Laboratory for Electrical Instrumentation and Embedded Systems
IMTEK – Department of Microsystems Engineering
University of Freiburg
Sensors Lab Course
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Lab Report M1
Acceleration and Pressure Sensors

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Data generated in a team together with

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1. Introduction

The environment around us is constantly changing. Perceiving these changes accurately is one of the modern-day challenges. Different sensors can be used to detect different types of stimuli. In this experiment, a pressure and acceleration sensor will be used to measure the change in height and velocity of an elevator.

2. Theory

If the change of pressure (*p*) with respect to the altitude is going to be calculated, the so-called “barometric formula” (Equation 1) is used. The barometric formula has several parameters. Namely, the reference pressure (p_0), gravity (*g*), the molar mass of air (*M*), height (*h*), universal gas constant (*R*), and the absolute temperature (*T*). In this module, we are going to measure the height with the help of the barometric formula.

$$p = p_0 \exp\left(-\frac{gMh}{RT}\right),$$

Equation 1

To calculate the height, the barometric formula should be rearranged [Equation 2]

$$h = \frac{R \cdot T}{g \cdot M}\left[\, ln(p_0) - ln(p)\,\right]$$

Equation 2

The only unknown parameter in the above equation (Equation 2) is the pressure (*p*), which will, later on, be measured with the help of the pressure sensor. The values for all of the constants in the formula are given below:

$R = 8.314\ J\ mol^{-1}\ K^{-1}$
$T = 288.15\ K$
$g = 9.81\ m\ s^{-2}$
$M = 0.02896\ kg\ mol^{-1}$
$p_0 = 1013.25\ hPa$

When the constant values are plugged into the formula (Equation 2), the below expression (Equation 3) is obtained:

$$h = 58.36 \cdot 10^3 - 8.43 \cdot 10^3 \cdot ln(p)$$

Equation 3

Another way of calculating the height is to use acceleration. This can be done using the potential energy and kinetic energy equations. If the initial velocity (*V*) is known, then it is possible to calculate the height. To derive the height, it is concluded that the potential energy that the object has before the start of its movement is converted to kinetic energy (Equation 4).

$$mgh = \frac{1}{2}mV^2$$

Equation 4

If the above equation (Equation 4) is rearranged to calculate the height of the object:

$$h = \frac{V^2}{2g}$$

Equation 5

The only know parameter in this equation (Equation 5) is the gravity (*g*), which is equal to 9.81 m/s². If we plug this value in, we get the following equation (Equation 6):

The only parameter missing in this equation is acceleration. To calculate the velocity

$$h = \frac{V^2}{19.62}$$

Equation 6

(*V*) using acceleration, the below equation must be used (Equation 7):

$$V(t) = V0 + a \cdot t$$

Equation 7

In this equation (Equation 7), V(t) stands for the velocity at time t (*s*) and V0 is the initial velocity. The units for both of these parameters are *m/s*. "a" stands for acceleration and its unit is *m/s²*. Lastly, t stands for time and it is measured in seconds (*s*).

A problem when using the acceleration data to calculate the velocity is the fact that the acceleration is usually measured as noisy time series data. To get rid of this noise, smoothing techniques can be used. One of these techniques is the moving average method. Moving average is a calculation to analyze data points by creating a series of averages of different subsets of the full data set. The Equation for the Moving Average (Equation 8) is given below:

$$\begin{aligned} SMA_k &= \frac{p_{n-k+1} + p_{n-k+2} + \cdots + p_n}{k} \\ &= \frac{1}{k} \sum_{i=n-k+1}^{n} p_i \end{aligned}$$

Equation 8 [1]

Where k is the last datapoint and n is the total number of entries.

Another way of smoothing time series data is to use the Exponential Smoothing technique. The equation (Equation 9) is given by:

$$s_t = \alpha x_t + (1-\alpha)s_{t-1} = s_{t-1} + \alpha(x_t - s_{t-1}).$$

Equation 9 [2]

Where α is the smoothing factor, and $0 \leq \alpha \leq 1$. In other words, the smoothed statistic s_t is a simple weighted average of the current observation x_t and the previous smoothed statistic s_{t-1}.

2.1. Acceleration Sensor

One of the sensors used in this experiment, namely BHI260 is a MEMS device that contains an acceleration sensor and a gyroscope. All accelerometers, including the one that is contained in BHI260, work on the same principle. A string inside the sensor is stretched or compressed once the sensor is moved

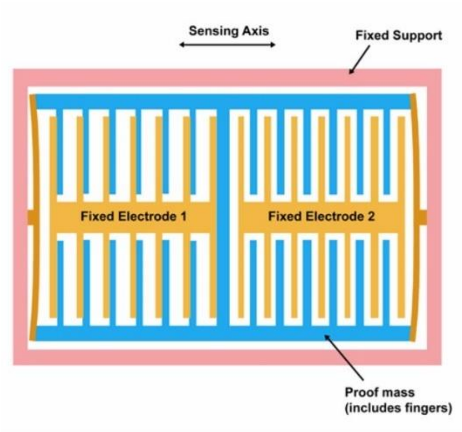

Figure 1 – Spring stretched to the right [3]

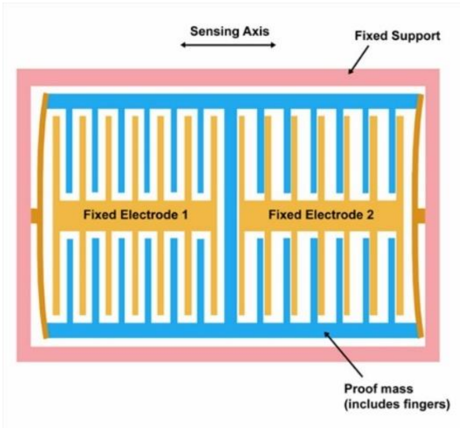

Figure 2 – Spring stretched to the left [3]

since the spring wants to remain stationary due to its inertia. MEMS accelerometers are used when linear motion is needed to be measured. The unit of acceleration is m/s², however, the convention is to use the unit "g", when using acceleration sensors. "g" is the unit of gravity and it corresponds to 9.81 m/s².

