MTE 201 Experimental Measurement and Statistical Analysis

Measurement System Project:
Vision Based Length Measurement & Calibration

Department of Mechanical and Mechatronics Engineering

Professor Hongxia Yang

Group 1: Siyuan Pan, Aston Ng, Leo Zhang, Cean Liu

Date: November 10, 2025

Table of Contents

Introduction

1.1 Summary:

The objective of this project was to design and construct a vision-based measurement system capable of determining the length and width of Lego bricks using a low-cost camera (e.g. phone camera) and a simple calibration procedure. The system converts pixel measurements from captured images at a specific condition into real-world distances using a calibration curve derived from a known standard (a ruler). This project demonstrates the use of digital image processing as a non-contact metrology tool and evaluates its accuracy through calibration and uncertainty analysis.

1.2 The measurement system consists of:

- A **phone camera** mounted at the edge approximately 15.5 cm above a flat surface.
- A **flat measurement platform** with clean, monotonic background.
- A **secondary standard** (ruler) placed beside the Lego block for calibration.
- A **Python/OpenCV software** script for image acquisition, edge detection, and pixel-to-length conversion.

The system determines the physical separation between two user-selected points in a photograph. The setup uses a smartphone camera positioned above the object to capture a top-down image under controlled conditions, and a Python-based software tool to process the image and calculate the pixel distance between the selected points.

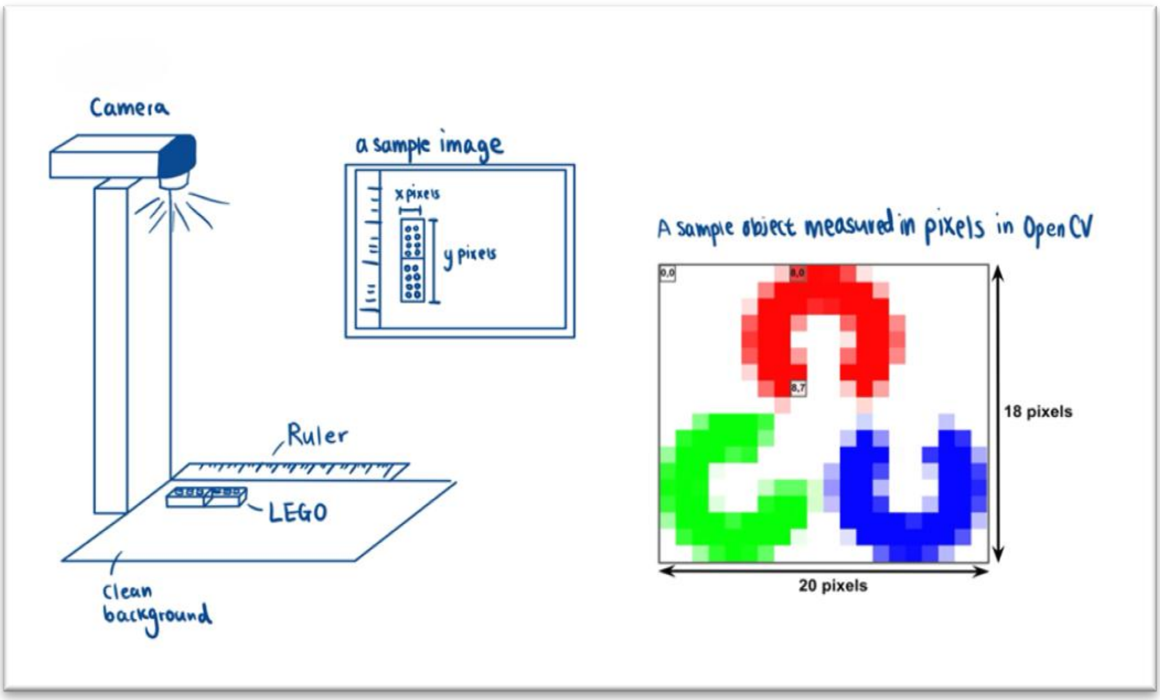

Figure 1: Sketch of the system setup.

