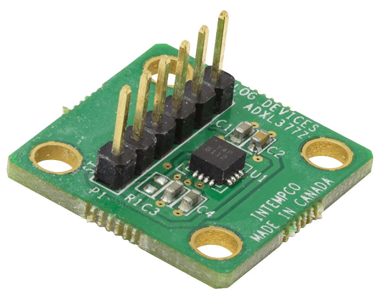
Course of Measurements for Automation and Industrial Production

ADXL377 inclinometer system Programmer's Guide



Course professor:
Sergio RAPUANO

Authors: Angelo CARAVELLA, Gerardo MANGANIELLO

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Contents

Aim of the project

The objective of this project is to develop a comprehensive system for the ADXL377 accelerometer, configured as an inclinometer to measure pitch (forward/backward tilt) and roll (side-to-side tilt) angles. The system includes the design and construction of a signal conditioning circuit to adapt the accelerometer for inclination measurements.After constructing the circuit, an adjustment process is performed using an ellipsoidal fitting procedure, followed by a precise calibration to ensure optimal performance of the entire system. The user can utilize the system to measure pitch and roll angles in real-time, with the ability to adjust the system for improved measurement accuracy. The visualization of the yaw angle is not supported.

Chapter 1

Introduction

This **programmer manual** provides an in-depth overview of the software architecture and design for the LabVIEW project focused on the ADXL377 accelerometer, configured as an **inclinometer**. The system is designed to measure pitch and roll angles accurately and in real-time.

The project encompasses several key components:

- **Hardware Integration**: the software interfaces with a custom-designed signal conditioning circuit that prepares the accelerometer for precise inclination measurements.
- **Data Acquisition**: The system facilitates the acquisition of voltage outputs from the accelerometer, which are then processed to derive the tilt angles.
- **Ellipsoidal Fitting**: The software implements an ellipsoidal fitting procedure for adjustment to ensure optimal performance of the measurement system.
- **Calibration**: the calibration process is critical for achieving accurate readings. A robotic arm is used as a reference for the angles during this calibration phase.

This manual is intended for developers looking to understand, modify, or extend the existing LabVIEW codebase. It includes:

- **System Architecture**: An overview of the hardware and software components involved in the project.
- **LabVIEW Design**: Detailed descriptions of the virtual instruments (VIs) used within the application.
- **Data Processing Techniques**: Insights into the algorithms utilized for data handling, adjustment and calibration.

Chapter 2

Hardware instrumentation used

In this chapter, the description of the hardware instrumentation used is provided:

- Accelerometer ADXL377
- National Instruments USB-6008 data acquisition (DAQ)
- Agilent Keysight, E3631A
- Operational amplifiers LM158

2.1 Accelerometer ADXL377

2.1.1 Hardware description

ADXL377 Datasheet [1]
The ADXL377 is a small, thin, low-power, complete 3-axis accelerometer with signal-conditioned voltage outputs. It measures acceleration resulting from motion, shock, or vibration, with a **typical full-scale range of ±200 g**.

However, using it as an inclinometer presents several challenges due to the difference among the acceleration ranges intended for each application. Below are the main difficulties.

[1] https://www.analog.com/media/en/technical-documentation/data-sheets/ADXL377.pdf

1. **Noise**: the accelerometer is sensitive to various sources of noise, including environmental vibrations, unwanted movements, and electrical disturbances. Noise can affect the accuracy of the measurement, particularly when small changes in inclination are to be detected.

2. **Calibration**: the ADXL377 is designed for high accelerations, so it is essential to calibrate the accelerometer for the lower accelerations typical in inclinometer applications. Calibration must account for variations in sensitivity under different operating conditions.

3. **Offset Compensation**: the accelerometer has an internal offset, so in order to use the ADXL377 as an inclinometer, it is necessary to compensate the offset to obtain accurate and stable readings.

4. **Electromagnetic Interference**: an environment with strong magnetic fields or other sources of electromagnetic interference can affect the precision of the measures.

In addition, **attention must be paid to the configuration and mounting of the accelerometer** to ensure that it is correctly oriented and fixed to accurately measure the desired inclination.

2.1.2 Main characteristics

As it has already been said, the accelerometer ADXL377 measures **acceleration** resulting from motion, shock, or vibration with a typical **full-scale range of ±200 g**.

It can be selected the bandwidth of the accelerometer by configuring the capacitors C_X, C_Y, and C_Z at the respectively pins X_{OUT}, Y_{OUT}, and Z_{OUT}. The bandwidth can be chosen according to the application: **from 0.5 Hz to 1300 Hz** for the **x-axis and y-axis**, and **from 0.5 Hz to 1000 Hz for the z-axis**.

The following picture shows the block diagram of the accelerometer.

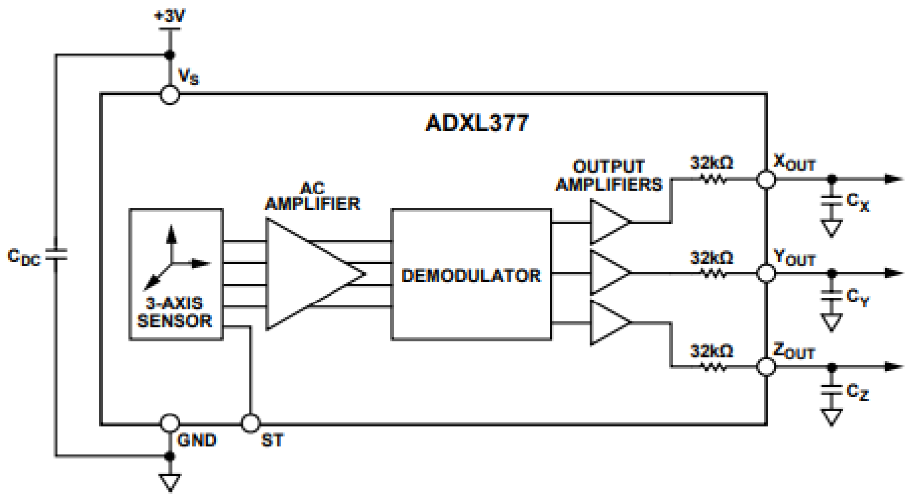


Figure 2.1: Functional block diagram

2.1.3 View of the sensor

The following images show how the sensor is located in the space (top, side, down). In addition, the corresponding values of gravitational acceleration **[g]** for each triaxial position **(x, y, z)** are shown.

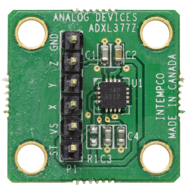
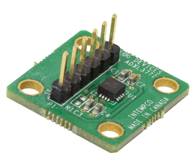
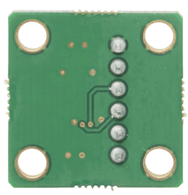
		
TOP	SIDE	DOWN

Table 2.1: View of the sensor

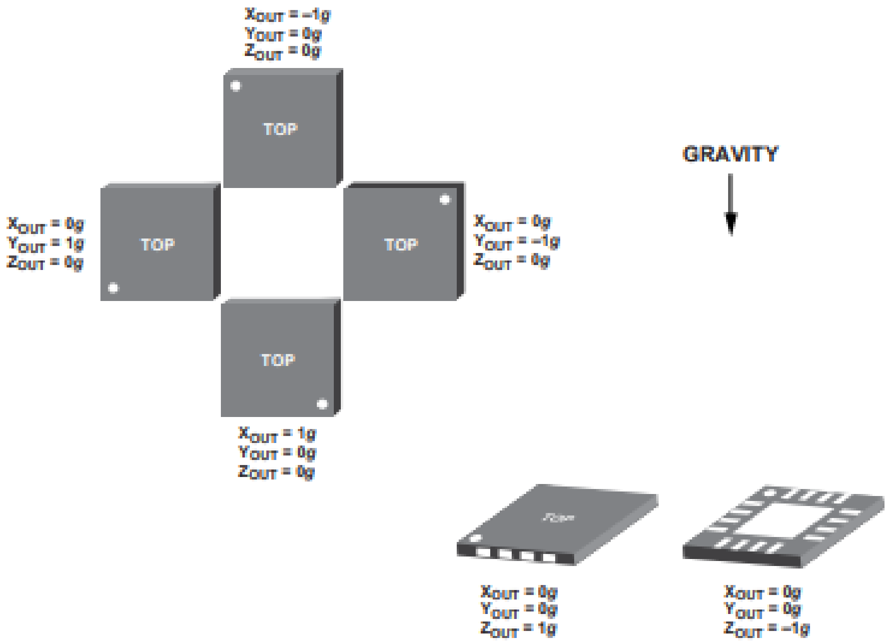


Figure 2.2: Values of g for different orientation of x, y and z axes

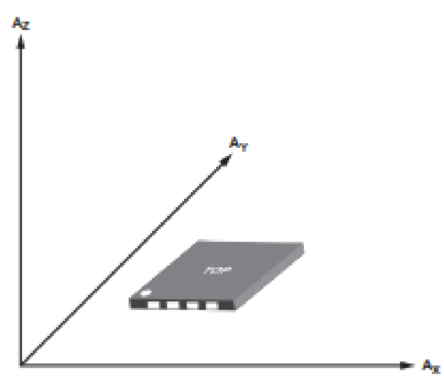


Figure 2.3: Axes of acceleration sensitivity

2.1.4 Offset

The accelerometer has an internal offset. As it can be observed from the graphs, at a temperature of approximately 20 degrees Celsius, the offset is equal to 1.5V.

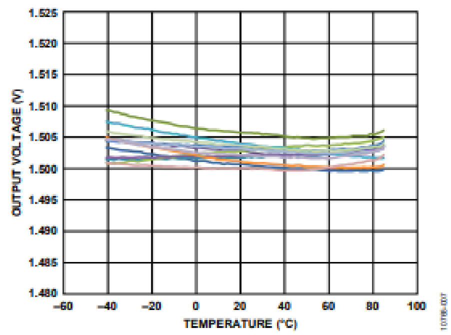


Figure 7. Y-Axis Zero g Offset vs. Temperature, $V_S = 3$ V (14 Parts Soldered to PCB)

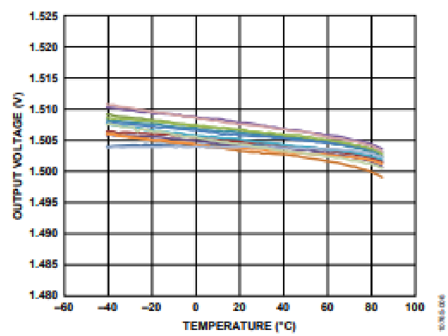


Figure 6. X-Axis Zero g Offset vs. Temperature, $V_S = 3$ V (14 Parts Soldered to PCB)

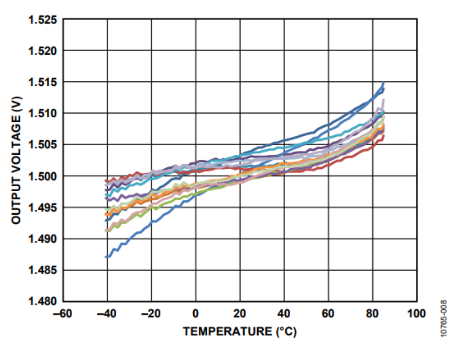


Figure 8. Z-Axis Zero g Offset vs. Temperature, $V_S = 3$ V (14 Parts Soldered to PCB)

2.2 National Instruments USB-6008 data acquisition device

Figure 2.4: Data acquisition device

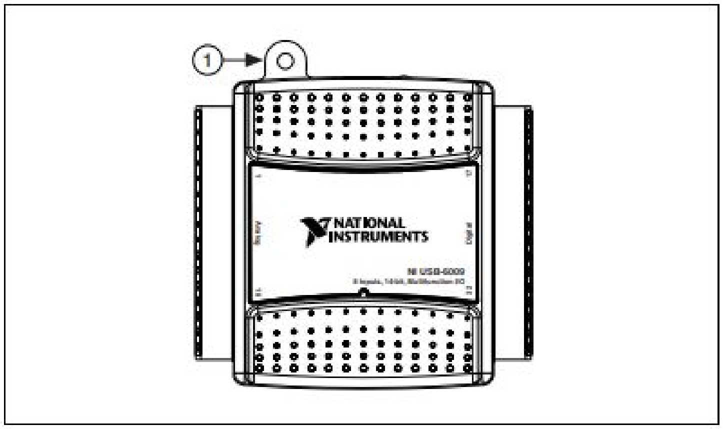
2.2.1 Overview

USB6008 Datasheet [2]
The NI USB-6008/6009 provides connection to eight analog input (AI) channels, two analog output (AO) channels, 12 digital input/output (DIO) channels, and a 32-bit counter with a full-speed USB interface.

Feature	USB-6008
AI Resolution	12 bits differential, 11 bits single-ended
Maximum AI Sample Rate, Single Channel*	10 kS/s
Maximum AI Sample Rate, Multiple Channels (Aggregate)*	10 kS/s
DIO Configuration	Open collector

Figure 2.5: Features of USB-6008

[2] https://users.physics.unc.edu/ sean/Phys351/techresource/docs/USB6009%20User%20Manual.pdf



1 USB Cable Strain Relief

Figure 2.6: USB-6008

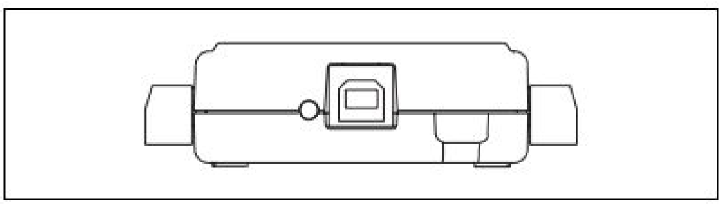


Figure 2.7: USB-6008 back-view

2.2.2 Hardware

The following block diagram shows key functional components of the USB-6008.