2.2. Pressure Sensor

The BMP390 combines a microelectromechanical system (MEMS) sensor element with an application-specific circuit (ASIC). The sensor features a relative accuracy of ±3 Pa. The metal case of the sensor has a tiny hole to allow pressure exchange.

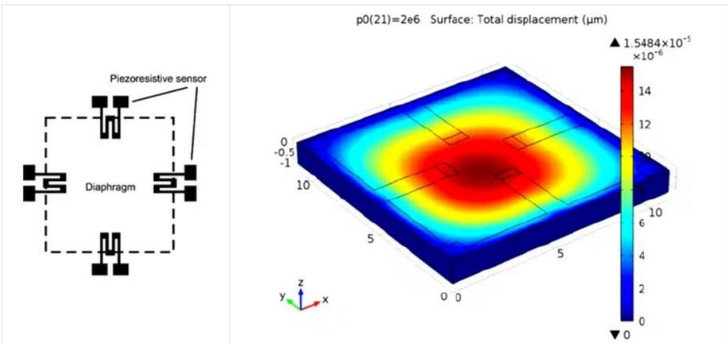

Figure 3 – Pressure Sensor [4]

3. Methods

The measurements are done using the BMP390 and BHI260 sensors on the Arduino Nicla Sense ME Board connected to a battery-powered notebook via USB. The notebook is used as both a power supply and a data logger for this experiment. The board was programmed using the Arduino IDE with the Arduino_BHY2 library version 1.5 (Bosch Sensortec). Excel Data Streamer was used for data logging.

The Arduino program read the sensors using the virtual sensors SENSOR_ID_ACC for the acceleration sensor and SENSOR_ID_BARO for the pressure sensor each 100 ms. The sensitivity of the acceleration sensor was 417.5 LSB $m^{\circ-1}$ s^2 (the default 8g range).

After a measurement is done, the Arduino program converts the readings into CSV format (Comma-separated Values), and through the serial interface, sends the data to the Excel Data Streamer every 100ms. Each experiment goes on until 1000 measurements are collected. For the first and second tasks, the Nicla Sense ME was kept stationary on a flat surface to collect the data. For the Third task, the board was taken into the elevator at the Universitätsbibliothek Freiburg building and was taken from the ground floor to the 5th floor, and vice versa. The interpretation of the collected measurements was done using Excel.

4. Results and Discussion

4.1 Task 1

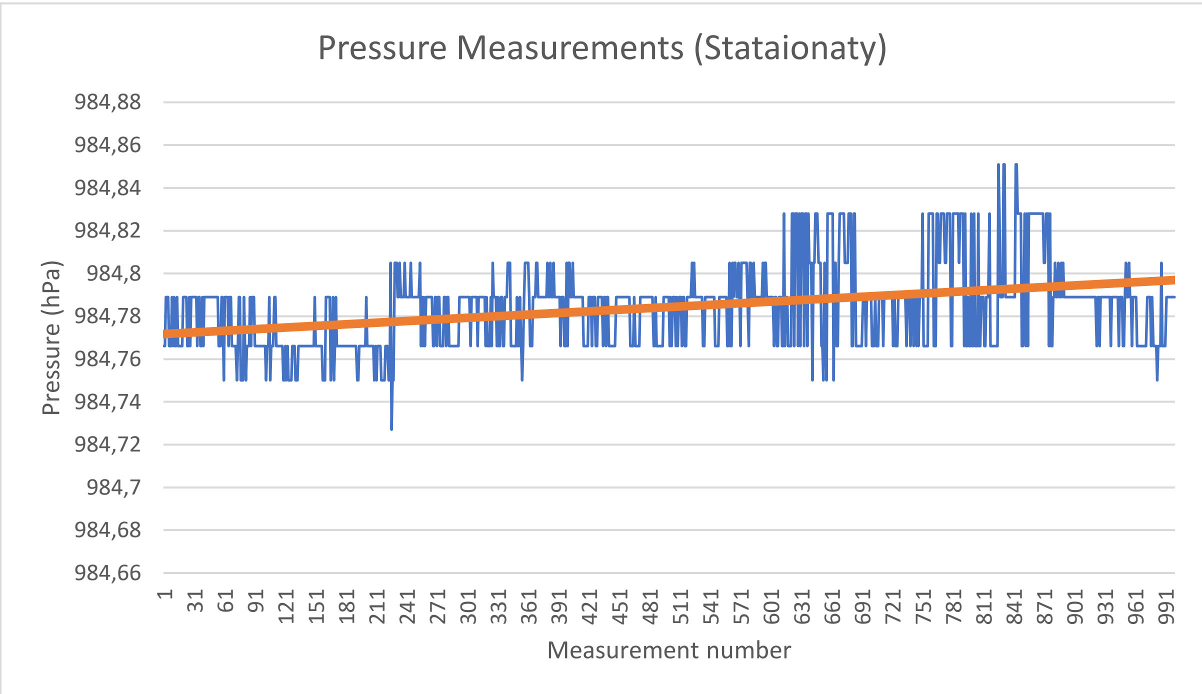

Figure 4 – Pressure Measurements

In the first part of this experiment, the Nicla Sense ME was held in a stationary position, and 1000 pressure readings were evaluated. As can be seen from the linear fit on Figure 4, a drift can be observed. However because the drift is very small, it can be neglected.