1.2.1 Common Elements of the Measurement System:

Sensor: The primary sensing component of the system is the smartphone camera, which functions as an optical sensor. It captures a digital image of the object within a known geometric configuration. Each pixel in the image corresponds to a specific portion of the real-world scene projected through the camera lens.

Signal Modification System: The image is processed through a custom Python application (pixel_measure.py file included in the Appendix) built using OpenCV and Tkinter. Within the program, the user can zoom, pan, and manually select two points corresponding to the edges or boundaries of the object being measured. The software computes the Euclidean pixel distance between the selected points using the formula:

$$D_{\text{pixels}} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

This pixel measurement can subsequently be converted into a physical distance in millimeters using a calibration relationship obtained from images of a ruler.

Indicator/Recorder: The calculated pixel distance and the corresponding coordinate differences (Δx, Δy) are displayed both within the OpenCV graphical interface and in the program's console output. The software therefore serves simultaneously as the system's indicator and recorder.

1.2.2 Theory of Operation

The system operates based on the first principle that a digital image represents a spatially discrete mapping of the physical world, where the number of pixels separating two object features is proportional to their real-world distance.

A one-time calibration procedure is performed by capturing images of a ruler with known spacing under fixed conditions (camera height, angle, and lighting). The measured pixel separations (D_{pixels}) corresponding to known physical distances (L_{true}) are plotted to establish a linear calibration equation:

$$L_{\text{true}} = a\, D_{\text{pixels}} + b$$

where *a* is the pixel-to-millimeter conversion factor and *b* accounts for small systematic offsets due to lens distortion or image thresholding. Once this calibration is completed, subsequent measurements can be made using only the object of interest such as the lego bricks—without including the ruler in the frame—provided that the camera conditions (height, orientation, and focus) remain identical to those used during calibration.

1.3 Assumptions

- The camera is positioned perpendicular to the measurement plane (≈ 90°).
- The surface is flat, and the Lego brick lies fully in the focus plane.
- Lens distortion in the central region of the image is assumed to be negligible within the small field of view (~160 mm × 90 mm).
- The imaging conditions, including camera height, angle, lighting and focus are uniform and constant across calibration and measurement.
- The relationship between pixel distance and true distance is linear within the measurement range (0–120 mm).
- The calibration ruler divisions are accurate to within ±0.1 mm and treated as the secondary standard.

1.4 Challenges

Several challenges arose during the system's development and testing. Small changes in camera angle or height caused perspective errors, making stable alignment essential. Lighting variations and surface reflections sometimes reduced edge clarity, so diffuse, even illumination was used. Since measurements relied on manual point selection, minor click inconsistencies introduced random uncertainty. Automatic refocusing and exposure adjustments on the smartphone camera occasionally altered the field of view, which was mitigated by using manual focus settings. Despite these factors, the system achieved consistent and accurate results, with an estimated uncertainty of about ±0.2 mm.

Calibration

2.1 Apparatus and Setup

Calibration was performed using a **ruler** with 1 mm divisions as the secondary standard. The ruler provided accurate reference distances for establishing the relationship between measured pixel distance and true physical length. The same smartphone camera and setup used for later Lego measurements were maintained during calibration to ensure consistent imaging geometry.

2.2 Procedure

1. Calibration images were captured under diffuse lighting with the camera positioned approximately 15.5 cm above the ruler and aligned perpendicular to the surface.
2. Known ruler intervals, ranging from 1 mm to 120 mm, were photographed (**Figure 2**). For each interval, the custom Python measurement software was used to manually select the start and end points of the segment, and the program automatically

computed the pixel distance between them. Sample measurements are shown in **Figure 3-5**.

3. Plot true length (L) versus the recorded pixel distance (D_{pixels}).
4. Fit a linear line of best fit model to find the calibration equation
5. Validate the calibration by measuring additional known distances and comparing measured versus actual values.

