Department of Mechanical & Mechatronics Engineering

MTE 201 – Experimental Measurements and Statistical Analysis

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Project Report

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Summary of Design and Construction of Measurement System

For this MTE 201 final project, a distance measurement device was constructed using a rotary potentiometer and digital display. This device, hereafter referred to as the caliper, is capable of measuring straight line distances from 0 - 101 mm with an uncertainty of ± 0.8 mm. This report details this caliper's theory, design, construction, and calibration procedures.

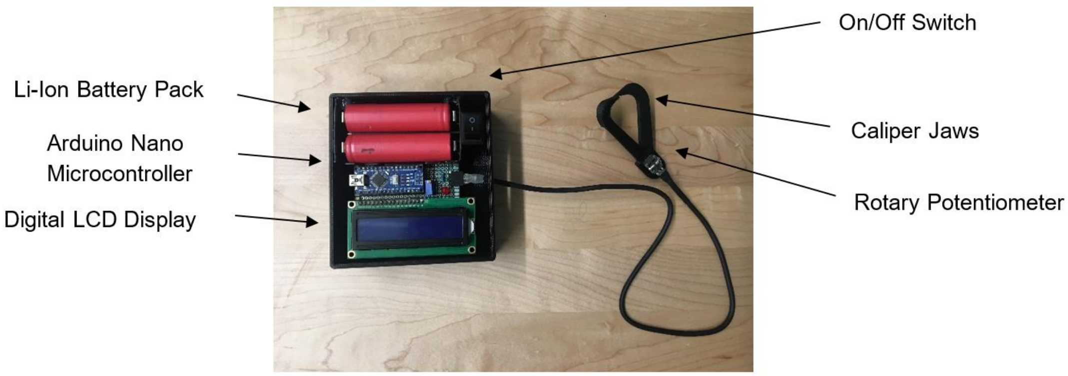

Figure 1: Caliper Photo

Shown below is a circuit schematic of the caliper.

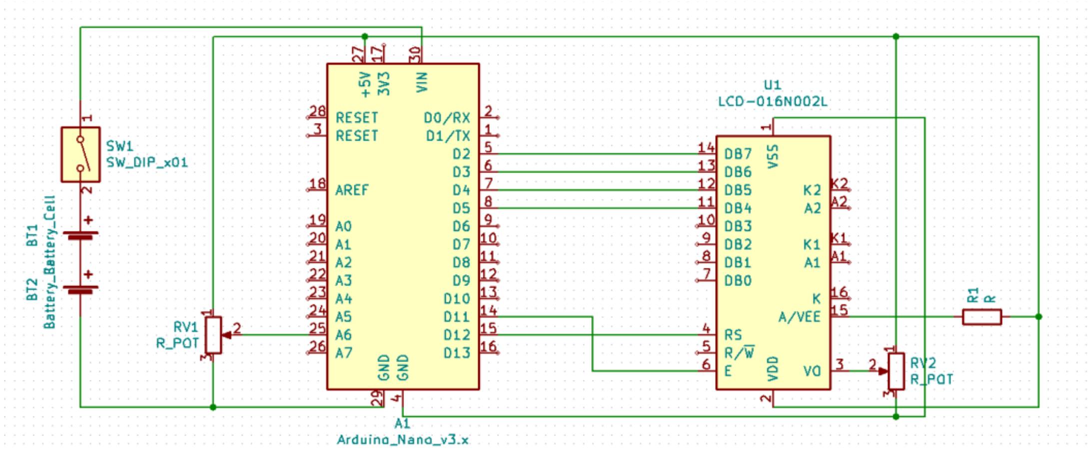

Figure 2: Caliper Schematic

The caliper's theory of operation is to sense a change in distance as a change in voltage, amplify that change in voltage using an analog-to-digital converter (ADC), calculate the distance using a calibration equation, and display the distance digitally. Thus, the sensor is the rotation of the rotary potentiometer as a function of distance, the signal modification system is the Arduino's ADC which converts tiny changes in voltage to digital values and the calibration equation firmware, and the indicator is the digital LCD display.

RV1 is the 10 kΩ rotary potentiometer used by the caliper jaws and is provided with an approximately 5V source by the Arduino Nano's internal 5V regulator. The potentiometer acts as a voltage divider, sending a voltage between 0 and 5V to analog pin 6, depending on its rotation angle. The rotation angle and voltage are linearly proportional. Analog pin 6 detects this voltage using the Arduino's ADC with a 10-bit resolution, compares it with GND and the same 5V regulator output, and converts it to a digital scaled voltage value between 0-1023 [1]. This digital value is converted to a distance using a calibration equation and displayed on U1, the LCD display, along with its uncertainty. This entire process is repeated at a frequency of 60Hz, fast enough to appear continuous to the human eye.