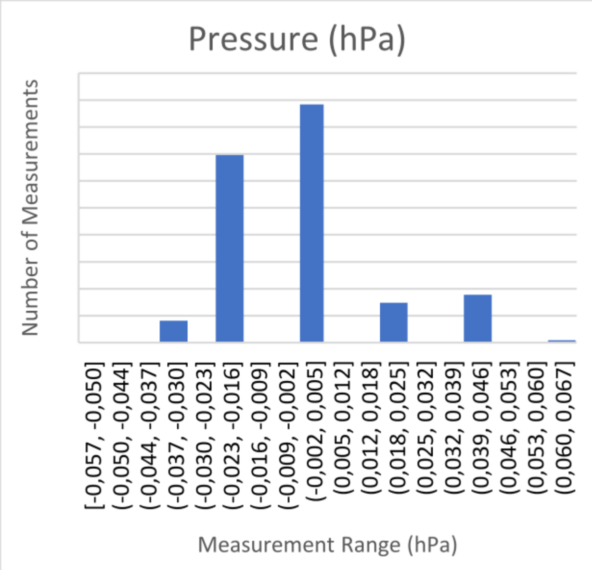

Figure 5 – Histogram of pressure readings

The pressure readings were conducted on the 3rd floor of the Universitätsbibliothek Freiburg building. After evaluating the data, the mean value $\bar{p}$ was found to be 984.8 hPa. This is expected since the raw readings from the BMP390 sensor correspond to the pressure of the environment in hPa. When subtracted from the data obtained from the pressure sensor, the histogram on the left (Figure 5) is obtained. As can be seen from the figure, nearly half of the data is between -0.002 and 0.005. This interval is the one that is closest to 0. This is acceptable since the accuracy of the BMP390 sensor is ±0.03 hPa.

4.2 Task 2

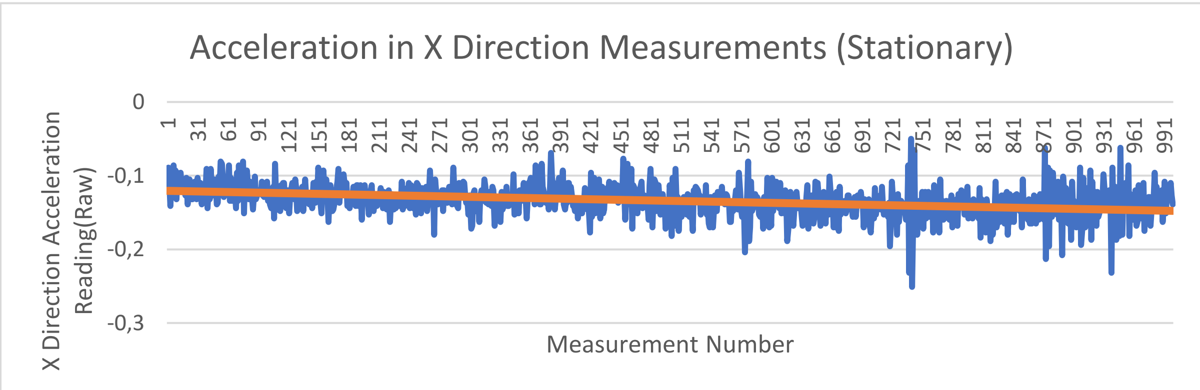

Figure 6 – Raw Acceleration Measurements (X Axis)

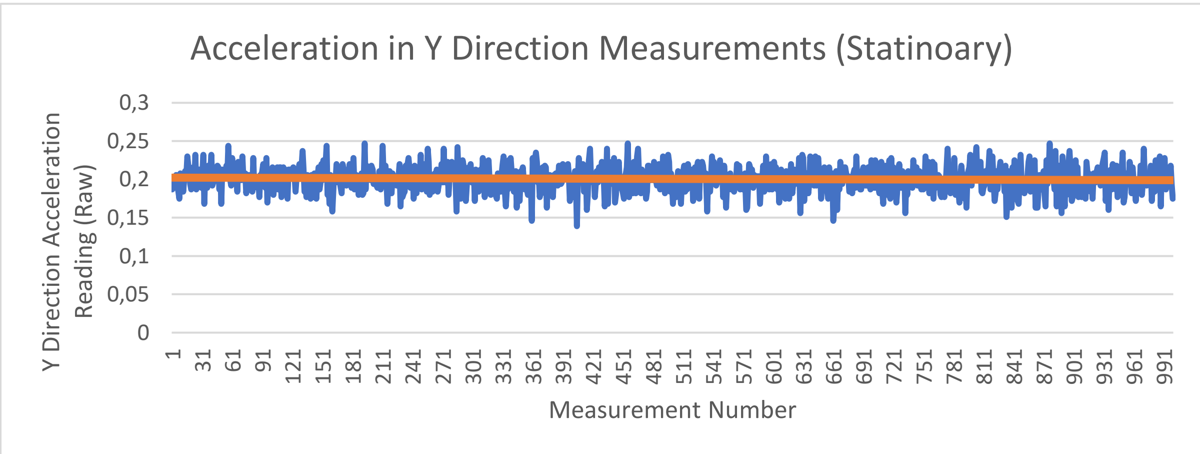

Figure 7 – Raw Acceleration Measurements (Y Axis)