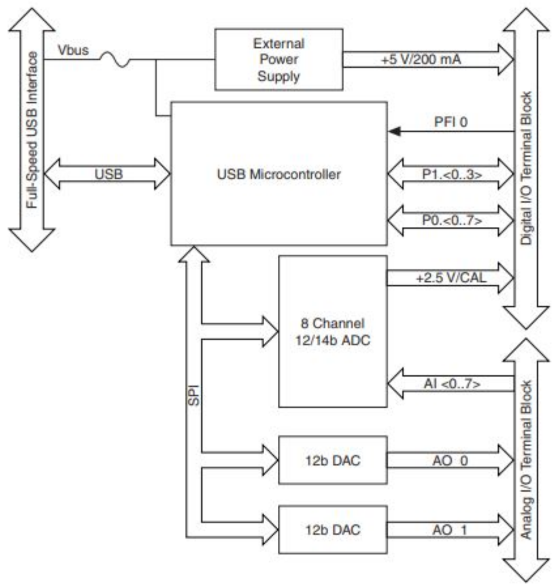
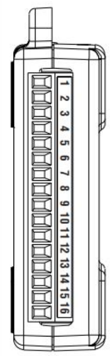


Figure 2.8: DAQ block diagram

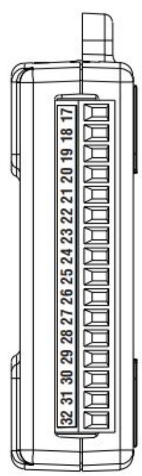
2.2.3 I/O connector

The following lists show the analog terminal assignment and the digital terminal assignment, respectively.



Module	Terminal	Signal, Single-Ended Mode	Signal, Differential Mode
	1	GND	GND
	2	AI 0	AI 0+
	3	AI 4	AI 0–
	4	GND	GND
	5	AI 1	AI 1+
	6	AI 5	AI 1–
	7	GND	GND
	8	AI 2	AI 2+
	9	AI 6	AI 2–
	10	GND	GND
	11	AI 3	AI 3+
	12	AI 7	AI 3–
	13	GND	GND
	14	AO 0	AO 0
	15	AO 1	AO 1
	16	GND	GND

Figure 2.9: Analog Terminal Assignments



Module	Terminal	Signal
	17	P0.0
	18	P0.1
	19	P0.2
	20	P0.3
	21	P0.4
	22	P0.5
	23	P0 6
	24	P0.7
	25	P1.0
	26	P1.1
	27	P1.2
	28	P1.3
	29	PFI 0
	30	+2.5 V
	31	+5 V
	32	GND

Figure 2.10: Digital Terminal Assignments

2.3 E3631A Agilent DC Power Supply

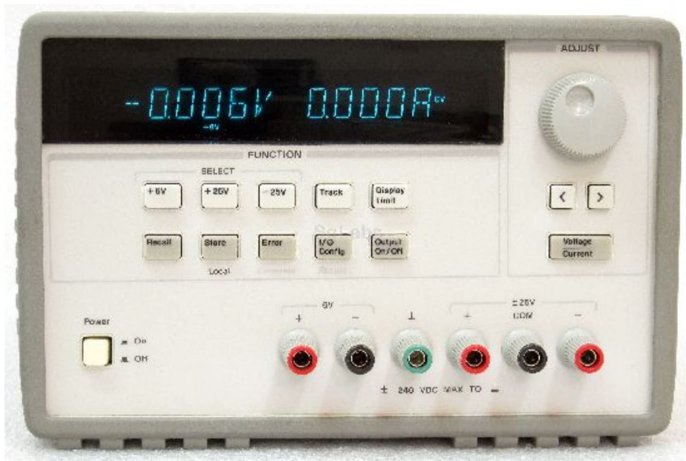


Figure 2.11: E3631A Agilent DC Power Supply

E3631A Datasheet [3]
The instrumentation hardware includes a basic DC power supply, the E3631A one.

2.3.1 Main characteristics

Output

- Output 1: 0 to 6 V, 0 to 5 A
- Output 2: 0 to +25 V, 0 to 1 A
- Output 3: 0 to −25 V, 0 to 1 A

Accuracy at 25°C ± 5°C:

$$\begin{aligned} &\text{Voltage:} \\ &\qquad 0.05\% + 20\text{ mV}, \quad 0.05\% + 20\text{ mV}, \quad 0.1\% + 5\text{ mV} \\ &\text{Current:} \\ &\qquad 0.15\% + 4\text{ mA}, \quad 0.15\% + 4\text{ mA}, \quad 0.2\% + 10\text{ mA} \end{aligned}$$

[3]https://www.sglabs.it/public/$HP_E3631A.pdf$

- **Maximum Current:** 5A
- **Display:** Digital
- **Interface:** GPIB, RS232
- **Maximum Voltage:** 25 V
- **Minimum Voltage:** -25 V

2.4 LM158 operation amplifier

LM158 Datasheet [4]
The device consists of two independent amplifiers which have high gain, internally frequency compensated and designed specifically to operate from a single power supply over a wide range of voltages. The following image shows the pin of the device.

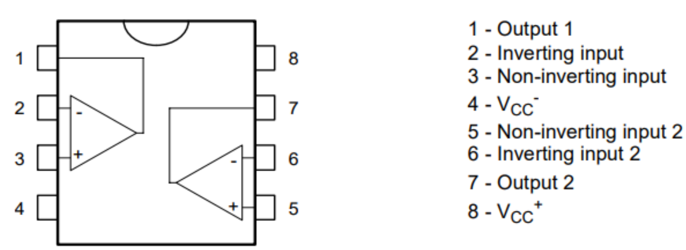


Figure 2.12: Pin connections

[4] https://digsys.upc.edu/csd/chips/analog/$OpAmp_LM358.pdf$

Chapter 3

Conditioning circuit

3.1 Design of the conditioning circuit

The conditioning circuit is designed to **remove the 1.5V offset from each output**. In addition, from the data-sheet, the typical change in output is shown as follows:

- **For the x-axis, the typical change is -1.08 g (corresponding to -6.5 mV)**
- **For the y-axis, the typical change is +1.08 g (or 6.5 mV)**
- **For the z-axis, the typical change is +1.83 g (or 11.5 mV)**

After the offset removal, the circuit amplifies the accelerometer voltage outputs by a factor of about **960** $\frac{V}{V}$.

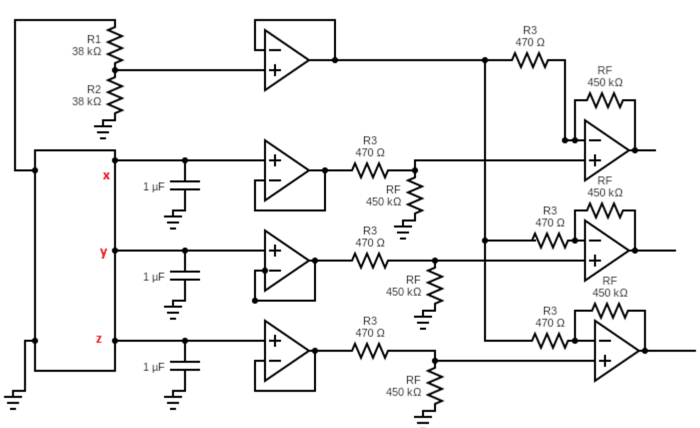


Figure 3.1: Conditioning circuit R1 = R2 = 38$k\Omega$ R3= 470Ω Rf= 450$k\Omega$

3.2 Subtractor

3.2.1 Voltage divider

The input voltage is 3V. **This circuit produces an output voltage of about 1.5V**.

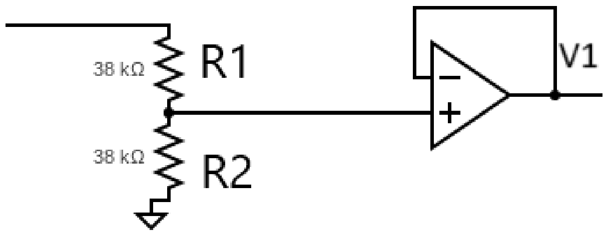


Figure 3.2: The circuit used to create a voltage divider

$$V_1 = \frac{3V \cdot R_2}{R_2 + R_1} = 1.5V$$

3.2.2 Low-pass filter

The accelerometer has provisions for band-limiting the X_{OUT}, Y_{OUT} and Z_{OUT} pins. A capacitor must be added at each of these pins to implement low-pass filtering for anti-aliasing and noise reduction.

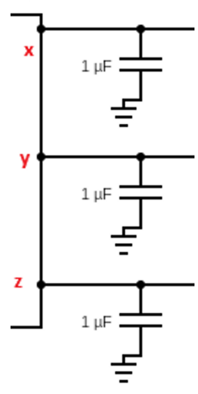


Figure 3.3: Low-pass filter

The equation for the $-3\,\mathrm{dB}$ bandwidth is

$$f_{-3\,\mathrm{dB}} = \frac{1}{2\pi \times 32\,\mathrm{k}\Omega \times C_x}$$

The tolerance of the internal resistor typically varies by as much as ±15% of its nominal value (32 kΩ, Figure 2.1, and the bandwidth varies accordingly. A minimum capacitance of 1000 pF for C_X, C_Y, and C_Z is recommended in all cases.
All the information about the following table and the internal resistance can be retrieved here: ADXL377 Datasheet, page 9

Bandwidth (Hz)	**Capacitor (μF)**
50	0.10
100	0.05
200	0.025
500	0.01
1000	0.005

Table 3.1: Filter Capacitor Selection for C_X, C_Y, and C_Z

3.2.3 Voltage follower

Using a voltage follower (also known as a buffer) between a capacitance (low-pass filter) and a resistance serves several useful purposes: preventing signal distortion, ensuring efficient signal transfer and providing isolation between the preceding and following stages of a circuit.

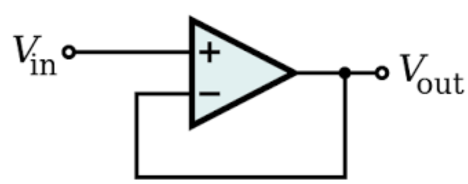


Figure 3.4: Voltage follower (buffer)

Overall, using a voltage follower enhances circuit performance by providing impedance matching, isolation, signal integrity, drive capability and stability.

3.2.4 Output

At the end of the subtractor circuit the three voltages are amplified by a factor of about **960** $\frac{V}{V}$.

Gain calculation

The voltage v_1 is the output from the buffer placed after the voltage divider and is fed into the inverting terminals of the three operational amplifiers. The voltage v_2, on the other hand, refers to the output from the buffers connected to the X, Y, and Z outputs of the accelerometer and is fed into the non-inverting terminals of the three operational amplifiers. Since equal resistors were used, the outputs of these three operational amplifiers will be the same.

$$V_{out} = -\frac{R_f}{R_3} \cdot v_1 + \left(1 + \frac{R_f}{R_3}\right) \cdot \left(\frac{R_f}{R_3+R_f}\right) \cdot v_2 =$$
$$= -\frac{R_f}{R_3} \cdot v_1 + \frac{R_3+R_f}{R_3} \cdot \left(\frac{R_f}{R_3+R_f}\right) \cdot v_2 =$$
$$= -\frac{R_f}{R_3} \cdot v_1 + \frac{R_f}{R_3} \cdot v_2 =$$
$$= \frac{R_f}{R_3} \cdot (v_2 - v_1) = 957.4 \cdot (v_2 - v_1)$$

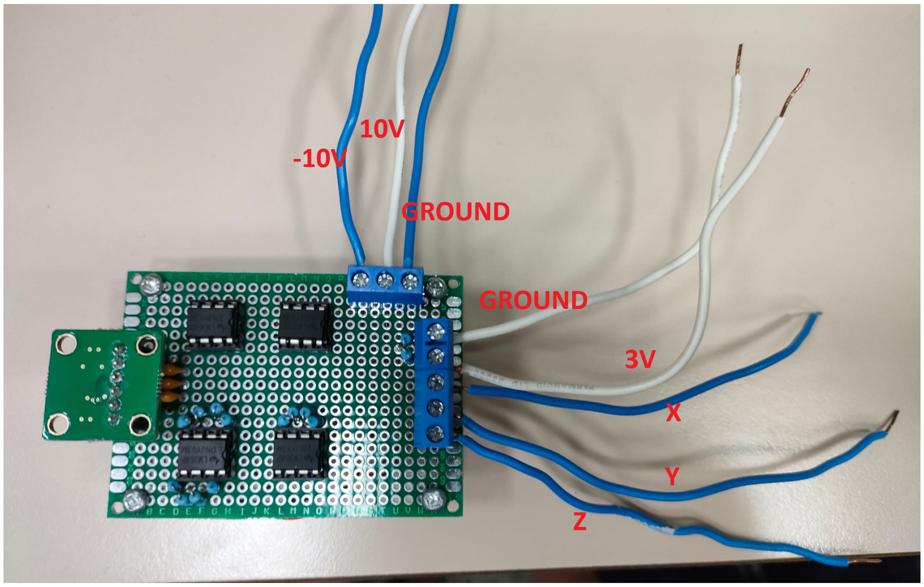


Figure 3.5: Top view of the circuit

Chapter 4

Software VI

4.1 Acquisition chain

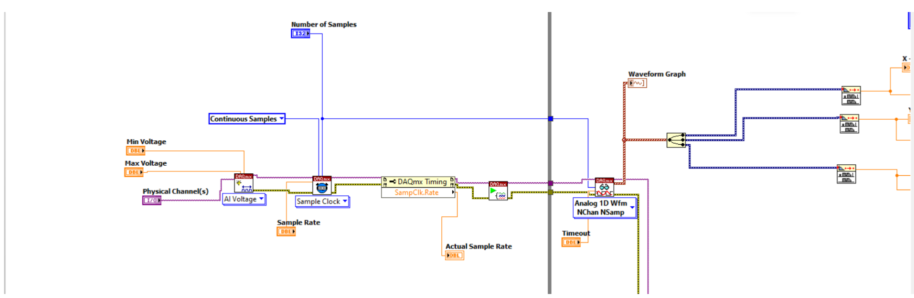


Figure 4.1: Basic chain for acquisition

This is the basic chain for acquisition where the maximum and minimum voltage are set. The type of acquisition is ”**continuous samples**”. Once the data is acquired, the **Split Signal** block is used to separate the voltage readings into individual channels corresponding to each axis of the accelerometer.