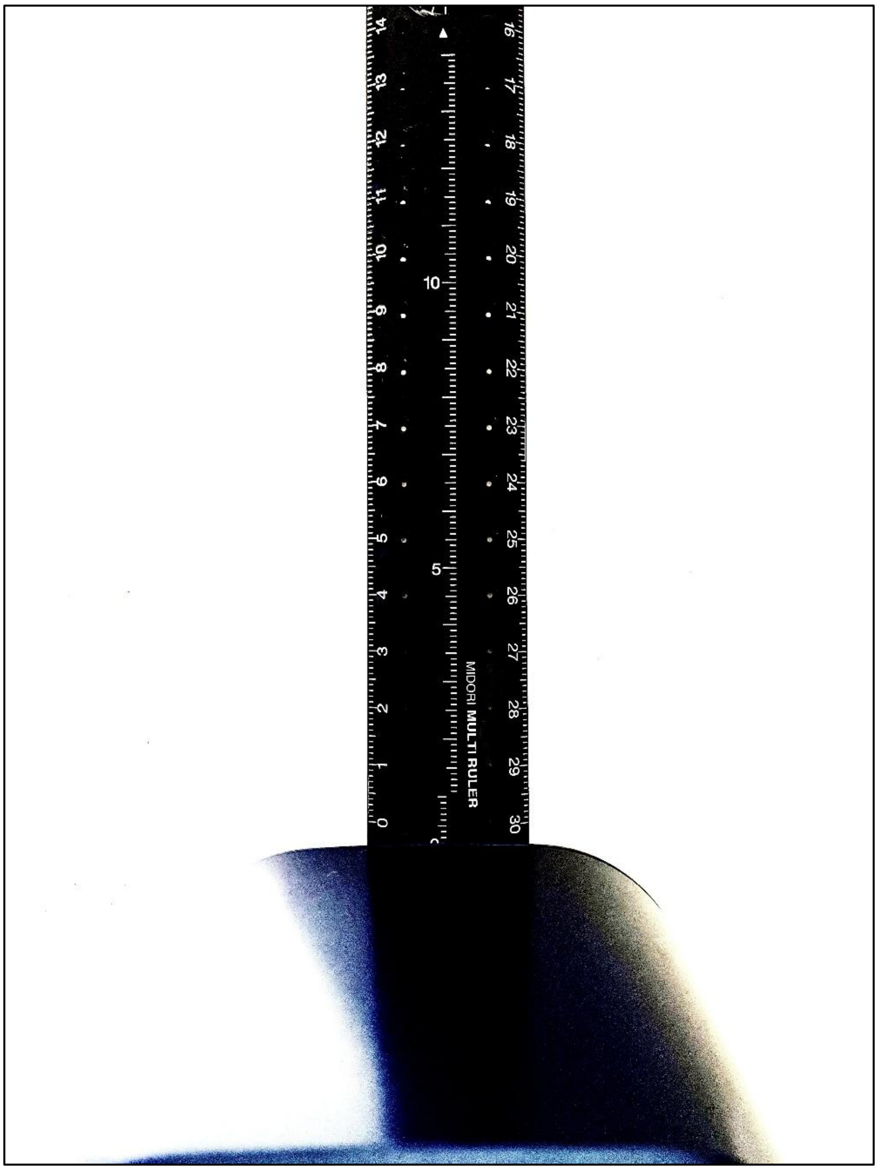

Figure 2: Standard used for calibration.

