Squared: 0.89043
4. Standard Deviation: 0.2418

Static Experimental Results - Uncertainty Calculations.

Design Stage Uncertainty from the Manufacturer Data:

1. **Voltage Uncertainty:** ±0.335V
2. **Distance Uncertainty (Linear Approximation):** ±2.27 cm

Experimental Uncertainty Calculations:

1. **Standard Uncertainty from Residuals:** $u = \sqrt{[\Sigma(\text{residuals}^2)/(n-4)]}$, where residuals = y_measured - y_fit
2. **Voltage Uncertainty** (95% Confidence) = t × u (t-val for 95% confidence)
3. **Distance Uncertainty** = Voltage_uncertainty/|dV/dd|, where |dV/dd| is the absolute sensitivity.

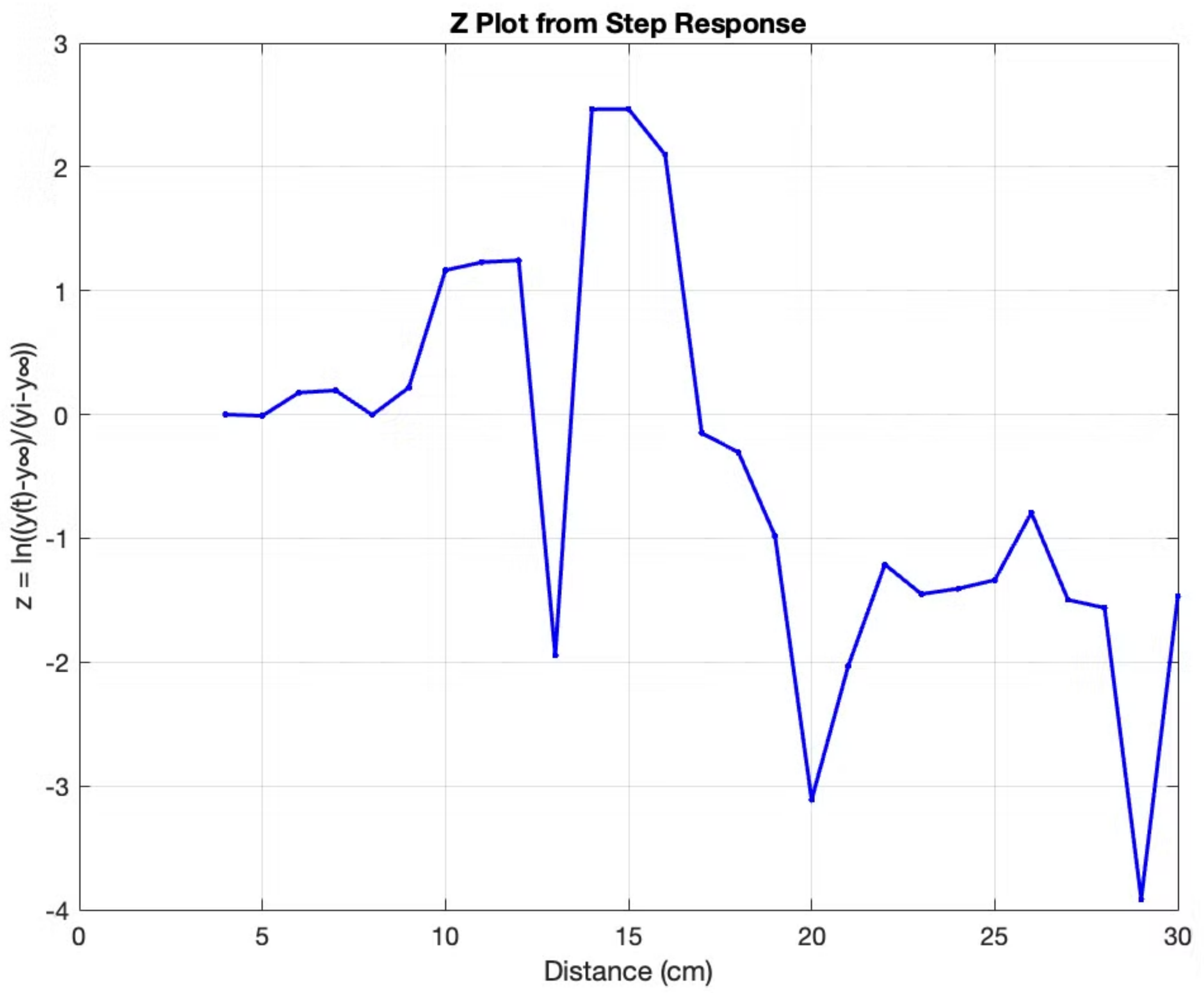
1. **Maximum quantization error in distance:** 0.008390 cm
2. **Quantization Error in Voltage:** 0.000038 V
3. **Voltage Standard Uncertainty:** 0.87401 V
4. **Average Distance Uncertainty:** 3.886851 cm
5. **Expanded Uncertainty (95%):** 8.040563 cm