4.2 Moving average filter

To improve data quality, a moving average filter is applied to the three distinct raw voltage signals before further processing. This filter smooths out fluctuations by averaging a specified number of previous readings, effectively reducing noise while maintaining important trends. This results in more stable and reliable measurements for calculating pitch and roll angles.

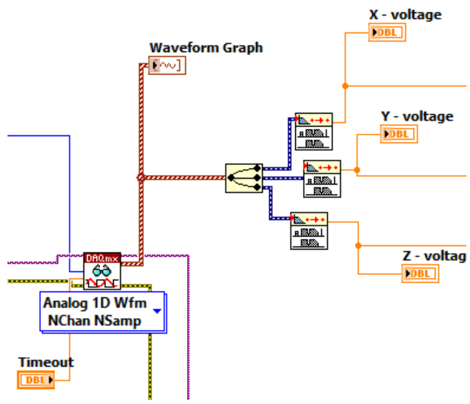


Figure 4.2: Moving average filter

For a sample size of 100 and a sample rate of 1000 Hz, it has observed that a second- order filter provides good estimates.

4.3 Acquisition Case

In the block diagram of the acquisition case, the three split signals are processed. If the internal case is set to true, the values are saved to a file, and as the file fills, the points are plotted on a 3D graph. If the internal case is set to false, there is no memory of past data, and the point is continuously updated based on the sensor's movement.

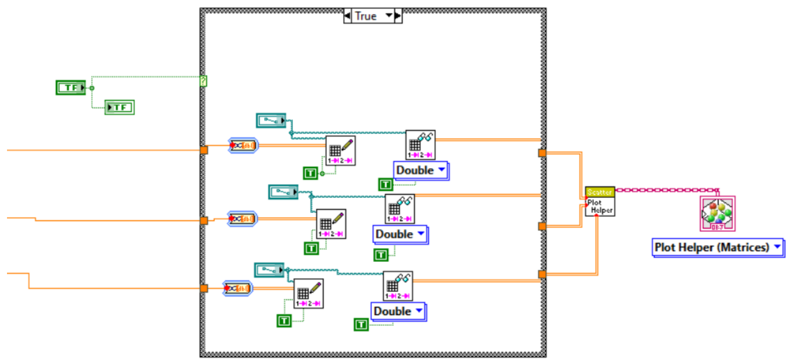


Figure 4.3: Acquisition - case **true**

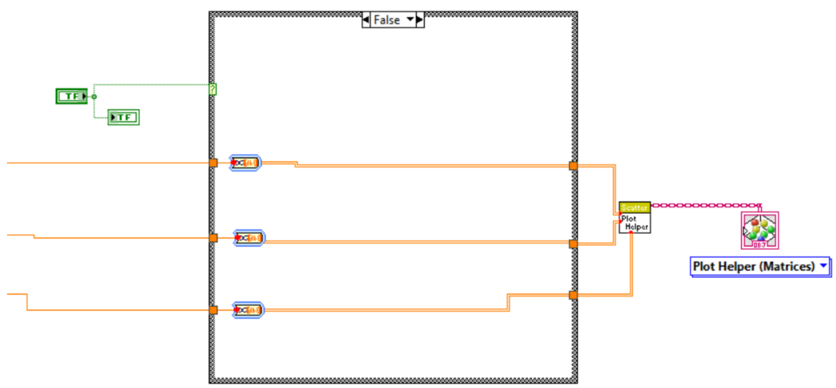


Figure 4.4: Acquisition - case **false**

4.4 Adjustment case

In the Adjustment Tab, the data saved in the acquisition files are sent to a SubVI called Adjustment.VI. This SubVI extracts four key outputs: the matrix **M_best** and the vector **b** which are utilized for the ellipsoidal fitting process. Additionally, the SubVI generates two graphs: the first visualizes the points before ellipsoidal compensation, representing the ellipsoid with voltage values, while the second graph displays a unit sphere with values corresponding to gravitational acceleration [g]. It is crucial to ensure that the acquired and saved voltage data form an ellipsoid to avoid unreliable results during the calibration phase.

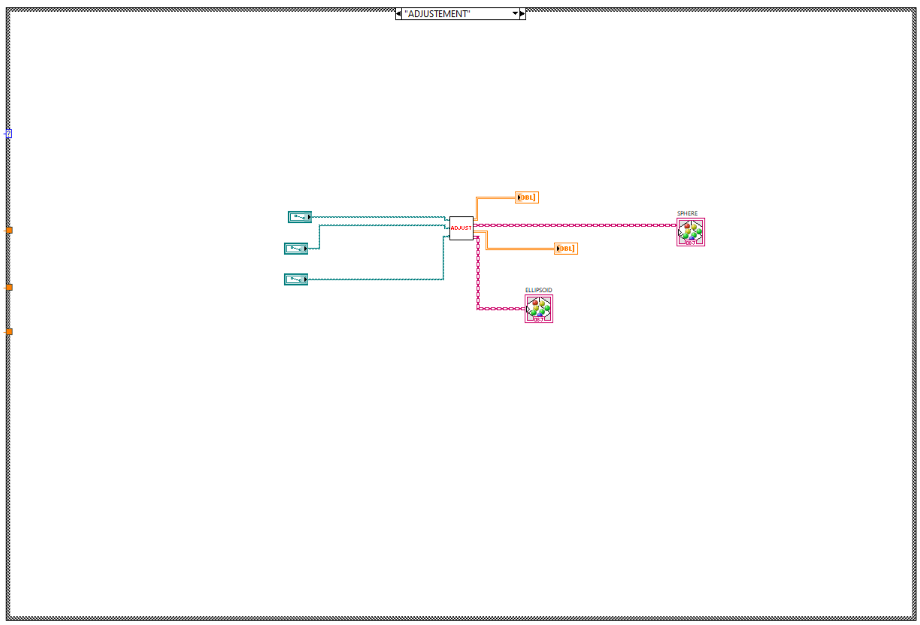


Figure 4.5: Adjustment case

4.4.1 Adjustment SubVI

The Adjustment SubVI is responsible for compensating the raw voltage data acquired from the accelerometer and converting it into **gravitational acceleration values [g]**. This process is crucial to ensure the correct adjustment of the system, allowing for accurate pitch and roll angle measurements.

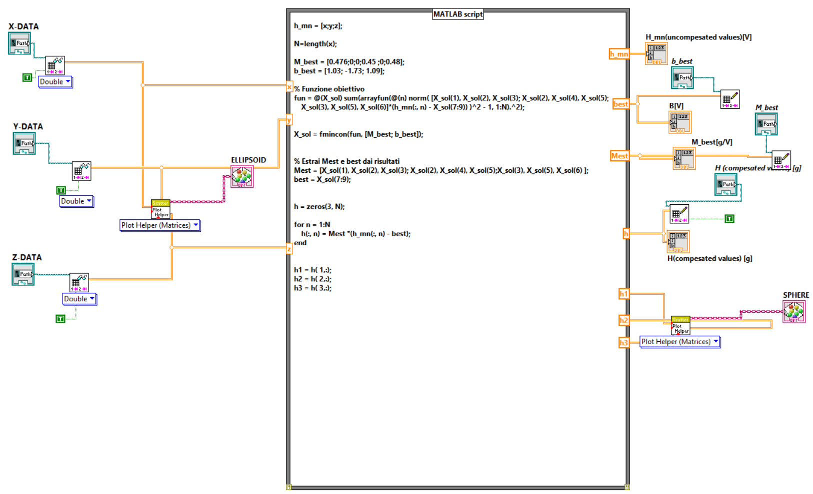


Figure 4.6: AdjustmentVI Block Diagram

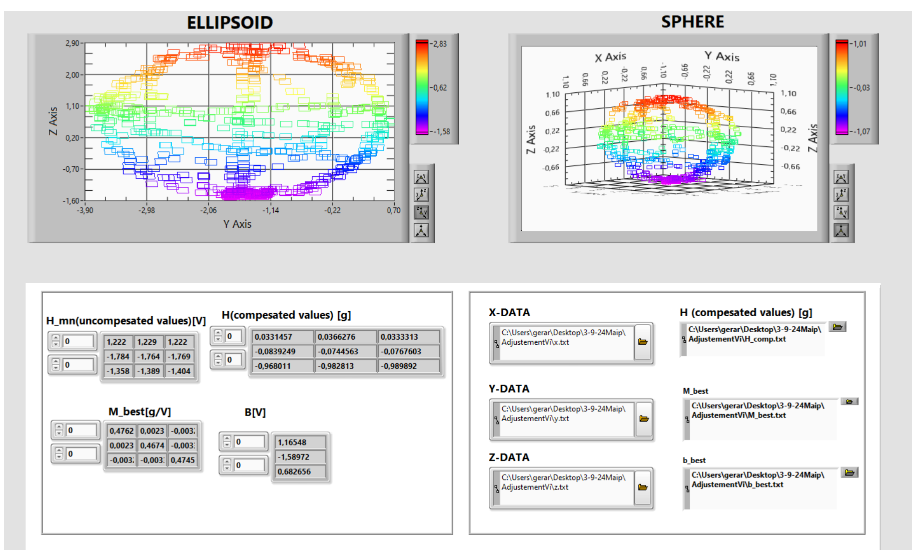


Figure 4.7: AdjustmentVI Front Panel

4.4.2 Ellipsoidal Compensation for Triaxial Accelerometer

Input data

The SubVI takes three raw voltage files as input, each corresponding to one of the accelerometer axes (X, Y, Z). These data points are plotted on a 3D graph. It is crucial that these points form an ellipsoid in space; otherwise, the algorithm will produce incorrect results, leading to an unreliable system.

Initial Conditions: Sensitivity Matrix

To properly initialize the ellipsoidal fitting algorithm, two important initial conditions are required: **the matrix M** and **the vector b**, which are derived from a **sensitivity matrix**.

Sensitivity Matrix The sensitivity matrix is a 3×3 matrix that contains the following information:

- On the main diagonal, it holds the measured voltage values for each axis when the accelerometer is in a 1g condition along that axis.
- The other elements in the same column represent the offsets introduced by the other axes when the main axis is at 1g.

From the sensitivity matrix, the initial values for the matrix M and the vector b used by the fitting algorithm are calculated.

Calculation of Matrix M and vector b

- **Matrix M**: this is a diagonal matrix that contains the sensitivities for each axis on its main diagonal. The sensitivity for an axis is calculated as the ratio of **1g** to the difference between the **measured voltage at 1g** and the **offset** for that axis.
- **Vector b:** this 3×1 vector contains the **offset for each axis** relative to its 1g value.

The structure of the matrix M and vector b is organized by the three main axes (X, Y, Z), with the respective values arranged by row.

Ellipsoidal Fitting Algorithm

Once initialized with the values of matrix M and vector b, the ellipsoidal fitting algorithm is executed to compensate the raw data. This algorithm uses non-linear least-squares minimization to fit the raw voltage data to an ellipsoid model, converting them into gravitational acceleration values.