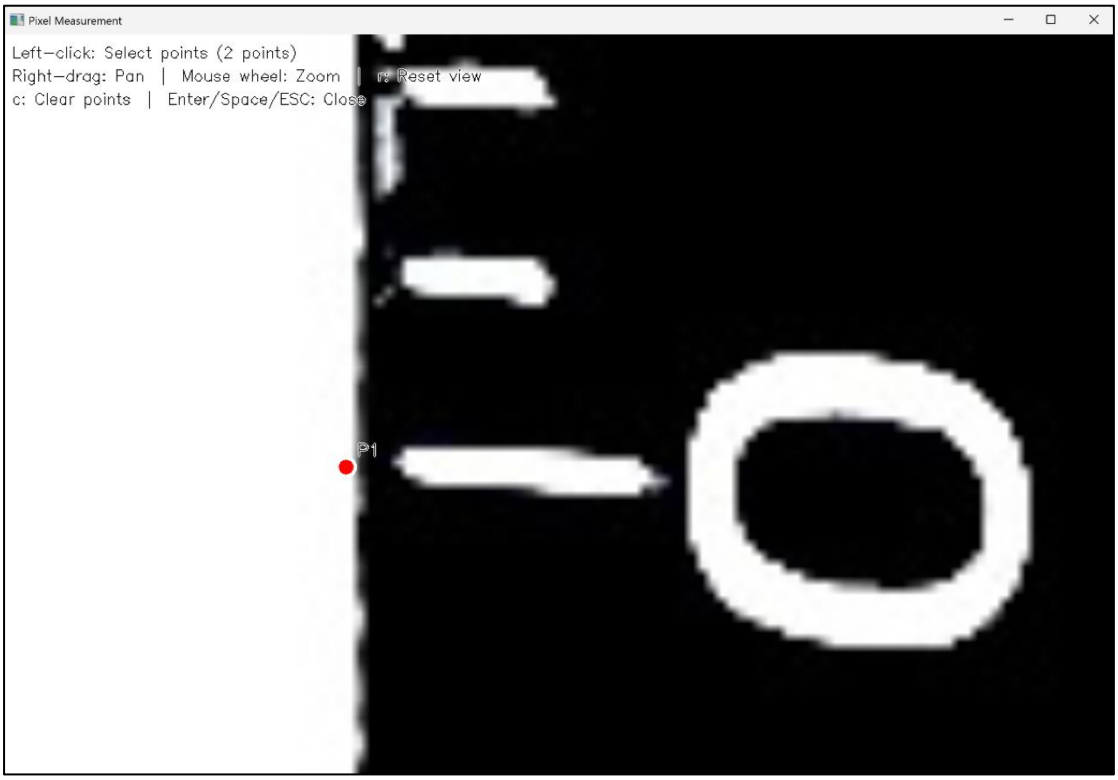

Figure 3: Choosing the 1st point in the OpenCV program.