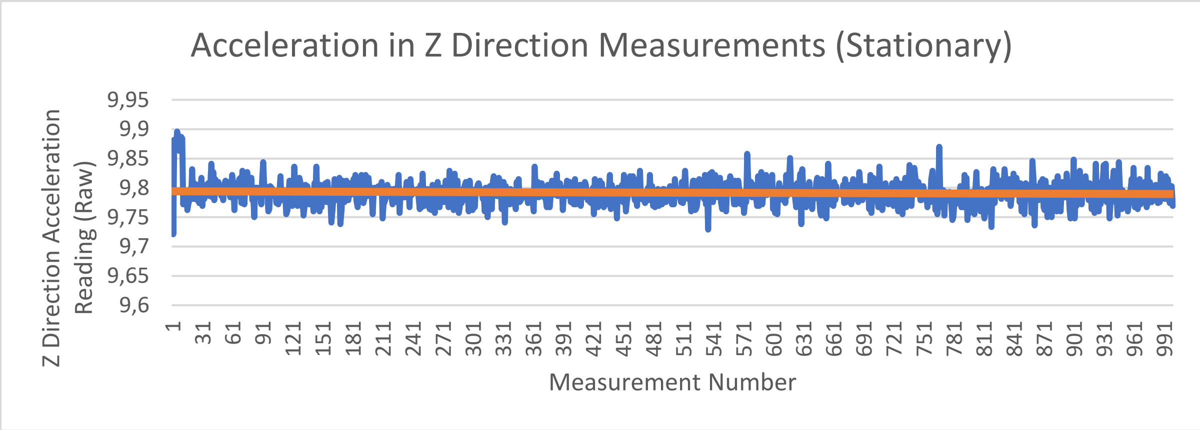

Figure 6 – Raw Acceleration Measurements (Z Axis)

In the second part of this experiment, the Nicla Sense ME was held stationary once more to read the acceleration values of the X, Y, and Z axes. As can be seen from the Figures 6, 7 and 8, there is only a slight drag on the X direction measurements, which can be neglected. After 1000 measurements were done, the mean value $\bar{a}$ was calculated and it is found to be -0.1 m/s² for the X axis, 0.2 m/s² for the Y axis, and 9.8 m/s² for the Z axis. As can be observed, the value for the Z axis is quite different than the values for the X and Y axes. This is because the Z axis is influenced by gravity, which accounts for around 9.8 m/s². When the offset was subtracted from each data point, the three histograms for all three axes were obtained (Figures 6, 7, 8). All of these histograms resemble the Gaussian Distribution and the mean values are all acceptable since the sensitivity error of the accelerometer output is ±0.8% (See BHI260 Datasheet page 137 [5]).