The algorithm minimizes the following objective function:

$$\{M_{\text{est}}, b_{\text{est}}\} = \arg\min_{(M,b)} \sum_{n=1}^{N} \left(\|M^{-1}(h_{mn} - b)\|^2 - 1 \right)^2 \tag{4.1}$$

Where:

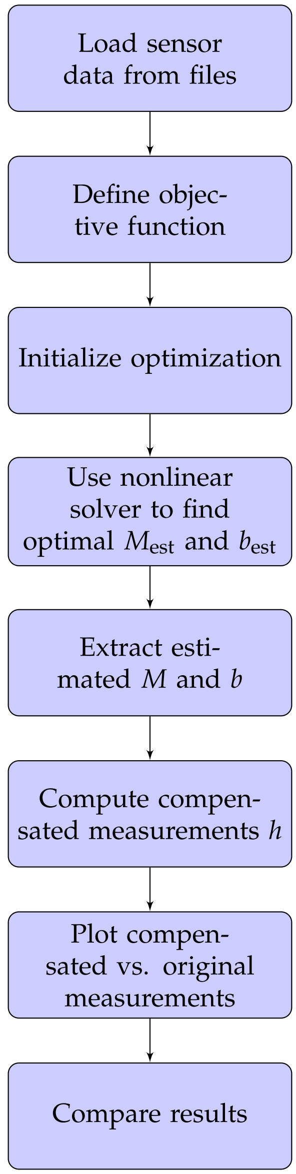
- M_{est} and b_{est} are the estimated model parameters that minimize the objective function.
- h_{mn} represents the $n - th$ raw measurement (voltage data).
- N is the total number of measurements.
- The term $(\|M^{-1}(h_{mn} - b)\|^2$ expresses the distance of each measurement point from the center of the ellipsoid, scaled by the transformation matrix M and offset by b.

The minimization of this function ensures that the fitted ellipsoid matches the raw data as closely as possible, while transforming it into a sphere of unit radius, corresponding to gravitational acceleration values **[g]**.

So, once the matrix M and vector b have been estimated through the fitting algorithm, the ”true” values of h (representing gravitational accelerations) are calculated using the equation:

$$h = M^{-1}(h_m - b) \tag{4.2}$$

In the next page the algorithm is explained step by step for the ellipsoidal fitting:


Load sensor data from files
Define objective function
Initialize optimization
Use nonlinear solver to find optimal M_{est} and b_{est}
Extract estimated M and b
Compute compensated measurements h
Plot compensated vs. original measurements
Compare results

4.4.3 MATLAB Code

```
%% Angelo Caravella
clear all      % Clear workspace, removing all variables.
close all      % Close all figure windows.
clc            % Clear command window.

%% Input Data
% Load data from CSV files
% These files contain the original 3D data points which form an ellipsoid.
x = load('C:\Users\Angelo␣CARAVELLA\Desktop\Dati\5_rivisto\X.csv'); % X coordinates
y = load('C:\Users\Angelo␣CARAVELLA\Desktop\Dati\5_rivisto\Y.csv'); % Y coordinates
z = load('C:\Users\Angelo␣CARAVELLA\Desktop\Dati\5_rivisto\Z.csv'); % Z coordinates

N = length(x);  % Length of the data vectors (assuming x, y, z are of same length)
h_mn = [x'; y'; z'];  % 3xN matrix where each column is a 3D data point

%%%%%%%%%%%%%%%%%%% COMPENSATION ALGORITHM
% The goal is to compensate the data such that the original ellipsoid (represented by h_mn)
% transforms into a perfect sphere. This is done by finding the optimal transformation matrix M
% and bias vector b that achieves this compensation.

% Initial estimates for the transformation matrix (M) and bias vector (b)
% M_best is initialized with values close to those expected for a transformation towards a sphere.
M_best = [0.49; 0; 0;
          0.47; 0; 0.49];
b_best = [1; -1.8; 0.6];  % Initial bias vector estimate

% Concatenate M and b into a single vector for optimization
valori_ = [M_best; b_best];

% Objective function to minimize
% This function calculates how close the transformed data points are to the surface of a unit sphere.
% The goal is to minimize the difference between the squared norm of each transformed point and 1 (which is the radius of the unit sphere).
fun = @(X_sol) sum(arrayfun(@(n) norm([X_sol(1), X_sol(2), X_sol(3);
                                       X_sol(2), X_sol(4), X_sol(5);
                                       X_sol(3), X_sol(5), X_sol(6)] *
                              (h_mn(:, n) - X_sol(7:9)))^2 - 1, 1:N).^2);

% Optimization using fmincon
```

```matlab
% fmincon is a constrained optimization function that can handle more complex cases like
% the non-linear problem of transforming an ellipsoid into a sphere.
% fminsearch, on the other hand, is a simpler unconstrained optimizer and may not handle
% the constraints or the non-linearities effectively, which is why it might not have worked as expected.
X_sol = fmincon(fun, valori_);

% Extract the optimized M and b from the results
Mest = [X_sol(1), X_sol(2), X_sol(3);
        X_sol(2), X_sol(4), X_sol(5);
        X_sol(3), X_sol(5), X_sol(6)];
best = X_sol(7:9);

% Calculate compensated data h for each column of h_mn
% Each original data point is transformed using the optimized M and b.
h = zeros(3, N);  % Initialize compensated data matrix
for n = 1:N
    h(:, n) = Mest * (h_mn(:, n) - best);
end

% Separate the compensated data matrix into 3 column vectors
hx = h(1, :);  % X-coordinates of compensated data
hy = h(2, :);  % Y-coordinates of compensated data
hz = h(3, :);  % Z-coordinates of compensated data

% Create a 3D plot comparing compensated (red) and uncompensated (blue) data
figure;
plot3(hx, hy, hz, 'r');  % Compensated data in red
hold on;
plot3(x', y', z', 'b');  % Uncompensated data in blue
xlabel('x');
ylabel('y');
zlabel('z');
title('Comparison:␣Red␣(Compensated),␣Blue␣(Uncompensated)');
grid on;
hold off;

% Create another plot to visualize the compensated data only
figure;
plot3(hx, hy, hz, 'r');  % Compensated data only
xlabel('x');
ylabel('y');
zlabel('z');
title('Compensated␣Data␣(Red)');
grid on;
```

Listing 4.1: Compensation Algorithm in MATLAB

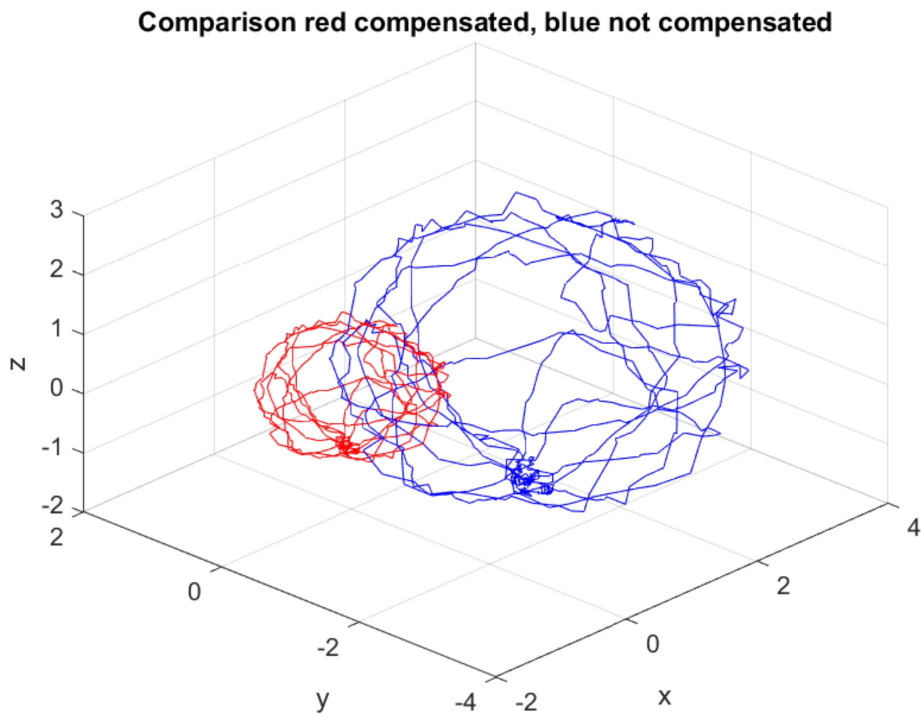
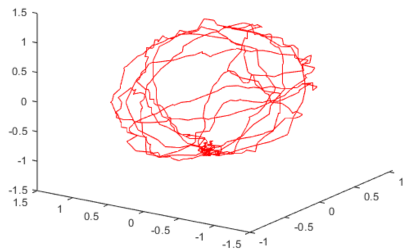
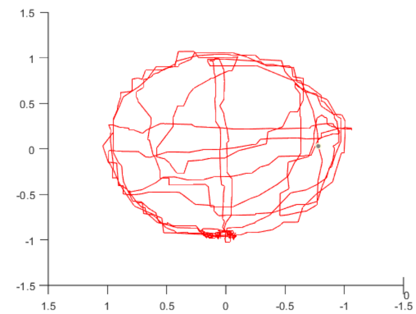


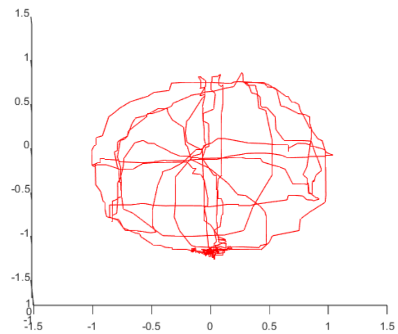
Figure 4.8: Blue surface is an ellipsoid, the red one is a sphere



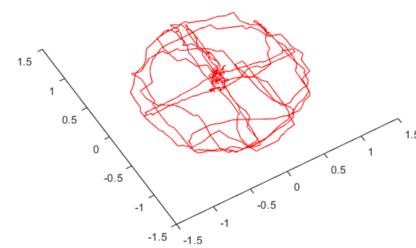
(a)



(b)



(c)



(d)

The **blue surface** represents an **ellipsoid** formed by the uncompensated values, while the **red surface** shows the compensated values and represents a **sphere**.

4.4.4 Results from the Ellipsodial compensation procedure

By using the following values for the sensitivity matrix and the initial matrix M and vector b:

- **Sensitivity Matrix**

$$S = \begin{bmatrix} 3.13\,\mathrm{V} & 1.03\,\mathrm{V} & 1.03\,\mathrm{V} \\ -1.73\,\mathrm{V} & 0.51\,\mathrm{V} & -1.73\,\mathrm{V} \\ 1.09\,\mathrm{V} & 1.09\,\mathrm{V} & 3.18\,\mathrm{V} \end{bmatrix}$$

- **Initial Matrix M**

$$M_{\text{initial}} = \begin{bmatrix} \frac{1g}{(3.13-1.03)\,\mathrm{V}} & 0 & 0 \\ 0 & \frac{1g}{(0.51-(-1.73))\,\mathrm{V}} & 0 \\ 0 & 0 & \frac{1g}{(3.18-1.09)\,\mathrm{V}} \end{bmatrix} = \begin{bmatrix} 0.476 & 0 & 0 \\ 0 & 0.45 & 0 \\ 0 & 0 & 0.48 \end{bmatrix}$$

- **Initial Vector b**

$$b = \begin{bmatrix} 1.03\,\mathrm{V} \\ -1.73\,\mathrm{V} \\ 1.09\,\mathrm{V} \end{bmatrix}$$

the fitting procedure yields the following estimated parameters:

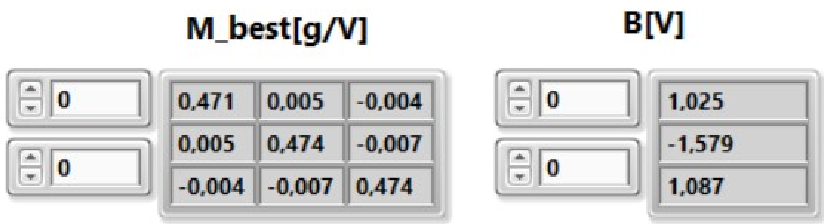


Figure 4.9: Best M and B parameters

4.5 Calibration Case

In the Calibration Case, there is a SubVI called **Calibration**. This SubVI provides ten outputs, which include:

1. **Calibration Curves**: The graphical representations of the calibration curves for both pitch and roll angles.
2. **Equations of the Curves**: The equations corresponding to each calibration curve, which describe the linear relationship between the measured values and the reference values.
3. **Slope Values**: The slopes of the calibration lines.
4. **Intercept Values**: The y-intercepts of both calibration lines.
5. **Absolute Uncertainties**: The calculated uncertainties associated with the calibration measurements, allowing for an assessment of measurement reliability.

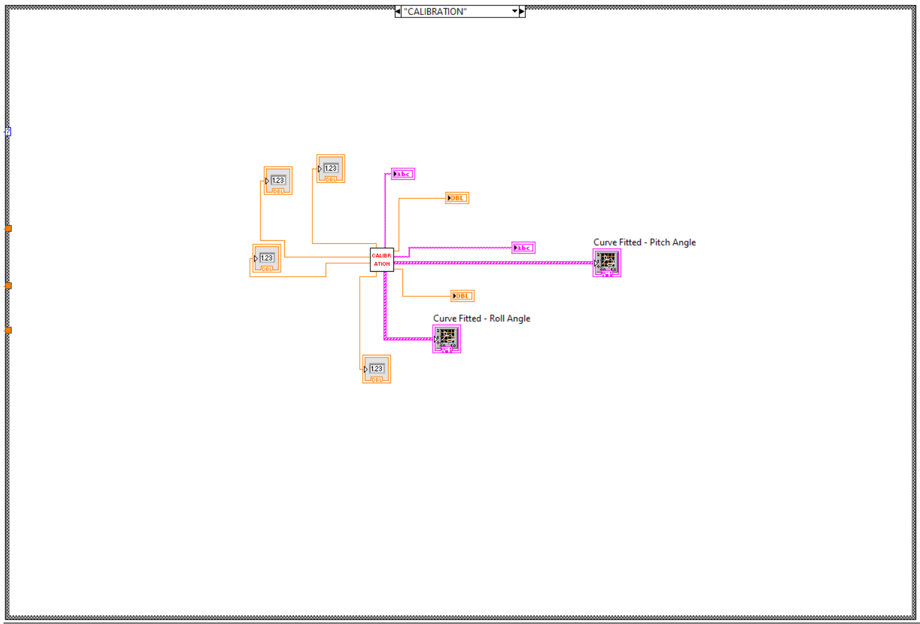


Figure 4.10: Calibration Case

4.5.1 Calibration SubVI

In the Calibration SubVI, the calibration data are processed. The following information are retrieved from the file:

- **Absolute Uncertainty**: The absolute uncertainty obtained during the calibration phase. For details see the chapter 5
- **Measured Angles**: The measured angles corresponding to the accelerometer readings.
- **True Angles**: The true reference angles corresponding to the measured angles.