Other key components of the caliper include the on/off switch (SW1), the 2s Li-ion battery pack (BT1 and BT2), supporting circuitry/components for the LCD display, and its 3D printed case and jaws.

Several assumptions were made during the design of this caliper. It was assumed that the caliper jaws would not slip from the rotary potentiometer head or body, and that its tips would not slide parallel to each other during measurements. To ensure this, the caliper jaws were carefully aligned before being superglued to the potentiometer, although there was still some wiggling in in the parallel direction. It was also assumed that the potentiometer would act as an ideal voltage divider, with negligible current being drawn by the analog read pin. To ensure this, an Arduino Nano microcontroller was chosen, with an analog pin resistance of ~100 MΩ, far higher than the 10 kΩ potentiometer. Finally, it was assumed that the distance to be measured in the demonstration was less than 101 mm, as the length of three 2x4 LEGO bricks is ~96 mm.

Calibration

The jaws were calibrated against a known standard for distance, a digital caliper (Neiko 01407A Electronic Digital Caliper) which had a reported uncertainty of 0.02 mm [2]. This was done by setting the Neiko caliper to a specific distance, measuring that distance with the jaws, then recording the raw output of the Arduino ADC in a spreadsheet along with the Neiko caliper's distance. This was done for distances from 0 to 100 mm, in increments of 5 mm for a total of 21 calibration data points.

Using the calibration procedure mentioned in the previous section, a set of data points were measured which could be used to create a calibration curve. This was done by plotting the real distance based on the standard (digital caliper readout) against the scaled voltage value read by the Arduino. The real value was plotted on the Y-axis and the scaled voltage value was plotted on the X-axis, in order to make it easier to determine the function to convert from the raw value to the actual measurement, as opposed to the typical calibration plot which has the axes flipped.

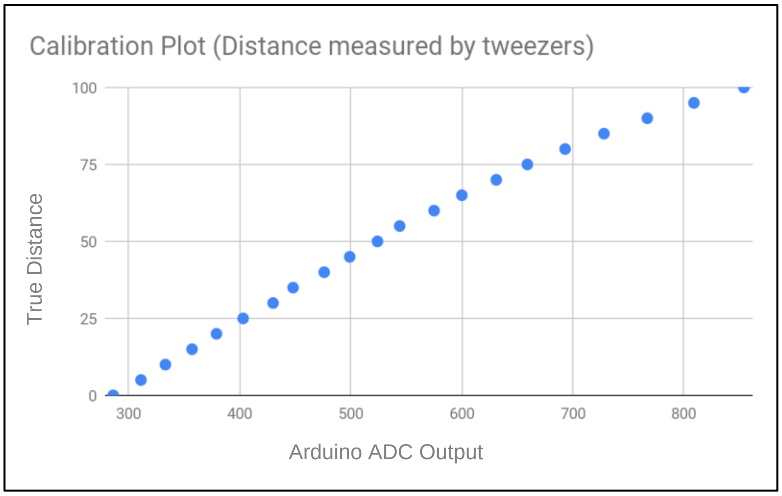

Figure 3: Arduino ADC Output vs. True Distance

The points plotted on the calibration plot do not form a linear relationship, which is consistent with the non-linear relationship between the angle and distance of the jaws. The relationship between the angle and distance can be found using cosine law, $c^2 = a^2 + b^2 - 2ab \times cos(C)$, which in this case is $X^2 = 54^2 + 54^2 - 2(55)(55) \times cos(\theta)$. Rearranged for x, it gives the form $X = 54\sqrt{2} \times \sqrt{(1 - cos(\theta)}$.

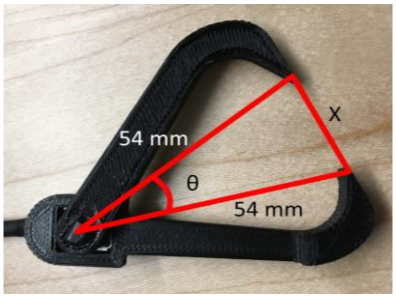

Figure 4: Geometric Relation between Potentiometer Angle and Distance

The angle θ can be found by considering the relationships between θ and the measured scaled voltage. The angle of the potentiometer has a linear relationship to its resistance and the relationship between resistance and voltage is linear. The ADC linearly maps voltages from 0 - 5 volts to a range of integer values from 0 - 1023 due to the nature of the 10-bit ADC chip. As such, all these relationships can all be combined into a single linear relationship that is represented in the form $\theta = \alpha(V - \beta)$, where V is the digital scaled voltage given by the ADC and α and β are constants. The full chain of conversions is represented in *Figure 5*.