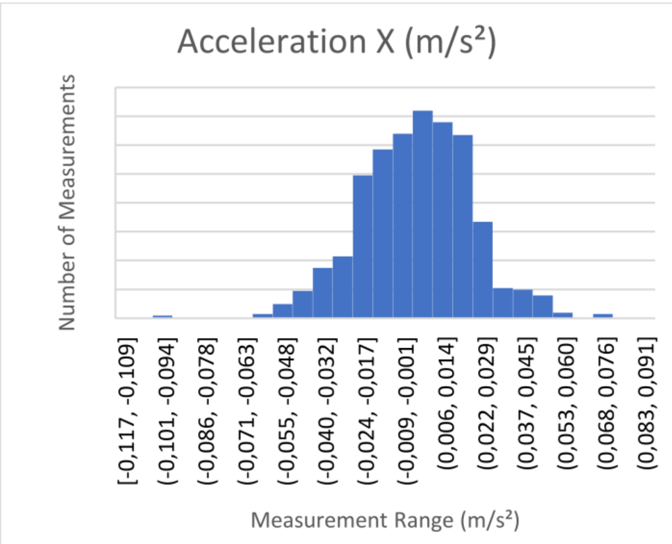

Figure 9 – Histogram for X axis readings

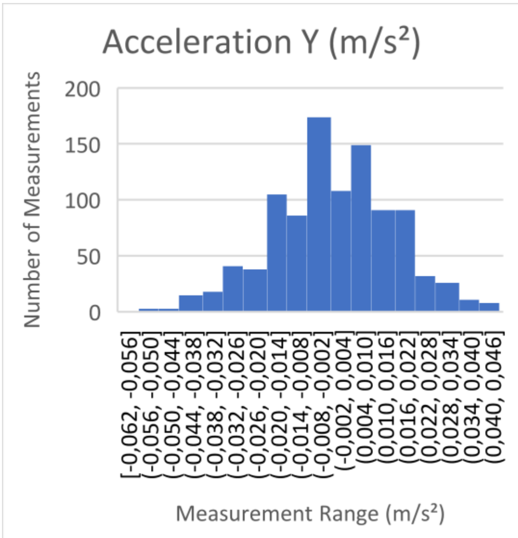

Figure 10 – Histogram for Y axis readings

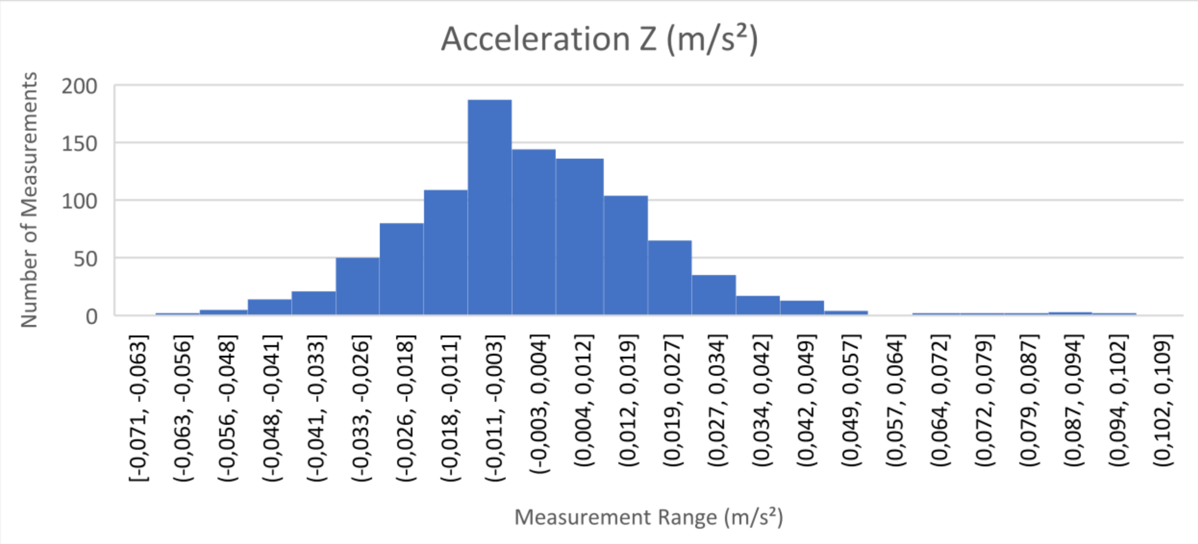

Figure 11 – Histogram for Z axis readings

4.3 Task 3

This part of the experiment was done together with Shweta Kempipatil. After preparing the Arduino program, We have taken the Arduino Nicla Sense ME board together with a notebook to the elevator at the Universitätsbibliothek Freiburg building and kept it in a stationary position. After that, the board was launched to do a measurement every 0.1 seconds, 1000 times. Once the board was launched, we went from the ground floor to the 5th floor, waited for a while, and returned to the ground floor. The measurements are given in the following sections.

Part a)

The data that was measured with the acceleration sensor is plotted below (Figure 9). A positive peak in the acceleration graph at the start shows that the elevator has started ascending from the ground floor. It accelerates and reaches a constant velocity. The negative peak occurs when the velocity of the elevator starts decreasing until it finally stops. The second negative peak occurs when the elevator starts descending from the 5th floor. Finally, a positive peak happens when the elevator slows down until it stops. As can be observed, the raw acceleration data (Figure 9) is very noisy. This noise is a result of many aspects such as vibrations in the elevator or the temperature. To get rid of this noise, we used two smoothing techniques.

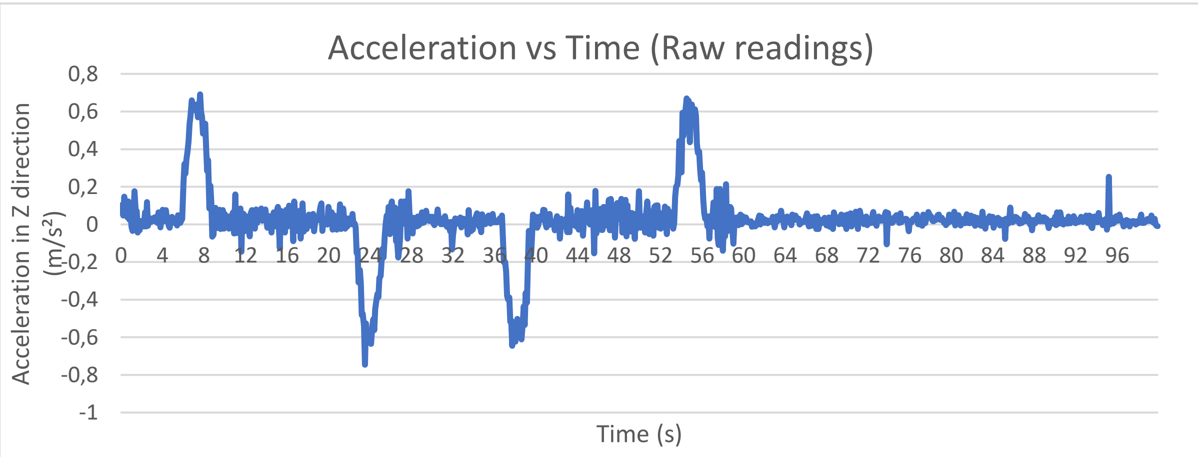

Figure 12 – Raw acceleration data in Z direction (offset subtracted)

As can be seen from the figures below (Figures 10, 11), two different approximation techniques were used to smoothen the acceleration data. Namely, moving average and exponential smoothing techniques. After each of these techniques, a lowpass filter is used to set the data to 0 under a certain threshold. Both of the smoothing techniques will affect the data differently since they will introduce different amounts of error. We will, later on, see how we can get different velocity data when different smoothing techniques are used.