The graph displays the calibration curve, specifically the best-fit line for the measurements in the file. This is provided for both pitch and roll angles, with the measured values also plotted. Additionally, the equation of the calibration line is presented, allowing for a clear understanding of the relationship between the measured and true angles.

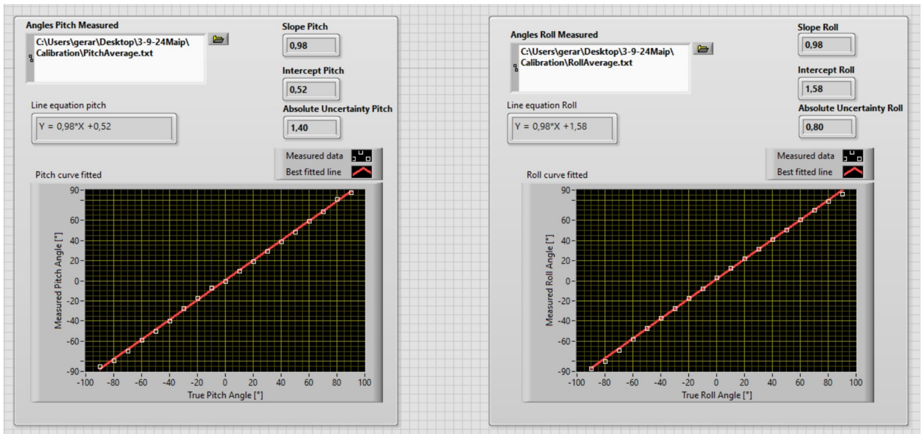


Figure 4.11: Calibration SubVI Front Panel

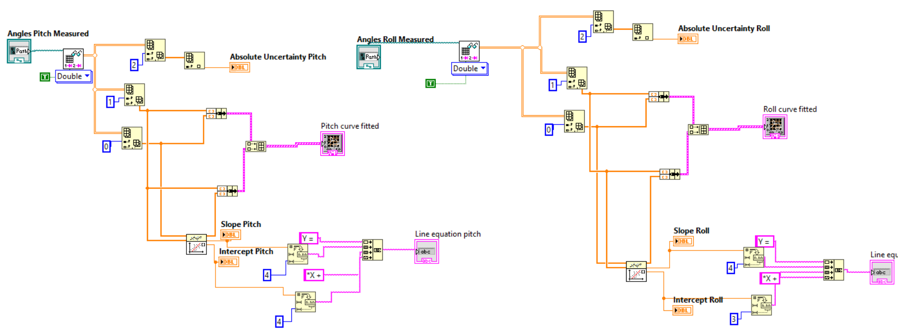


Figure 4.12: Calibration SubVI Block Diagram

4.6 Visualization Case

In the Visualization Case, the voltage data from the sensor are first merged using the `Merge Signal` block and then compensated. Two files are used, containing the best matrix **M** and the best vector **b** calculated during the adjustment phase.

The compensation process involves subtracting the offsets in the vector **b** from the voltage data and then multiplying the result by the matrix **M**, thus obtaining the values in terms of gravitational acceleration **g**. The compensated signals are then split again, with each signal sent to distinct SubVIs for the calculation of the pitch and roll angles.

The outputs from the **Pitch SubVI** and **Roll SubVI** provide the measurements of their respective angles. From the **Calibration SubVI**, the slope and intercept of the two calibration curves, as well as the uncertainties obtained during the calibration phase, are retrieved. At this point, the measurements from the **Pitch SubVI** and **Roll SubVI** have their respective intercepts subtracted and are then divided by their corresponding slopes, thus obtaining the "true" angle values.

An `Average` block calculates the average of 30 incoming measurements, and this average is plotted on the screen in real time as new data is acquired. Finally, the averaged data can be saved to a file for later analysis.

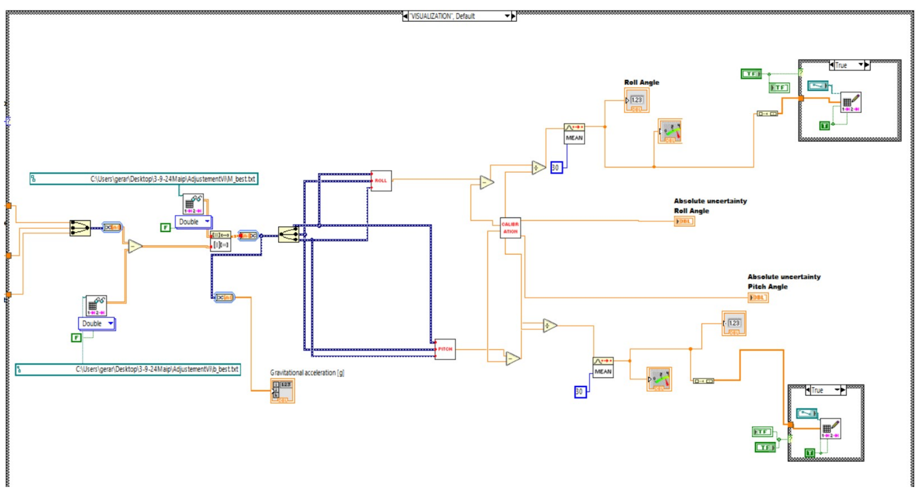


Figure 4.13: Visualization Case

4.6.1 Pitch and Roll SubVIs

The **Pitch SubVI** and **Roll SubVI** take the gravitational acceleration values as inputs and calculate the corresponding pitch and roll angles. The roll angle is calculated using the formula:

$$\theta_{\text{roll}} = \arctan\left(\frac{g_x}{\sqrt{g_y^2 + g_z^2}}\right)$$

Similarly, the pitch angle is calculated as:

$$\theta_{\text{pitch}} = \arctan\left(\frac{g_y}{\sqrt{g_x^2 + g_z^2}}\right)$$

Figure 4.14: Front panel Roll and Pitch SubVis

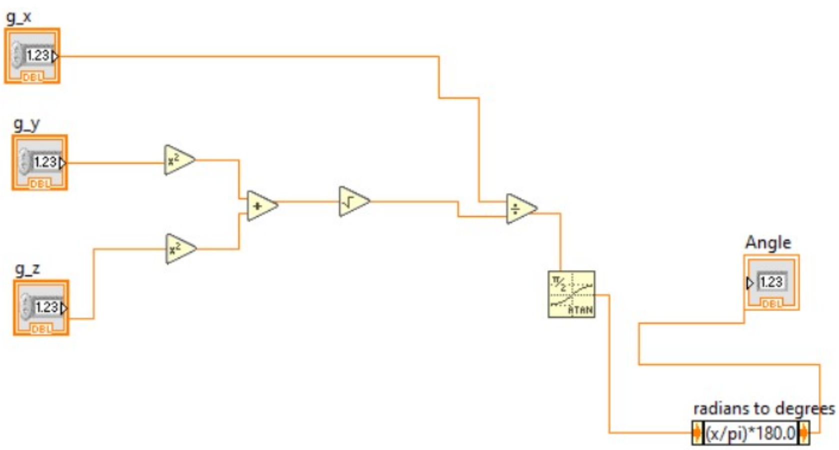


Figure 4.15: Roll Block Diagram

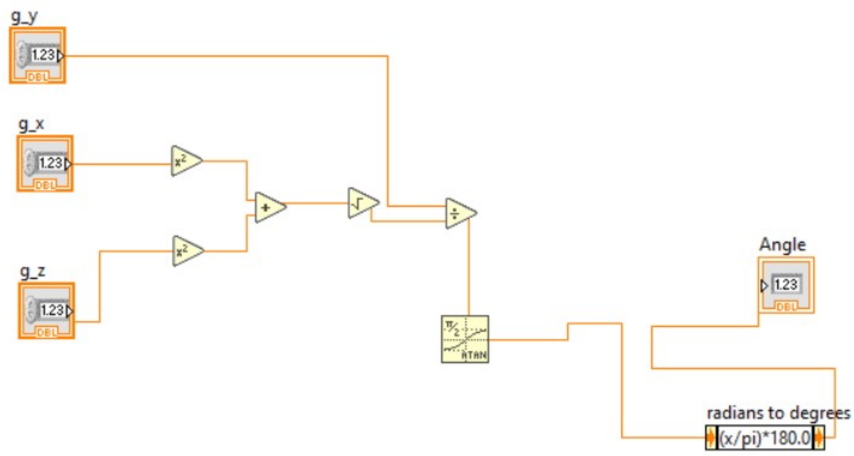


Figure 4.16: Pitch Block Diagram

4.7 Error handling

The system incorporates an error handling mechanism to ensure that any malfunction is detected and appropriately communicated. Specifically, the DAQmx Stop Task.VI block is equipped with an error output that captures any issues encountered during data acquisition.

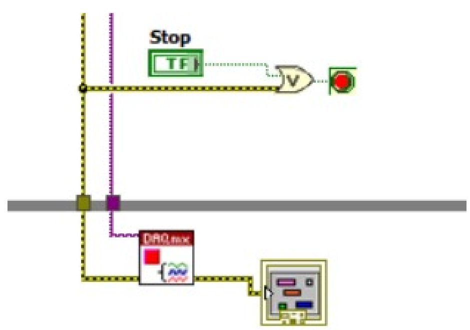


Figure 4.17: Error Output

Chapter 5

Calibration Phase

5.1 Overview

The calibration process is crucial for transforming raw voltage measurements from the ADXL377 accelerometer into accurate gravitational acceleration values, which are then used to calculate pitch and roll angles.

5.1.1 Calibration Procedure

1. **Parameter Estimation**: After obtaining the best estimates for matrix M and vector b, the raw voltage measurements are converted to gravitational acceleration values (g). This is done using the equation:

   $$h = M^{-1}(h_m - b)$$

   where h_m represents the measured voltages.

2. **Compensation for Gravitational Acceleration**: so, as voltage samples are acquired, they are compensated to yield values of gravitational acceleration g_x, g_y, g_z corresponding to the X, Y, and Z axes.

3. **Angle Calculation**:

   - The roll angle is calculated using the formula:

     $$\text{roll} = \arctan\left(\frac{g_x}{\sqrt{g_y^2 + g_z^2}}\right)$$

   - The pitch angle is obtained with the formula:

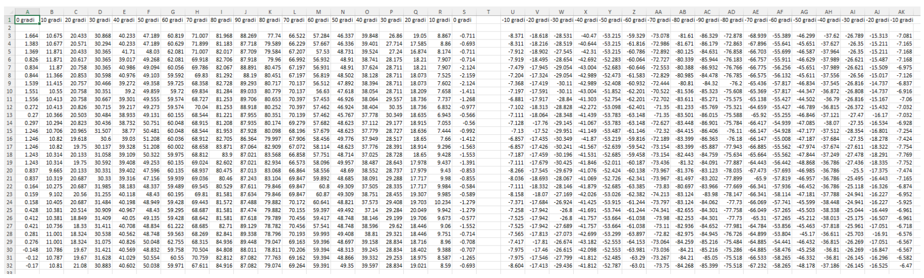
     $$\text{pitch} = \arctan\left(\frac{g_y}{\sqrt{g_x^2 + g_z^2}}\right)$$

4. **Using the Robotic Arm as a Reference**: To calibrate the system, a robotic arm was used as a reference for the true angle values. Measurements were taken at various angles, specifically between -90° and +90°, with 30 samples collected for each angle during both ascent and descent phase.

5. **Data Recording**: All measurement data were saved in Excel files for further analysis and adjustments.

5.1.2 Calibration Data

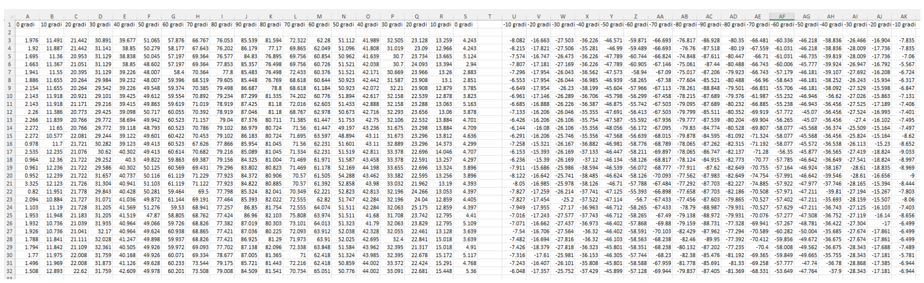
The following measurements were utilized for the calibration process.