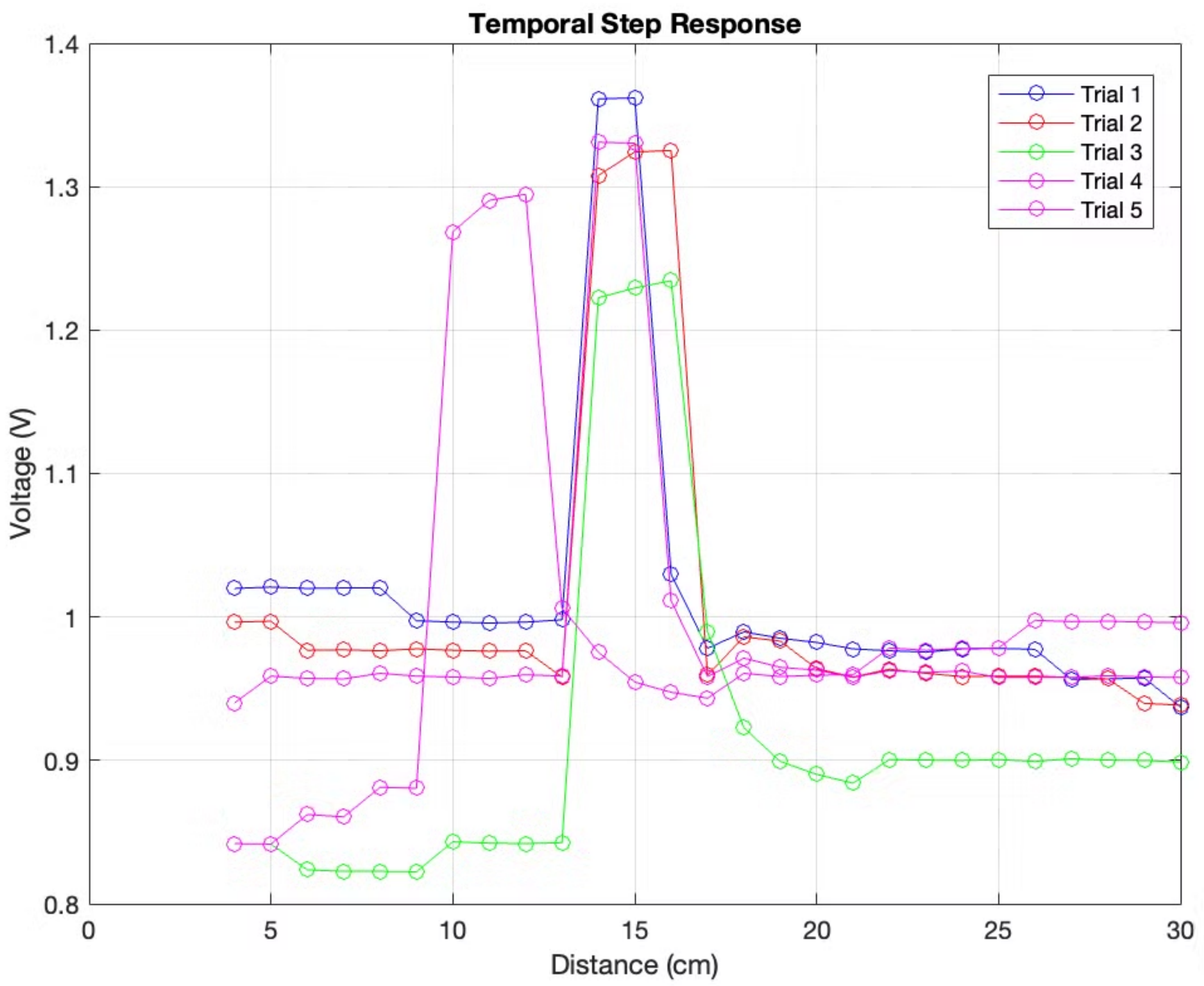
% Difference Voltage Uncertainty: 160.13%

% Difference Distance Uncertainty: 71.02%

Dynamic Experimental Results.