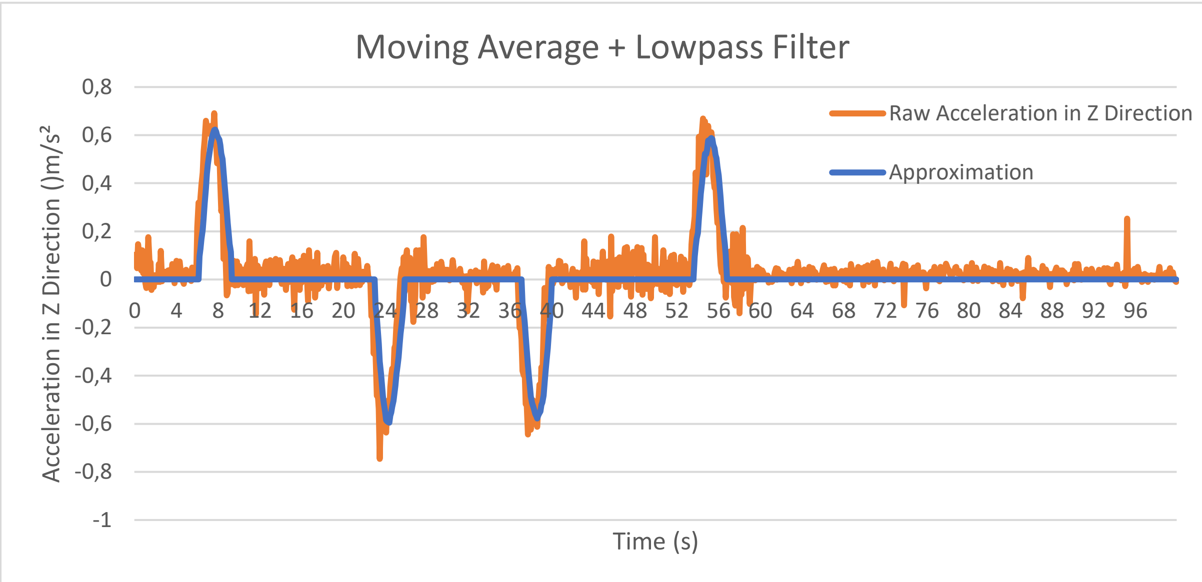

Figure 13 – Approximation with moving average smoothing

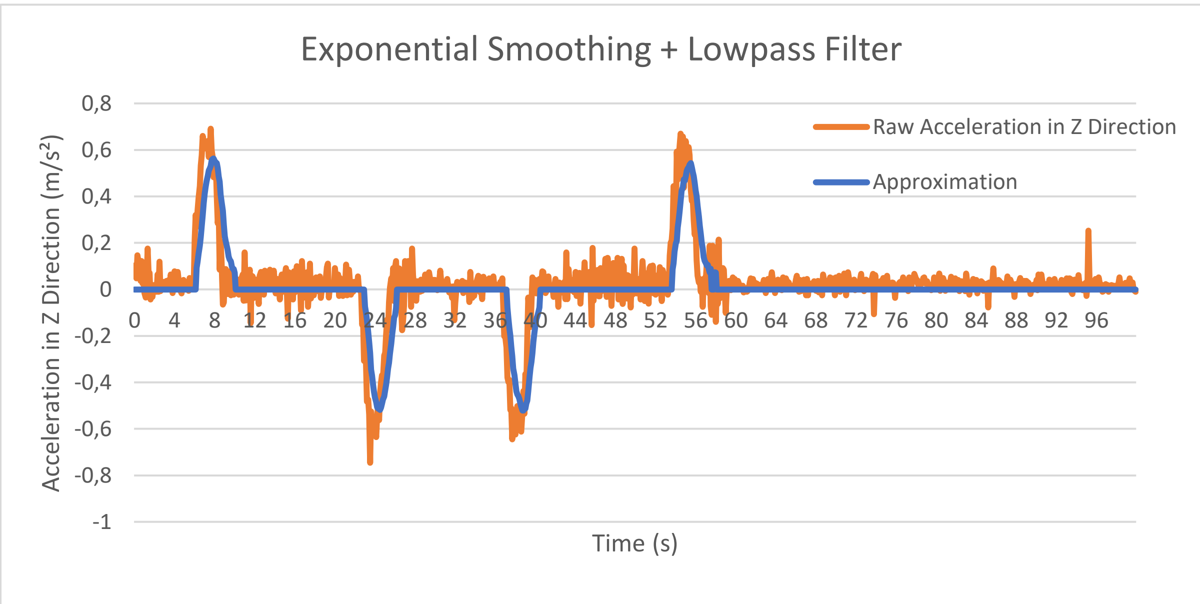

Figure 14 – Approximation with exponential smoothing

Another measurement that was done is the pressure measurements. 1000 pressure measurements were conducted during the elevator ride from the ground floor to the 5th floor and back. The BMP390 sensor outputs pressure values in hPa. As can be seen from the figure (Figure 12). The pressure reading is initially around 987.3 hPa and it becomes around 985 hPa once it reaches the 5th floor. The reading becomes 987.3 hPa once again when the elevator descends from the 5th floor to the ground floor. Compared to the acceleration readings, the pressure sensor has much less noise since its readings are not significantly affected by the vibrations in the elevator, unlike the acceleration sensor.

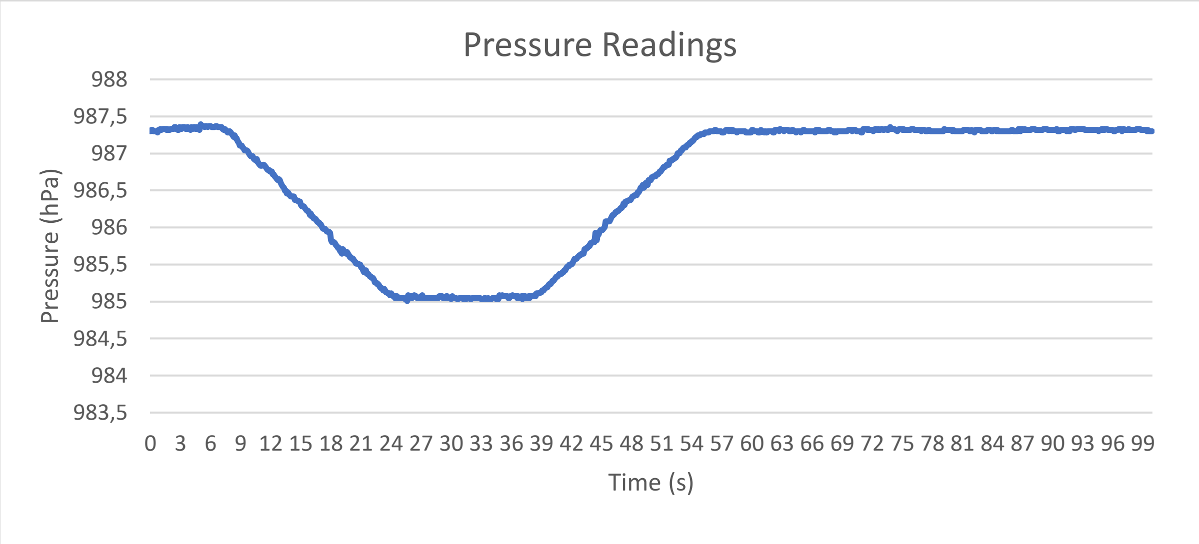

Figure 15 – Measure pressure data

Part b)