1	0 gradi	10 gradi	20 gradi	30 gradi	40 gradi	50 gradi	60 gradi	70 gradi	80 gradi	90 gradi	80 gradi	70 gradi	60 gradi	50 gradi	40 gradi	30 gradi	20 gradi	10 gradi	0 gradi
2																			
3	1.664	10.675	20.433	30.868	40.233	47.189	60.819	71.007	81.968	88.269	77.74	66.522	57.284	46.337	39.848	26.86	19.05	8.867	-0.711
4	1.383	10.677	20.571	30.294	40.233	47.189	60.629	71.899	81.183	87.718	79.589	66.229	57.667	46.336	39.401	27.714	17.585	8.86	-0.693
5	1.369	11.871	20.433	30.365	41.71	48.03	62.081	71.007	82.017	87.709	79.584	67.207	57.53	48.731	39.524	27.24	16.874	8.174	-0.711
6	0.826	11.871	20.617	30.365	39.017	49.268	62.081	69.918	82.706	87.918	79.96	66.992	56.932	48.91	38.741	28.175	18.21	7.907	-0.714
7	0.834	11.87	20.758	30.365	40.986	49.094	60.056	69.786	82.067	88.891	80.475	67.197	56.931	48.91	37.624	28.711	18.21	7.907	-2.124
8	0.844	11.366	20.853	30.598	40.976	49.103	59.592	69.83	81.292	88.19	80.451	67.197	56.819	48.502	38.128	28.711	18.073	7.525	-2.159
9	1.539	11.415	20.757	30.466	39.272	49.358	59.725	68.358	82.728	89.293	80.717	70.137	56.512	47.892	38.394	28.711	18.073	7.602	-2.124
10	1.551	10.55	20.758	30.351	39.2	49.859	59.72	69.834	81.284	89.033	80.779	70.137	56.63	47.618	38.054	28.711	18.209	7.658	-1.411
11	1.556	10.413	20.758	30.667	39.301	49.555	59.574	68.727	81.253	89.706	80.653	70.397	57.453	46.926	38.064	29.557	18.736	7.737	-1.268
12	0.272	10.413	20.826	30.715	39.217	49.273	59.574	70.04	81.253	88.918	80.252	70.397	57.462	46.924	38.404	30.35	18.736	6.832	-0.977
13	0.27	10.366	20.503	30.484	38.933	49.131	60.155	68.544	81.221	87.955	80.351	70.139	57.462	45.767	37.778	30.349	18.635	6.943	-0.566
14	0.297	10.294	20.823	30.436	38.732	50.751	60.048	68.915	81.208	87.935	80.174	69.279	57.682	48.623	37.112	29.177	18.915	7.053	-0.56
15	1.246	10.706	20.965	31.507	38.77	50.481	60.048	68.544	81.953	87.928	80.098	68.196	57.679	48.623	37.779	28.727	18.636	7.444	-0.992
16	1.246	10.82	19.618	30.6	39.03	51.208	60.036	68.912	82.705	86.364	79.997	67.906	58.456	49.776	37.949	28.517	18.65	7.66	-1.412
17	1.246	10.82	19.75	30.137	39.328	51.208	60.002	68.658	83.871	87.064	82.909	67.072	58.114	48.623	37.776	28.391	18.914	9.296	-1.563
18	1.243	10.314	20.133	31.058	39.109	50.322	59.975	68.812	83.9	87.021	83.568	66.858	57.751	48.714	37.025	28.728	18.65	9.428	-1.553
19	1.243	10.314	19.75	30.592	39.408	49.253	60.135	69.024	82.602	87.021	82.934	66.573	58.096	49.957	38.487	28.643	17.978	9.437	-1.391
20	0.837	9.665	20.133	30.331	39.402	47.596	60.135	68.937	80.475	87.013	83.068	66.864	58.556	48.69	38.552	28.737	17.979	9.43	-0.853
21	0.837	10.319	20.687	30.33	39.316	47.156	59.939	69.036	80.46	87.243	83.104	69.847	59.892	48.685	38.091	29.288	17.717	9.98	-0.855
22	0.164	10.275	20.687	31.985	38.183	48.337	59.489	69.545	80.529	87.611	79.846	69.847	60.8	49.309	37.505	28.335	17.717	9.984	-0.584
23	0.159	9.102	20.56	31.255	40.118	48.43	60.195	69.81	81.581	87.634	79.846	69.847	60.87	49.309	38.751	28.455	19.307	9.985	-0.589
24	0.158	10.405	20.687	31.484	40.198	48.949	59.428	69.443	81.572	87.488	79.882	70.172	60.641	48.821	37.573	29.408	19.703	10.234	-1.279
25	0.428	10.381	20.514	30.909	40.967	48.43	59.295	68.687	81.581	87.474	79.882	70.155	59.397	49.492	37.14	29.284	20.049	9.942	-1.279
26	0.412	10.381	18.849	31.409	40.05	49.135	59.428	68.642	81.581	87.618	79.789	70.456	59.417	48.748	38.146	29.199	19.706	9.673	-0.577
27	0.421	10.736	18.33	31.411	40.708	48.834	61.222	68.685	82.71	89.129	78.782	70.456	57.541	48.748	38.596	29.62	18.446	9.06	-1.552
28	0.281	11.001	18.324	30.538	40.562	48.748	59.563	68.269	82.841	89.338	78.796	70.193	59.993	49.408	38.81	29.321	18.446	9.751	-0.714
29	0.276	11.001	18.324	31.075	40.826	50.048	62.755	68.315	84.936	89.448	79.047	69.163	59.396	48.697	39.158	28.834	18.716	8.96	-0.708
30	-0.148	10.786	19.67	31.421	40.569	48.832	59.758	70.504	84.808	88.011	78.811	70.206	59.394	48.313	39.245	28.834	18.402	9.388	-0.707
31	-0.12	10.787	19.67	31.628	41.029	50.554	60.55	70.759	82.812	87.082	77.763	69.162	59.394	48.866	39.332	29.253	18.975	8.587	-1.265
32	-0.17	10.81	21.08	30.883	40.602	50.038	59.971	67.611	84.916	87.082	79.074	69.264	59.391	49.35	39.597	28.834	19.021	8.59	-0.693

1	-10 gradi	-20 gradi	-30 gradi	-40 gradi	-50 gradi	-60 gradi	-70 gradi	-80 gradi	-90 gradi	-80 gradi	-70 gradi	-60 gradi	-50 gradi	-40 gradi	-30 gradi	-20 gradi	-10 gradi
2																	
3	-8.371	-18.618	-28.531	-40.47	-53.215	-59.329	-73.078	-81.61	-86.329	-72.878	-68.939	-55.389	-46.299	-37.62	-26.789	-15.313	-7.081
4	-8.311	-18.216	-28.519	-40.644	-53.215	-61.816	-72.986	-81.671	-86.179	-72.863	-67.896	-55.641	-45.651	-37.627	-26.35	-15.211	-7.165
5	-7.912	-18.902	-27.545	-42.31	-53.215	-60.786	-72.892	-80.125	-84.631	-76.858	-66.703	-55.699	-46.587	-37.964	-26.35	-15.211	-7.168
6	-7.919	-18.495	-28.654	-42.692	-52.283	-60.064	-72.727	-80.339	-85.944	-76.183	-66.757	-55.911	-46.629	-37.989	-26.621	-15.487	-7.168
7	-7.479	-17.945	-29.054	-43.004	-52.683	-60.646	-72.553	-80.388	-86.932	-76.766	-66.775	-56.256	-45.651	-37.989	-26.621	-15.509	-6.975
8	-7.204	-17.324	-29.054	-42.989	-52.473	-61.583	-72.829	-80.985	-84.478	-76.785	-66.575	-56.132	-45.611	-37.556	-26.56	-15.017	-7.126
9	-7.368	-17.419	-30.11	-42.989	-52.408	-60.932	-72.444	-80.81	-84.32	-76.2	-65.436	-57.817	-46.834	-37.545	-26.816	-14.737	-6.837
10	-7.197	-17.591	-30.11	-43.004	-51.852	-62.201	-70.522	-81.536	-85.323	-75.608	-65.369	-57.817	-44.347	-36.872	-26.808	-14.737	-6.916
11	-6.881	-17.917	-28.84	-41.303	-52.754	-62.201	-72.702	-83.611	-85.271	-75.575	-65.138	-55.427	-44.502	-36.79	-26.816	-15.167	-7.06
12	-7.102	-18.313	-28.828	-42.272	-53.098	-62.401	-71.35	-81.233	-85.769	-75.321	-64.659	-55.427	-46.789	-36.815	-26.372	-15.432	-7.032
13	-7.111	-18.064	-28.348	-41.439	-53.783	-63.148	-71.35	-83.501	-86.015	-75.588	-65.92	-55.255	-46.846	-37.121	-27.47	-16.17	-7.032
14	-7.128	-17.76	-29.145	-41.067	-53.783	-63.148	-72.627	-83.448	-86.901	-75.784	-66.417	-54.939	-47.085	-38.07	-27.35	-16.534	-6.928
15	-7.13	-17.52	-29.951	-41.149	-53.487	-61.146	-72.32	-84.415	-86.406	-76.11	-66.147	-54.928	-47.177	-37.512	-28.354	-16.801	-7.254
16	-6.857	-17.435	-30.349	-41.87	-53.219	-59.816	-72.189	-83.399	-86.363	-76.18	-66.147	-55.008	-47.187	-37.684	-27.35	-18.278	-7.424
17	-6.857	-17.426	-30.241	-41.567	-52.639	-59.542	-73.154	-83.399	-85.887	-77.943	-66.885	-55.562	-47.974	-37.674	-27.611	-18.322	-7.754
18	-7.187	-17.459	-30.196	-41.531	-52.685	-59.458	-73.154	-82.443	-84.759	-75.634	-65.664	-55.562	-47.844	-37.249	-27.478	-18.291	-7.769
19	-7.111	-17.679	-30.425	-41.846	-52.011	-60.187	-73.436	-81.32	-84.091	-77.887	-64.443	-56.442	-48.868	-36.786	-27.436	-18.335	-7.752
20	-8.266	-17.545	-29.679	-41.076	-52.424	-60.138	-73.967	-81.376	-83.123	-78.035	-67.473	-57.693	-46.985	-36.786	-25.5	-17.375	-7.474
21	-8.036	-18.693	-28.067	-41.069	-52.726	-62.341	-73.967	-81.497	-83.202	-77.899	-65.9	-57.819	-46.957	-36.786	-25.495	-16.443	-7.165
22	-7.111	-18.332	-28.146	-41.879	-52.685	-63.385	-73.83	-80.697	-83.966	-77.669	-66.341	-57.936	-46.452	-36.786	-25.118	-16.326	-6.874
23	-8.158	-18.07	-27.169	-42.026	-53.026	-62.382	-74.213	-83.124	-83.98	-78.147	-66.341	-58.114	-47.181	-37.788	-24.941	-16.227	-6.952
24	-7.371	-17.684	-26.924	-41.425	-53.915	-61.244	-73.797	-83.124	-84.062	-77.73	-66.069	-57.741	-45.599	-38.448	-24.941	-16.227	-5.925
25	-7.258	-17.942	-26.8	-41.691	-53.744	-61.244	-74.341	-82.655	-84.301	-77.758	-66.049	-57.265	-45.503	-38.338	-25.044	-16.449	-6.961
26	-7.525	-17.942	-26.8	-41.757	-53.664	-61.038	-73.98	-82.253	-84.301	-77.73	-65.31	-57.265	-45.212	-38.013	-25.175	-16.507	-6.961
27	-7.525	-17.942	-27.689	-41.757	-53.664	-61.038	-73.11	-82.936	-84.652	-77.981	-64.784	-53.856	-45.463	-37.818	-25.961	-17.051	-6.718
28	-7.565	-17.813	-27.073	-42.699	-53.299	-63.897	-72.82	-82.975	-84.945	-76.726	-64.899	-53.804	-45.17	-36.611	-25.703	-16.91	-6.576
29	-7.417	-17.81	-26.674	-43.182	-52.553	-64.153	-73.064	-84.259	-85.216	-75.484	-64.885	-54.441	-46.432	-36.815	-26.269	-17.051	-6.567
30	-7.975	-17.46	-26.615	-42.098	-52.553	-63.981	-73.036	-84.21	-85.216	-75.286	-64.885	-58.476	-45.258	-36.81	-26.269	-16.847	-6.567
31	-7.975	-17.546	-27.799	-41.812	-52.485	-63.29	-73.267	-84.21	-85.05	-75.518	-66.533	-58.265	-46.332	-36.81	-26.145	-16.296	-6.582
32	-8.604	-17.413	-29.436	-41.812	-52.787	-63.01	-73.75	-84.268	-85.399	-75.518	-67.232	-58.265	-48.178	-37.186	-26.145	-16.525	-6.47