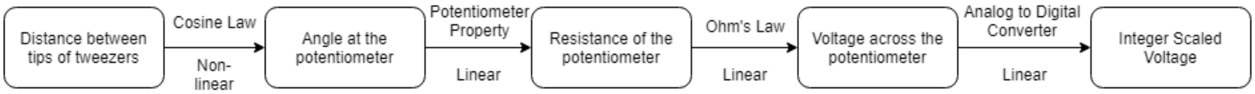

Figure 5: Proportionality Chain of Key Values

Overall, the complete function is of the form $X = 54\sqrt{2} \times \sqrt{(1 - cos(\alpha(V - \beta))}$. This function was fit to the data points by modifying the α and β constants. This was done initially through visual inspection by comparing the graph and the data points to obtain rough values for α and β.

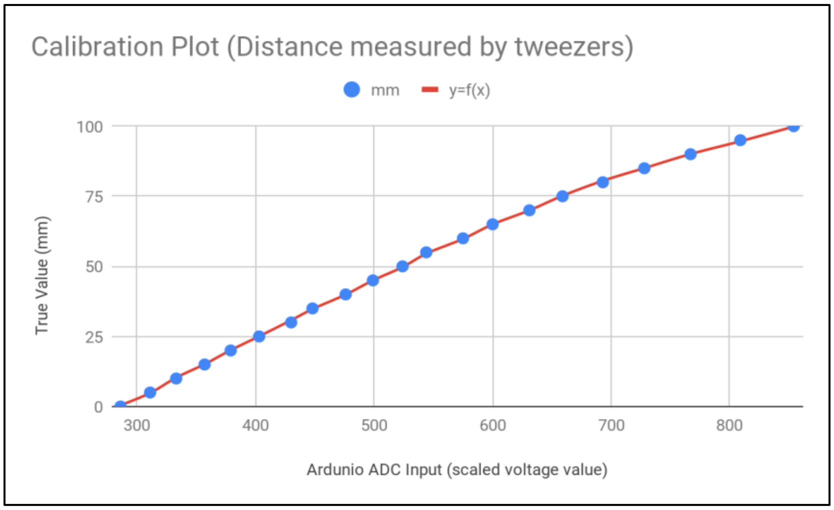

Figure 6: Calibration Plot

In order to fine tune a and b to reduce the range of uncertainty, a heuristic value (r) was created to represent the overall absolute amount of difference between the true value and the calculated value in the form of $r = \sum_{20}^{i=0}(true\ value\ -\ calculated\ value)^2$. α and β were modified iteratively to minimize the value of r and thus reduce the error of the calculated values. The final formula used as for the calibration curve is as follows:

$$X = 54\sqrt{2} \times \sqrt{(1 - cos(0.2335 \times (x - 289.1)}$$

With the constants α = 0.2335 and β = 289.1.

Uncertainty Analysis

To plot the deviation of the calibration curve, the deviation was calculated by subtracting the y-value of the calibration curve from the true value. As the deviation plot shown below, the maximum uncertainty is 0.8mm.

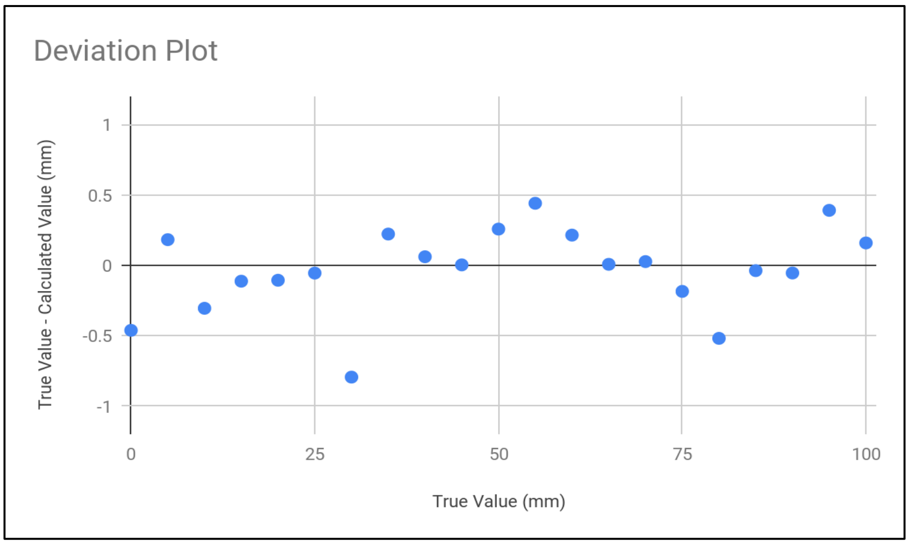

Figure 7: Deviation Plot

One source of random error was the slipping of the jaws in the z-axis during calibration. As seen in *Figure* 8, the two jaws are not fixed and can move in the z-axis when taking measurements. When the jaw is held in the air to take the measurement, the inconsistent twisting between the two arms in the z-direction caused a random error.