The barometric formula is used to calculate the height data of the elevator ride. As can be seen from the figure below (Figure 13) the height at the ground floor is not 0 m. This is because the reference pressure was the pressure at the sea level while implementing the barometric formula. If we subtract the maximum height (238.1 m) from the minimum height (218.5 m) we find out that the distance between the ground floor and the 5th floor is approximately 19.6 m.

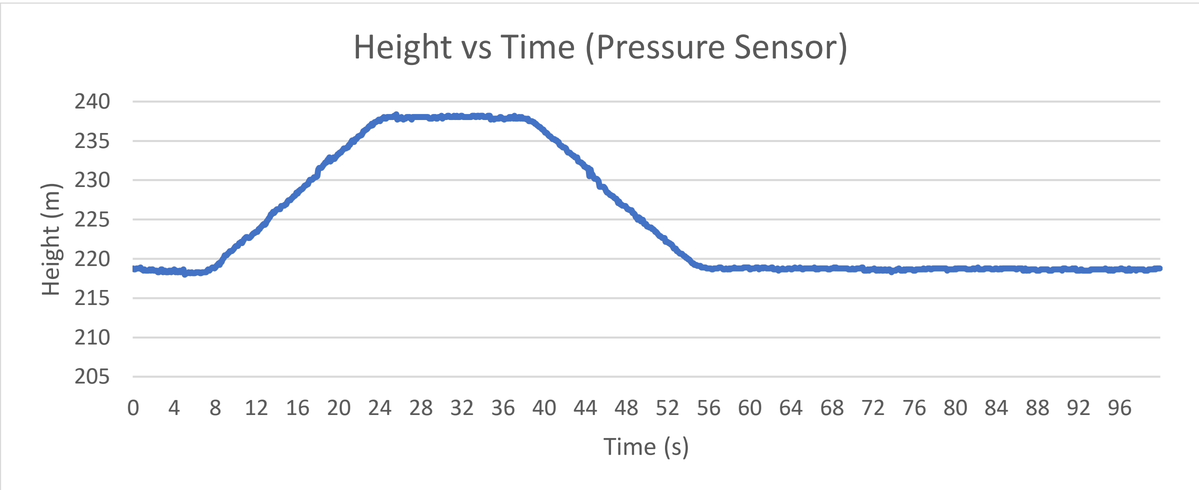

Figure 16 – Height data calculated using the pressure data

Part c)

Velocity data were derived using two smoothing techniques. Namely, exponential smoothing and the moving average technique. As can be seen from the figures below (Figures 14, 15), we obtain different velocity data when different smoothing techniques are used. Moreover, an error in both of the graphs can be seen. When the elevator stops at the 5th floor, the velocity does not become 0 for both of the graphs. Also, when the elevator goes back to the ground floor, the velocity seems to be greater than 0 for both of the velocity graphs. This occurs due to the noise at the acceleration readings.

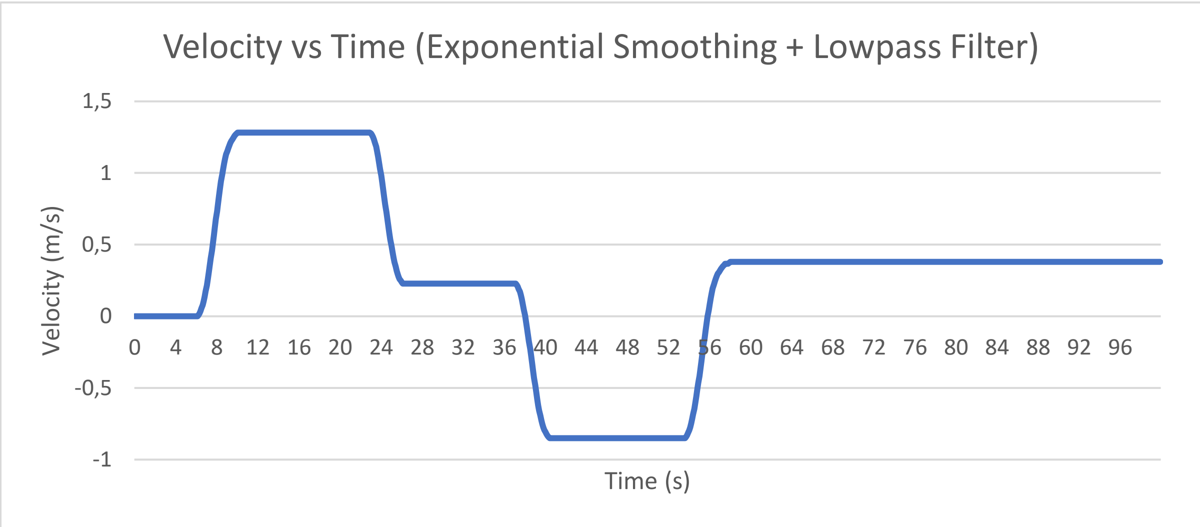

Figure 17 – Velocity data calculated using the acceleration & exponential smoothing