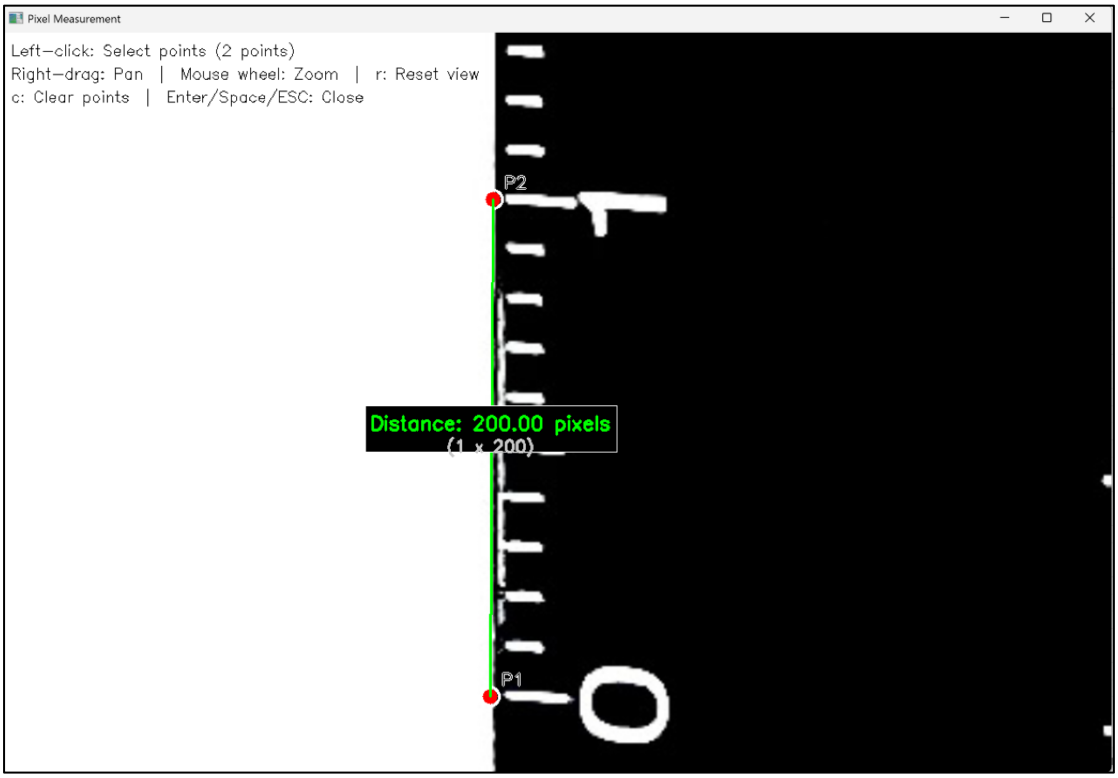

Figure 4: Choosing the 2nd point in the OpenCV program. The shown pixel displacement of 200 pixels corresponds to a known distance of 10 mm in the real world.

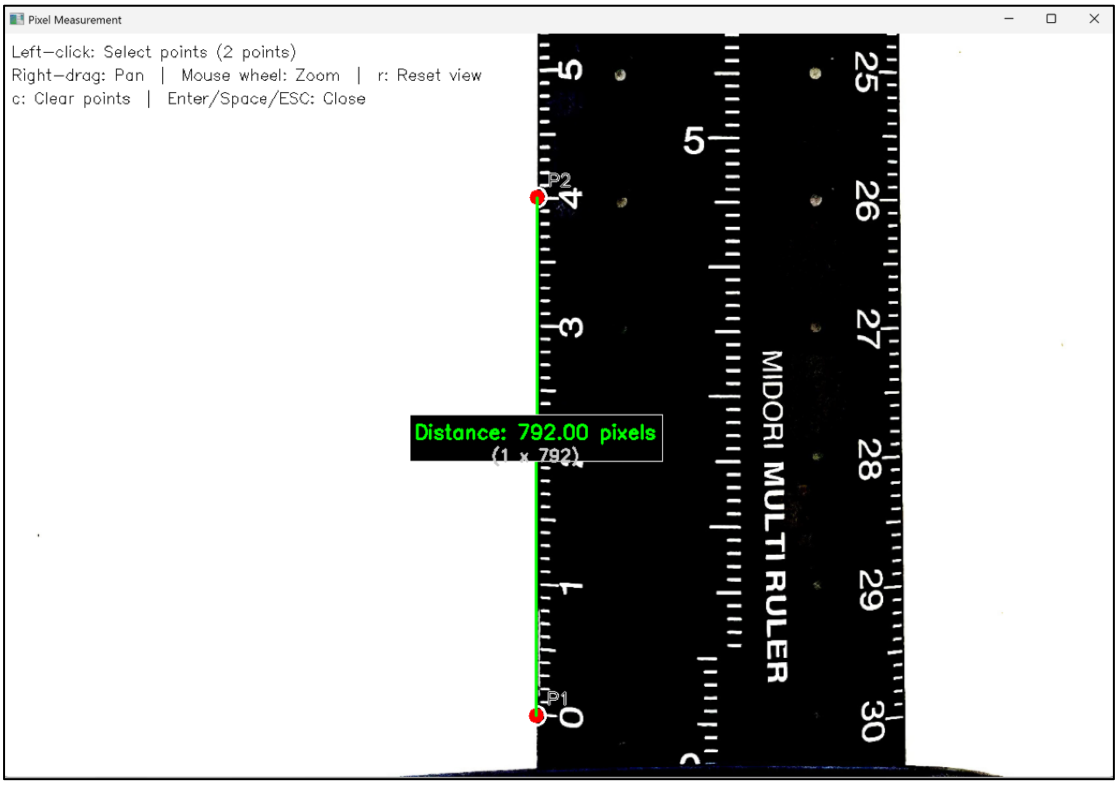

Figure 5: Another pixel measurement taken for a known distance of 40 mm.