Our collected data from LabView were txt files with voltage vs distance data points. Using MATLAB, here are our findings for the data.





The temporal step response shows the sensor's voltage output as the target moves rapidly from 4cm to 30cm, with a characteristic voltage **spike** of around 15cm across all trials.

The Z-plot analysis, derived from the natural logarithm of the normalized response, demonstrates the system's dynamic behavior and reveals transitions in sensor sensitivity across its measurement range, particularly evident in the **steep changes** at 15cm and 30cm.

Dynamic Experimental Results.

From our results, we got a Time Constant (τ) of **5.43 cm**.

The time constant (τ) of 5.43 cm in this context represents the spatial distance over which the sensor reaches approximately **63.2%** of its final steady-state value during a dynamic change.

Since our dynamic test involved moving the target through space (rather than measuring pure time), our time constant is expressed in centimeters rather than seconds. This means the sensor requires about 5.43 cm of target movement to significantly respond to and adjust its output voltage, indicating the spatial resolution of the sensor's dynamic response.

For practical applications, this suggests that:

1. The sensor needs about **5.43 cm** of target movement to meaningfully track distance changes.
2. Full response ($\approx 4\tau$ or 99%) would occur over roughly **21.72 cm** of movement.

Results Summary.

The main findings from the analysis of the static and dynamic data are:

1. High R-squared of **0.89**, indicating a strong linear correlation between the variables
2. Low quantization errors: **0.008 cm** for distance, **0.00004 V** for voltage
3. Voltage uncertainty of ±0.335 V
4. Distance uncertainty of ±2.27 cm
5. Voltage standard uncertainty of 0.874 V
6. Average distance uncertainty of 3.89 cm
7. Expanded uncertainty (95% confidence) of ±8.04 cm
8. Relatively high percent differences: **160%** for voltage, **71%** for distance

9. The calculated time constant (τ) is **5.43 cm**, representing the system's dynamic behavior.

Overall, the results demonstrate high-quality, precise static measurements, but greater uncertainty in the dynamic data, as evidenced by the higher percent differences. The time constant provides insight into the system's temporal response.

SHARP GP2Y0A41SK0F Experimental Data Sheet.

Parameter	Symbol	Conditions	MIN.	TYPE	MAX.	UNIT
Measuring distance range	**ΔL**	(Note)	4		30	cm
Output terminal voltage	**Vo**	Range	0.9		3.1	V
Time constant	**τ**	Dynamic response	-	5.43	-	cm
Linear correlation	**R^2**	Static calibration	-	0.89	-	-
Quantization error	**eq**	Distance	-	0.008	-	cm
Voltage uncertainty	**uv**	95% confidence	-	0.874	-	V
Distance uncertainty	**ud**	95% confidence	-	3.89	8.04	cm

Note: Using white paper target with controlled linear motion.

Learning Moments.

Here are the key takeaways from our optical sensor project:

Engineering Insights:

- Nonlinear sensor behavior proved more accurate than linear approximation, evidenced by our static calibration results.
- Dynamic response showed predictable behavior with a time constant of 5.43 cm, suitable for real-world applications.
- Experimental uncertainties (160% higher than design specs) revealed real-world challenges not captured in datasheets.

Team Learnings:

- Successfully integrated hardware setup with LabVIEW/MATLAB analysis.
- Data validation through multiple trials enhanced measurement reliability.
- Comprehensive uncertainty analysis provided realistic performance metrics.

Future Considerations:

- The system could be optimized for specific distance ranges within 4-30 cm.
- Potential applications in automated dispensing systems look promising.

This project demonstrated the importance of thorough testing and validation when implementing theoretical designs in practical applications and working together as a team throughout the semester.

Pitch

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