Figure 5.1: Pitch data - Download Calibration Data



1	0 gradi	10 gradi	20 gradi	30 gradi	40 gradi	50 gradi	60 gradi	70 gradi	80 gradi	90 gradi	80 gradi	70 gradi	60 gradi	50 gradi	40 gradi	30 gradi	20 gradi	10 gradi	0 gradi
2																			
3	1.976	11.491	21.442	30.891	39.677	51.065	57.876	66.767	76.053	85.539	81.594	72.322	62.28	51.112	41.989	32.505	23.128	13.259	4.243
4	1.92	11.887	21.442	31.141	38.85	50.279	58.177	67.643	76.202	86.179	77.17	69.865	62.049	51.096	41.808	31.019	23.09	12.966	4.243
5	1.695	11.36	20.953	31.129	38.838	50.045	57.197	69.364	76.577	84.83	76.895	69.756	60.854	50.962	41.639	30.7	23.734	13.665	3.124
6	1.663	11.367	21.051	31.129	38.85	48.602	57.197	69.364	77.853	85.357	76.498	69.756	60.726	51.521	42.038	30.7	24.093	13.394	2.94
7	1.941	11.55	20.395	31.129	39.226	48.007	58.4	70.364	77.8	85.483	76.498	72.433	60.376	51.521	42.171	30.669	23.966	13.26	2.883
8	1.886	11.655	20.264	29.984	39.232	48.007	59.396	68.519	79.605	85.448	76.769	68.618	60.644	50.923	42.442	31.587	23.908	13.1	2.851
9	2.154	11.655	20.264	29.542	39.226	49.548	59.374	70.385	79.498	86.687	78.8	68.618	61.184	50.923	42.072	32.21	23.908	12.879	3.785
10	2.143	11.918	20.921	29.101	39.425	49.612	59.554	70.892	79.234	87.299	81.335	74.202	60.776	51.894	42.617	32.158	22.539	12.878	3.823
11	2.143	11.918	21.171	29.216	39.415	49.863	59.619	71.019	78.919	87.425	81.18	72.016	62.603	51.433	42.888	32.158	23.288	13.063	5.163
12	2.26	11.386	20.773	29.425	39.098	50.717	60.055	70.392	78.919	87.046	81.18	68.767	62.978	50.673	42.716	32.293	23.656	13.06	3.878
13	2.266	11.839	20.766	29.772	38.694	49.942	60.523	71.157	79.04	87.376	80.711	71.385	61.447	51.753	42.75	32.106	22.532	13.884	4.701
14	2.272	11.65	20.766	29.772	39.118	48.793	60.523	70.786	79.102	86.979	80.724	71.56	61.447	49.197	43.236	31.675	23.298	13.884	4.709
15	2.272	10.577	22.081	29.244	39.122	49.601	60.422	70.453	79.102	86.183	80.724	71.695	63.597	48.894	43.11	31.673	23.296	13.812	4.636
16	0.978	11.7	21.721	30.282	39.123	49.413	60.523	67.626	77.866	85.954	81.045	71.56	62.231	51.601	43.11	32.889	23.296	14.373	4.299
17	2.535	12.235	21.076	30.62	40.302	49.413	60.614	70.682	79.216	85.089	81.045	71.334	62.231	51.519	42.811	33.378	22.696	14.046	4.707
18	0.964	12.36	21.722	29.252	40.3	49.822	59.863	69.387	79.156	84.325	81.004	71.469	61.971	51.587	43.458	33.378	22.591	13.257	4.297
19	0.961	12.236	21.722	29.586	40.302	50.125	60.569	69.431	79.296	83.802	80.823	71.469	61.178	52.169	44.198	33.655	22.696	13.324	3.896
20	0.952	12.239	21.722	31.657	40.737	50.116	61.119	71.229	77.923	84.372	80.906	70.57	61.505	54.288	43.462	33.382	22.595	13.256	3.896
21	3.325	12.123	21.726	31.304	40.941	51.103	61.119	71.122	77.923	84.822	80.885	70.57	61.392	52.858	43.98	33.032	21.962	13.19	4.393
22	0.82	11.951	21.778	29.843	40.428	50.281	59.464	69.5	77.798	85.324	82.041	70.349	62.221	52.823	42.813	32.196	24.266	13.053	4.397
23	2.094	10.884	21.727	31.071	41.036	49.872	61.144	69.191	77.464	85.393	82.022	72.555	62.82	51.747	42.284	32.196	24.04	12.859	4.405
24	1.103	11.19	21.728	31.205	41.569	51.276	59.53	68.941	77.257	86.85	81.754	72.555	64.074	51.511	42.284	32.063	25.175	12.859	4.397
25	1.953	11.948	21.183	31.205	41.519	47.87	58.805	68.762	77.424	86.96	82.103	75.808	63.974	51.511	41.68	31.708	23.742	12.795	4.41
26	1.932	10.736	21.039	31.935	40.964	49.066	59.726	68.826	77.382	87.019	80.303	73.101	64.013	51.323	41.79	32.063	23.829	12.795	5.109
27	1.926	10.736	21.041	32.17	40.964	49.624	60.938	68.865	77.421	87.036	80.225	72.093	63.912	52.038	42.328	32.055	22.461	13.128	3.639
28	1.788	11.841	21.111	32.028	41.247	49.898	59.937	68.826	77.421	86.925	81.29	71.973	63.91	52.025	42.695	32.4	22.841	15.018	3.639
29	1.794	11.842	21.109	32.361	40.505	49.926	59.972	69.093	77.702	87.138	82.096	72.338	63.848	51.584	43.962	32.395	21.317	15.018	4.91
30	1.77	11.975	22.008	31.759	40.168	49.926	60.071	69.334	78.677	87.005	81.365	71	62.418	51.324	43.985	32.395	22.678	15.172	5.117
31	1.496	11.969	22.008	31.873	41.126	49.628	60.233	73.544	79.175	85.721	81.443	72.216	62.418	50.859	44.002	33.372	22.424	15.291	4.768
32	1.508	12.893	22.62	31.759	42.609	49.978	60.201	73.508	79.008	84.509	81.541	70.734	65.051	50.776	44.002	33.091	22.681	15.448	5.36

1	-10 gradi	-20 gradi	-30 gradi	-40 gradi	-50 gradi	-60 gradi	-70 gradi	-80 gradi	-90 gradi	-80 gradi	-70 gradi	-60 gradi	-50 gradi	-40 gradi	-30 gradi	-20 gradi	-10 gradi
2																	
3	-8.082	-16.663	-27.503	-36.226	-46.571	-59.871	-66.693	-76.817	-86.928	-80.35	-66.481	-60.336	-46.218	-38.836	-26.466	-16.904	-7.835
4	-8.215	-17.821	-27.506	-35.281	-46.99	-59.489	-66.693	-76.76	-87.518	-80.19	-67.559	-61.031	-46.218	-38.836	-28.009	-17.736	-7.835
5	-7.574	-16.747	-26.473	-36.226	-47.789	-60.744	-66.824	-74.848	-87.611	-80.447	-66.71	-61.031	-46.735	-39.819	-28.009	-17.736	-7.06
6	-7.807	-17.181	-27.169	-36.226	-47.789	-60.905	-67.146	-75.061	-87.44	-80.488	-66.743	-60.006	-45.777	-39.924	-26.947	-16.792	-5.567
7	-7.296	-17.954	-26.043	-36.562	-47.573	-58.94	-67.09	-75.017	-87.206	-79.923	-66.743	-57.179	-46.181	-39.107	-27.692	-16.208	-6.724
8	-6.553	-17.954	-26.044	-36.985	-46.939	-58.265	-67.38	-77.604	-85.521	-80.488	-66.96	-58.643	-46.181	-38.252	-26.243	-15.934	-6.317
9	-6.649	-17.954	-26.23	-38.199	-45.604	-57.966	-67.113	-78.261	-88.848	-79.501	-66.831	-55.706	-46.181	-38.092	-27.329	-15.598	-6.847
10	-6.961	-17.146	-26.289	-36.706	-45.798	-56.299	-67.458	-78.215	-87.689	-79.376	-61.987	-55.232	-46.946	-36.62	-27.026	-15.863	-7.131
11	-6.685	-16.888	-26.226	-36.387	-46.875	-55.742	-67.503	-79.095	-87.689	-80.232	-66.885	-55.238	-46.943	-36.456	-27.525	-17.189	-7.406
12	-7.133	-16.206	-26.046	-35.355	-47.691	-56.413	-67.503	-79.799	-85.511	-80.352	-69.919	-57.772	-45.07	-36.456	-27.524	-16.993	-7.401
13	-6.426	-16.206	-26.106	-35.754	-47.587	-55.592	-67.936	-79.777	-87.539	-80.204	-69.904	-56.265	-45.07	-36.456	-27.4	-16.102	-7.495
14	-6.144	-16.08	-26.106	-35.356	-48.056	-56.172	-67.095	-79.83	-84.774	-80.528	-69.807	-58.077	-45.568	-36.374	-25.509	-15.164	-7.497
15	-6.291	-16.206	-25.746	-35.356	-47.568	-56.639	-68.015	-79.878	-84.595	-81.092	-71.324	-58.077	-45.568	-36.456	-25.824	-15.164	-8.62
16	-7.258	-15.321	-26.167	-36.882	-46.981	-58.776	-68.789	-78.065	-87.262	-82.315	-71.192	-58.077	-45.572	-36.538	-26.113	-15.23	-8.652
17	-6.153	-15.393	-26.169	-37.133	-46.447	-58.211	-69.897	-78.065	-86.747	-82.137	-71.28	-56.35	-45.877	-36.565	-27.419	-18.824	-9.033
18	-6.236	-15.39	-26.169	-37.12	-46.134	-58.126	-68.817	-78.124	-84.915	-82.773	-70.77	-57.785	-46.642	-36.649	-27.541	-18.824	-8.997
19	-7.911	-15.686	-25.986	-38.594	-46.539	-56.072	-68.777	-77.911	-87.62	-82.649	-70.755	-57.164	-46.924	-38.167	-28.61	-18.835	-8.969
20	-8.122	-16.642	-25.741	-38.485	-46.624	-58.126	-70.093	-77.562	-87.983	-82.649	-74.754	-57.991	-46.642	-39.546	-28.61	-16.656	-9
21	-8.05	-16.985	-25.978	-38.126	-46.71	-57.788	-67.484	-77.292	-87.703	-82.227	-74.885	-57.922	-47.977	-37.746	-28.165	-15.394	-8.444
22	-7.827	-17.259	-26.214	-37.741	-47.125	-55.393	-66.898	-77.658	-87.703	-82.186	-70.508	-57.971	-47.211	-39.81	-27.194	-15.267	-7.803
23	-7.827	-17.454	-25.2	-37.522	-47.114	-56.7	-67.433	-77.456	-87.603	-79.865	-70.527	-57.402	-47.211	-35.693	-28.159	-15.507	-8.06
24	-7.949	-17.955	-27.17	-36.963	-46.712	-58.265	-67.433	-78.79	-88.987	-79.931	-70.527	-57.629	-47.211	-36.743	-27.125	-16.103	-7.403
25	-7.016	-17.243	-27.577	-37.743	-46.712	-58.265	-67.49	-79.138	-88.972	-79.931	-70.076	-57.277	-47.508	-36.752	-27.119	-16.14	-8.656
26	-7.071	-16.662	-27.437	-36.973	-46.402	-57.868	-69.88	-79.159	-88.731	-77.328	-69.941	-57.267	-48.781	-36.422	-27.304	-17	-6.499
27	-7.54	-16.706	-27.564	-36.32	-46.402	-58.591	-70.103	-82.429	-87.962	-77.294	-70.589	-60.282	-50.004	-35.685	-27.674	-17.861	-6.499
28	-7.482	-16.694	-27.816	-36.32	-46.103	-58.563	-68.238	-82.46	-89.95	-77.392	-70.412	-59.856	-49.672	-36.675	-27.674	-17.861	-6.499
29	-7.426	-18.379	-27.818	-36.323	-45.801	-58.351	-68.238	-80.132	-87.202	-77.235	-70.4	-58.008	-49.562	-36.675	-28.343	-17.688	-7.489
30	-7.316	-17.61	-25.981	-36.153	-46.305	-57.744	-68.23	-82.38	-85.476	-81.192	-69.365	-59.849	-49.665	-35.755	-28.343	-17.181	-5.781
31	-7.243	-16.407	-26.101	-35.808	-45.801	-58.588	-67.959	-81.778	-85.691	-81.33	-69.258	-57.777	-47.74	-36.78	-28.868	-17.385	-6.944
32	-6.048	-17.357	-25.752	-37.429	-45.899	-57.128	-69.944	-79.837	-87.405	-81.369	-68.331	-53.649	-47.764	-37.9	-28.343	-17.181	-6.944

Figure 5.2: Roll data - Download Calibration Data

5.1.3 Uncertainty assessment

Once thirty measurements of an angle are taken, both in ascent and descent phase, the following values are calculated:

1. The **mean** $\bar{\theta}$ of the measurements:

$$\bar{\theta} = \frac{1}{N} \sum_{i=1}^{N} \theta_i$$

where $N = 30$ is the number of measurements and θ_i are the individual angle measurements.