2.3 Calibration Data and Results

Table 1: Number of Pixels measured for known lengths of 1-120 mm. Measured length is computed through the derived calibration equation and is compared to the true length to obtain the deviation.

Number of Pixels	True Length [mm]	Measured Length [mm]	Deviation [mm]
20.00	1	0.8574	0.1426
39.80	2	1.8632	0.1368
61.00	3	2.9402	0.0598
80.00	4	3.9054	0.0946
100.00	5	4.9214	0.0786
200.00	10	10.0014	-0.0014
302.00	15	15.1830	-0.1830
401.00	20	20.2122	-0.2122
499.00	25	25.1906	-0.1906
596.00	30	30.1182	-0.1182
693.00	35	35.0458	-0.0458
792.00	40	40.0750	-0.0750
890.00	45	45.0534	-0.0534
988.00	50	50.0318	-0.0318
1085.00	55	54.9594	0.0406
1183.00	60	59.9378	0.0622
1282.00	65	64.9670	0.0330
1380.00	70	69.9454	0.0546
1479.00	75	74.9746	0.0254
1577.00	80	79.9530	0.0470
1677.00	85	85.0330	-0.0330
1774.00	90	89.9606	0.0394
1873.00	95	94.9898	0.0102
1972.00	100	100.0190	-0.0190
2070.00	105	104.9974	0.0026
2169.00	110	110.0266	-0.0266
2268.00	115	115.0558	-0.0558
2367.00	120	120.0850	-0.0850

A best-fit linear trendline of the dataset yielded the calibration relationship:

$$\boldsymbol{L}_{\mathbf{true}} = \mathbf{0.0508}\,\boldsymbol{D}_{\mathbf{pixels}} - \mathbf{0.1586}$$

Where:

- $\boldsymbol{L}_{\mathbf{true}}$ is the length in mm and
- $\boldsymbol{D}_{\mathbf{pixels}}$ is the measured number of pixels using a phone captured photo with 3024 x 4032 resolution taken at 15.5 cm height and 90 degrees angle.
- The slope of **0.0508 mm / px** defines the conversion scale, indicating that each pixel corresponds to approximately 0.051 mm in real distance.
- The small negative intercept (−0.1586 mm) represents a minor offset likely arising from pixel quantization or manual edge placement.