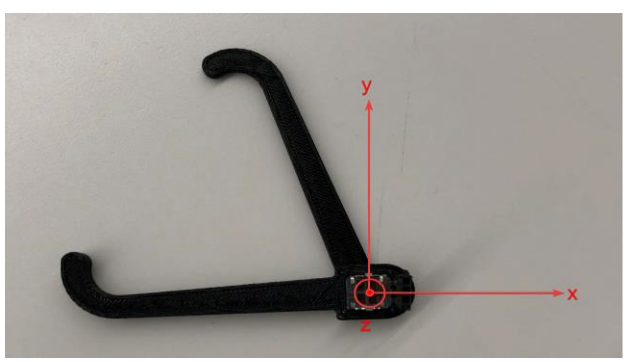

Figure 8: Caliper Jaw Axes

To reduce this error, the measuring method changed from measuring in the air to pressing the two jaw arms on a flat surface (i.e. on the table). This way, the distance between the two arms in z-direction becomes consistent.

One source of systematic error is caused by human error during the measurement. When measuring an object between the jaws, the object could be accidentally rotated in the x-y plane, which could result in a longer measured value. This effect is shown in *Figure 9* below with exaggeration.

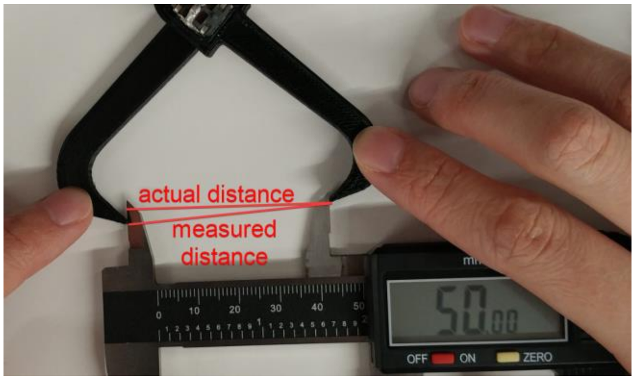

Figure 9: Systematic Error of Object Rotation

Another source of random error was the limited precision of the Arduino's ADC. With a 10-bit resolution, its digital output only spanned from 0-1023. As the device was required to measure a distance of at least 96 mm, this corresponded to an uncertainty of 0.1 mm from just the ADC.

Several suggestions for reducing random and systematic error are discussed in the recommendations below.

Conclusions and Recommendations for Future Work

In conclusion, the design, construction, and calibration of the caliper were successful in the design objective of creating a distance measuring device with a predicted uncertainty, able to measure up to 3 2x4 LEGO bricks. The caliper, which used 3D printed jaws, a rotary potentiometer, an Arduino Nano microcontroller, and an LCD display, was reliable, robust, and relatively portable. The caliper was successfully calibrated using a calibration plot and deviation curve, and its measurement uncertainty was successfully determined to be 0.8 mm. However, the caliper jaw design resulted in a considerable random error during calibration due to slippage, resulting in a relatively high measurement uncertainty. Also, the Arduino Nano ADC's 10-bit resolution was quite low, which was apparent during calibration and also increased the measurement uncertainty. Despite these areas of improvement, the caliper was overall successful in fulfilling all design objectives.

Several possible improvements to this caliper's design and calibration could be made in the future. For instance, jaw slip could be reduced by using a rack and pinion to convert linear displacement to rotation, which would not be susceptible to slippage. Also, the Arduino Nano ADC's 10-bit resolution could be improved by using a dedicated 16-bit ADC such as the ADS1115 [3]. With a digital output range from 0-65535, this would essentially eliminate ADC uncertainty as a source of random error. Finally, the rotary potentiometer could be replaced with a continuous encoder, which measures rotation angle without any upper limit. With a 3D printed gear increaser attached to a rack and pinion, this could greatly decrease random error and increase measurement precision.

References

[1]"Arduino Reference", Arduino.cc, 2018. [Online]. Available: https://www.arduino.cc/reference/en/language/functions/analog-io/analogread/. [Accessed: 21- Nov- 2018].

[2]"Neiko 01407A Electronic Digital Caliper Stainless Steel Body with Large LCD Screen | 0 - 6 Inches | Inch/Fractions/Millimeter Conversion", Amazon.com, 2006. [Online]. Available: https://www.amazon.com/Neiko-01407A-Electronic-Digital-Stainless/dp/B000GSLKIW. [Accessed: 21- Nov- 2018].

[3]ADS111x Ultra-Small, Low-Power, I 2C-Compatible, 860-SPS, 16-Bit ADCs With Internal Reference, Oscillator, and Programmable Comparator. Texas Instruments, 2009, p. 1.