2. The **standard deviation** σ_θ of the measurements:

$$\sigma_\theta = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\theta_i - \bar{\theta})^2}$$

3. The **standard uncertainty** u_θ, calculated as the standard deviation divided by the square root of the number of measurements N:

$$u_\theta = \frac{\sigma_\theta}{\sqrt{N}}$$

4. The **expanded uncertainty** U_θ, obtained by multiplying the standard uncertainty by the coverage factor $k = 3$:

$$U_\theta = k \cdot u_\theta$$

5. After calculating the expanded uncertainty for each angle, the **maximum value of expanded uncertainty** in the upward direction U_{up} and the downward direction U_{down} is determined.

6. Finally, the **combined uncertainty** U_{combined} was calculated as the square root of the sum of the squares of the two expanded uncertainties:

$$U_{\text{combined}} = \sqrt{U_{\text{up}}^2 + U_{\text{down}}^2}$$

This procedure is iterated for the **pitch angles** and the **roll angles**.

Pitch angle - uncertainty evaluation

The uncertainty for the measurements taken during the ascent is found to be **0.78 degrees**, while for the descent it is **0.83 degrees**. Consequently, the combined uncertainty is **1.14 degrees**.

Analyzing the obtained curve, the maximum deviation between two points measuring the same angle is **6.90 degrees (measured at -70 degrees)**, which exceeds the previously calculated combined uncertainty. This indicates the presence of hysteresis in the system.

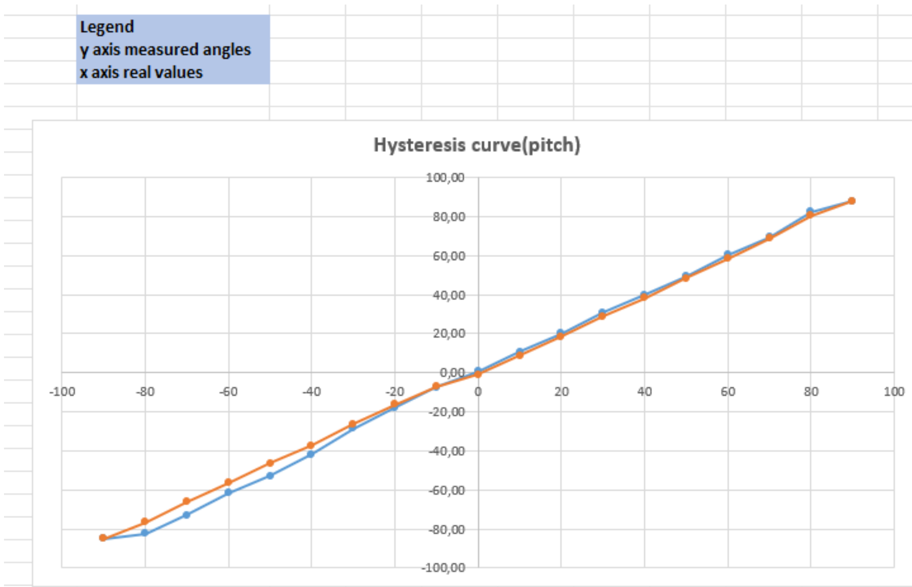


Figure 5.3: Hysteresis curve for the pitch angle

	Mean up (blue)	Mean down (orange)
-90	-85,10	-85,10
-80	-82,39	-76,39
-70	-72,98	-66,09
-60	-61,65	-56,34
-50	-52,94	-46,42
-40	-41,88	-37,40
-30	-28,56	-26,40
-20	-17,88	-16,36
-10	-7,53	-7,01
0	0,74	-1,09
10	10,68	8,66
20	20,19	18,54
30	30,82	28,82
40	39,87	38,35
50	49,18	48,45
60	60,20	58,37
70	69,34	68,80
80	82,20	80,26
90	87,97	87,97

Figure 5.4: Pitch data of hysteresis curve

	Hysteresis amplitude (Mean up- Mean down)	Maximum of the hysteresis
-90	0,00	6,90
-80	6,01	
-70	6,90	
-60	5,31	
-50	6,52	
-40	4,49	
-30	2,16	
-20	1,52	
-10	0,52	
0	1,82	
10	2,02	
20	1,65	
30	2,00	
40	1,51	
50	0,73	
60	1,83	
70	0,53	
80	1,94	
90	0,00	

Figure 5.5: Hysteresis table for the pitch angle

Having established the existence of hysteresis, we combined all ascent and descent measurements and recalculated the uncertainty, this time based on 60 measurements. The maximum uncertainty is found to be **1.4 degrees**.

For details: Download Calibration Data

Calibration curve - pitch angle

The calibration curve is represented by the equation:

$$Y = 0.98X + 0.52$$

The coefficient of determination, R^2, is calculated to be 0.9994. This high value indicates an excellent fit of the calibration curve to the measured data, suggesting that the model reliably represents the relationship between the inputs and outputs.

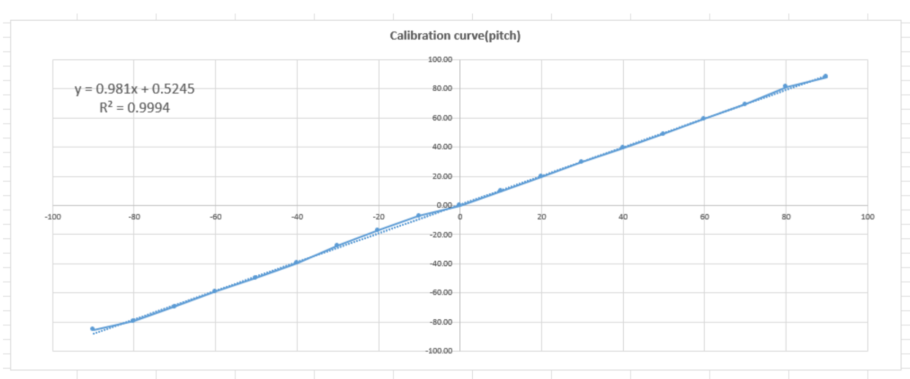


Figure 5.6: Calibration curve for the pitch angle

	Mean	STDEV	INC	k=3
-90	-85.10	1.02	0.13	0.40
-80	-79.39	3.32	0.43	1.28
-70	-69.53	3.60	0.47	1.40
-60	-58.99	3.03	0.39	1.17
-50	-49.68	3.40	0.44	1.32
-40	-39.64	2.35	0.30	0.91
-30	-27.48	1.53	0.20	0.59
-20	-17.12	1.11	0.14	0.43
-10	-7.27	0.52	0.07	0.20
0	-0.17	1.06	0.14	0.41
10	9.67	1.32	0.17	0.51
20	19.37	1.11	0.14	0.43
30	29.82	1.18	0.15	0.46
40	39.11	1.12	0.15	0.44
50	48.82	1.13	0.15	0.44
60	59.29	1.42	0.18	0.55
70	69.07	1.30	0.17	0.50
80	81.23	1.69	0.22	0.65
90	87.97	0.88	0.11	0.34
				MAX UNC
				1.40

Figure 5.7: Data used for calibration curve

Roll angle - uncertainty evaluation

The uncertainty for the measurements taken during the ascent is found to be **1.11 degrees**, while for the descent it is **1.40 degrees**. Consequently, the combined uncertainty is **1.78 degrees**.

Analyzing the obtained curve, the maximum deviation between two points measuring the same angle is **2.72 degrees (measured at 40 degrees)**, which exceeds the previously calculated combined uncertainty. This indicates the presence of hysteresis in the system.

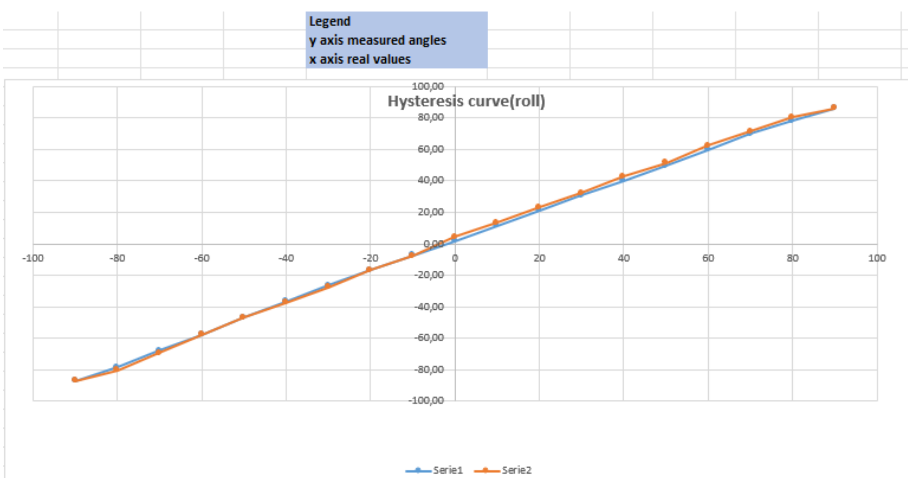


Figure 5.8: Hysteresis curve for the roll angle

	Mean up (blue)	Mean down (orange)
-90	-87,23	-87,23
-80	-78,64	-80,43
-70	-68,01	-69,38
-60	-57,85	-57,89
-50	-46,75	-47,02
-40	-36,74	-37,39
-30	-26,48	-27,47
-20	-16,87	-16,74
-10	-7,21	-7,51
0	1,82	4,22
10	11,70	13,60
20	21,31	23,19
30	30,71	32,24
40	40,09	42,81
50	49,71	51,45
60	59,74	62,34
70	69,83	71,42
80	78,20	80,40
90	86,00	86,00

Figure 5.9: Roll data of hysteresis curve

	Hysteresis amplitude (Mean up- Mean down)	Maximum of the hysteresis
-90	0,00	2,72
-80	1,79	
-70	1,38	
-60	0,04	
-50	0,27	
-40	0,65	
-30	0,99	
-20	0,13	
-10	0,30	
0	2,40	
10	1,90	
20	1,88	
30	1,52	
40	2,72	
50	1,73	
60	2,60	
70	1,59	
80	2,20	
90	0,00	

Figure 5.10: Hysteresis table for the roll angle

Having established the existence of hysteresis, we combined all ascent and descent measurements and recalculated the uncertainty, this time based on 60 measurements. The maximum uncertainty was found to be **0.80 degrees**.

For details: Download Calibration Data

Calibration curve - roll angle

The calibration curve is represented by the equation:

$$Y = 0.98X + 1.58$$

The coefficient of determination, R^2, is calculated to be 0.9994. This high value indicates an excellent fit of the calibration curve to the measured data, suggesting that the model reliably represents the relationship between the inputs and outputs.

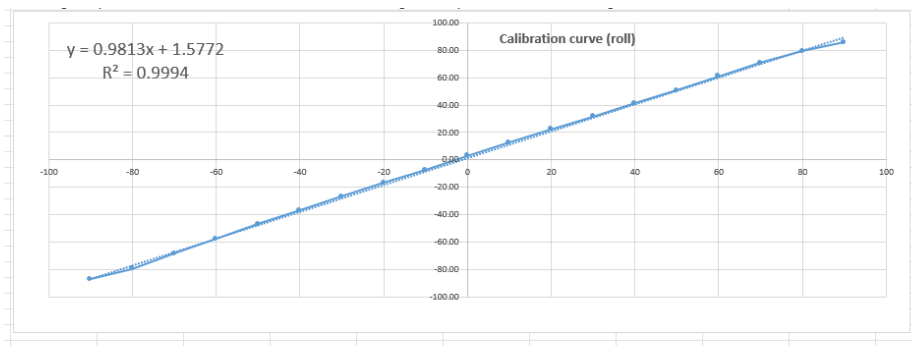


Figure 5.11: Calibration curve

	Mean	STDEV	INC	k=3
-90	-87.23	1.33	0.17	0.51
-80	-79.54	2.01	0.26	0.78
-70	-68.69	2.06	0.27	0.80
-60	-57.87	1.58	0.20	0.61
-50	-46.89	1.09	0.14	0.42
-40	-37.07	1.19	0.15	0.46
-30	-26.97	0.93	0.12	0.36
-20	-16.81	0.98	0.13	0.38
-10	-7.36	0.84	0.11	0.33
0	3.02	1.36	0.18	0.53
10	12.65	1.17	0.15	0.46
20	22.25	1.17	0.15	0.45
30	31.47	1.20	0.15	0.46
40	41.45	1.65	0.21	0.64
50	50.58	1.26	0.16	0.49
60	61.04	1.75	0.23	0.68
70	70.63	1.72	0.22	0.67
80	79.30	1.81	0.23	0.70
90	86.00	1.07	0.14	0.42
				MAX UNC
				0.80

Figure 5.12: Data used for calibration curve

Appendix A

Specifications of the National Instruments USB-6008 DAQ Device

For detailed specifications and features of the National Instruments USB-6008 DAQ device, please refer to the official datasheet available online at the following link: USB-6008 DAQ Device [1]

[1] https://users.physics.unc.edu/ sean/Phys351/techresource/docs/USB6009%20User%20Manual.pdf

Appendix B

Ellipsoidal Fitting Algorithm

For an in-depth understanding of the ellipsoidal fitting procedure used in adjustment, refer to the following paper:

- **Title**: "A Method for Real-Time Compensation of Magnetometers Embedded on Smartphones"
- **Authors**: Pasquale Daponte, Luca De Vito, Francesco Picariello, Sergio Rapuano, Carmine Sementa
- **Published in**: Institute of Electrical and Electronics Engineers (2016)

List of Figures