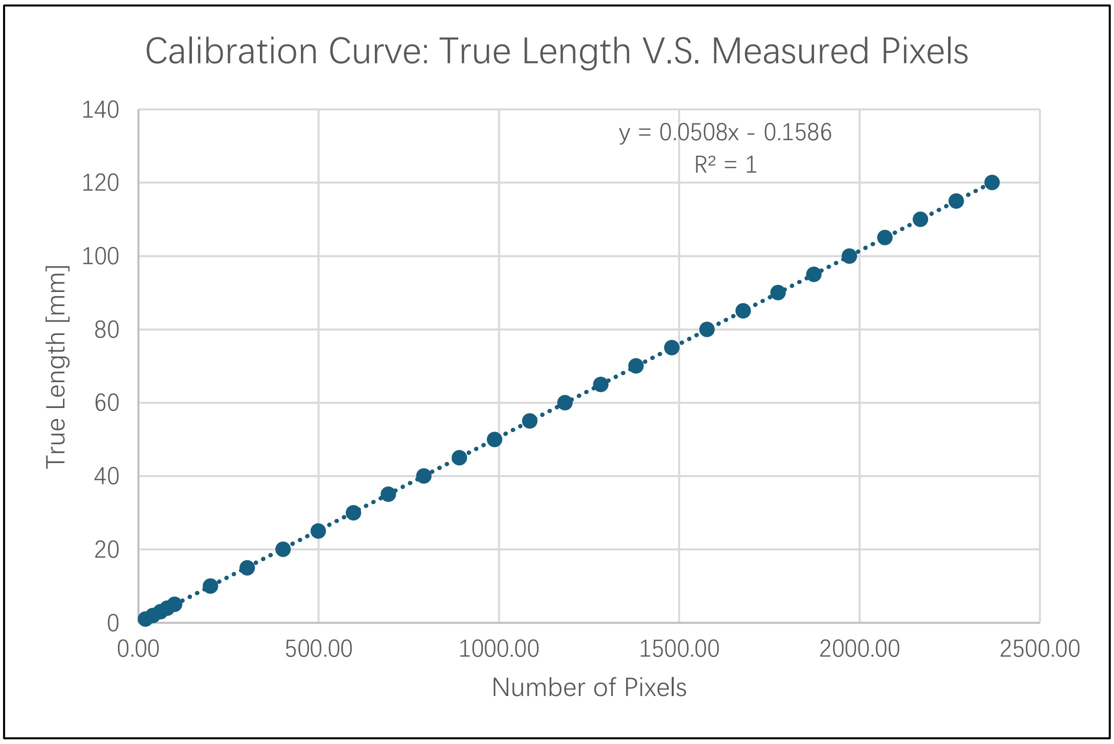

Figure 6: Calibration curve of true length vs. measured pixels.

The calibration curve displayed near-perfect linearity with a correlation coefficient of $\mathbf{R^2 \approx 1}$, confirming that a linear model accurately represents the relationship between pixel distance and true distance.

Uncertainty Analysis

3.1 Deviation Plot:

A deviation plot was constructed by calculating the (True - Measured) values and comparing it with the true length. The graph is shown in Figure 7.

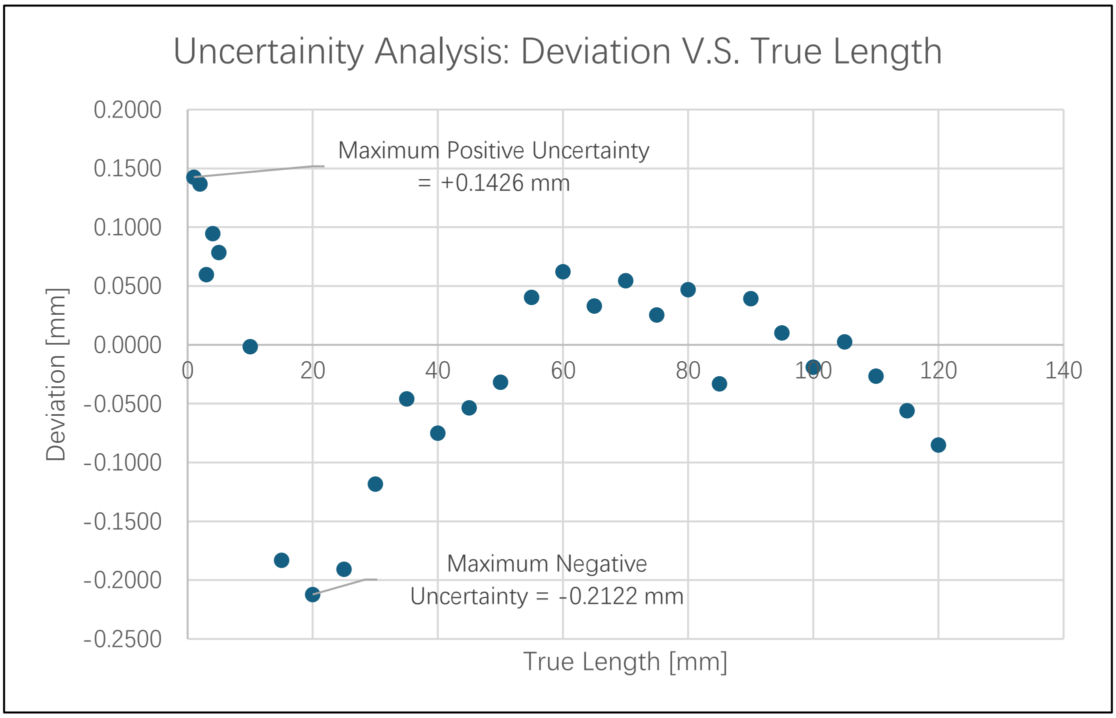

Figure 7: Deviation plot including both positive and negative uncertainty.

3.2 Maximum Uncertainty

From experimental data and the deviation plot, the following results can be observed:

- Deviations range between **–0.21 mm maximum negative uncertainty** and **+0.14 mm maximum positive uncertainty**.
- The deviations alternate slightly between positive and negative across the entire length range.
- There is no consistent increasing or decreasing trend in deviation with increasing true length. However, the deviation is larger for smaller true lengths (0-40mm), and smaller for longer true lengths.
- The **mean deviation was –0.0108 mm**, which is close to 0.
- The **standard deviation (S) was 0.0906 mm**, showing that the random scatter of points is about $\pm 0.09\ mm$ around the mean.

Alternatively, a statistical interpretation can also be used to estimate the maximum uncertainty of the results. Assuming that these random errors follow a normal distribution, approximately 95% of all errors fall within ± 1.96 standard deviations of the mean.

Hence the 95% coverage uncertainty is:

$$\boldsymbol{U_{95} = 1.96(S) = 1.96(0.0906) = \pm 0.18mm}$$

This theoretical value ($\pm 0.18mm$) means that in repeated measurements under the same setup, about 95% of the results are expected to fall within this range.

3.3 Systematic Error and Random Error

The deviation pattern suggests that random error is the dominant source of uncertainty, with minimal evidence of systematic bias. The mean deviation of –0.0108 mm is effectively zero relative to the ±0.18 mm, 95% coverage range or the +0.14 mm and -0.21 mm maximum uncertainty, and the deviations alternate between positive and negative across the measurement range. This alternating sign and near-zero mean indicate random scatter rather than a consistent directional bias. Furthermore, no monotonic trend (consistently increasing or decreasing) is observed between deviation and true length, confirming that the calibration scale factor is accurate and free of systematic drift.

Larger deviations at shorter lengths (0–40 mm) could arise from pixel-level uncertainty in manual point selection, where even small click differences translate to measurable length variation. Overall, the deviations are evenly distributed about zero with no substantial trend, confirming that the measurement uncertainty primarily originates from random user and image factors rather than systematic error.

Conclusion

The project successfully demonstrated the use of a low-cost, vision-based measurement system for determining the physical dimensions of Lego bricks. By capturing images under controlled geometric conditions and establishing a pixel-to-length calibration curve using a secondary standard, pixel measurements can be converted into accurate real-world distances. The calibration results confirmed an approximately linear relationship between pixel separation and true physical length over the measurement range of 0–120 mm.

The system achieved a maximum observed deviation of approximately ±0.21 mm, with a statistically estimated 95% coverage uncertainty of ±0.18 mm. The mean deviation was close to zero, indicating minimal systematic error. Small systematic effects were noted mainly at shorter measurement lengths, which are likely attributed to lens distortion or reduced calibration precision near the edges of the field of view. Random errors were present due to manual point selection and slight lighting or focus variations, but these were relatively small (standard deviation ≈ 0.09 mm) and did not significantly impact overall measurement reliability.

Overall, the system demonstrated strong repeatability, acceptable measurement precision, and practical applicability for non-contact dimensional inspection using only consumer-grade imaging equipment and open-source software tools. The results confirm that with consistent imaging conditions, a phone camera–based measurement system can serve as an effective and inexpensive metrology solution for small-scale laboratory or prototyping tasks.

For future improvements, several refinements could enhance system accuracy and usability. Implementing automated edge detection and point selection would reduce the influence of human variability and further decrease random error. Additionally, fixing camera focus and exposure settings would help maintain consistent imaging conditions and prevent subtle geometric variation between calibration and measurement. With these enhancements, the system could be extended for more precise laboratory applications, batch measurements, or integration into automated inspection workflows.

Appendix

Source code can be found on GitHub: https://github.com/CeanLiu/MTE201-project-