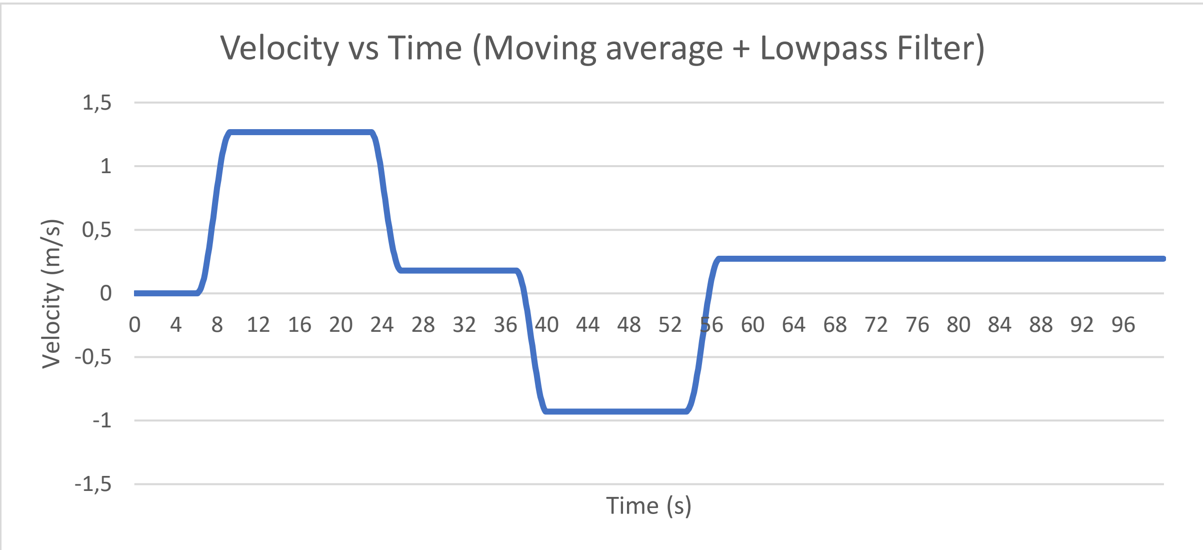

Figure 18 – Velocity data calculated using the acceleration & the moving average smoothing

Part d)

Finally, the height data of the elevator ride was derived using the calculated velocity. Because the error was less, the moving average smoothing was preferred while doing the calculation. As can be seen from the graph below (Figure 16), the calculated height is not error-free. Due to the noise on the acceleration data and the losses introduced by the moving average smoothing, the height on the graph is not going back to 0 when the elevator descends from the 5th floor to the ground floor. Also, the maximum height (13.2 m) is less than 19.6 m, which was the height from the ground floor to the 5th floor calculated with the pressure sensor. Taking into account all the noise and errors, it can be concluded that an acceleration sensor is not very reliable while calculating height.

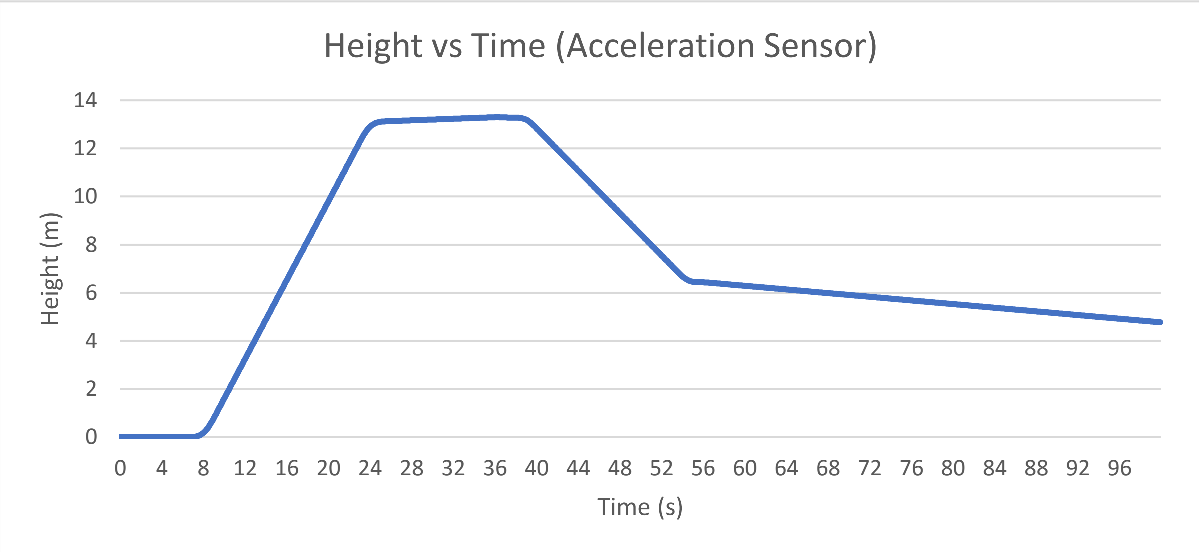

Figure 19 – Height data calculated using the acceleration sensor

5. Summary

In this experiment, the sensors BHI260 and BMP390 were tested and their offset values were calculated while the Arduino Nicla Sense ME board was stationary. Then, the board was taken into an elevator. From the acceleration and the pressure measurements acquired from the elevator ride, velocity and height were calculated. When the height calculations are compared, it can be easily said that a pressure sensor is more suitable to calculate the height since it is affected by fewer factors during the ride, and less noise is introduced to the sensor, unlike the acceleration sensor.

References

[1] *Moving average* (2022) *Wikipedia*. Wikimedia Foundation. Available at: https://en.wikipedia.org/wiki/Moving_average?oldformat=true (Accessed: December 26, 2022).

[2] *Exponential smoothing* (2022) *Wikipedia*. Wikimedia Foundation. Available at: https://en.wikipedia.org/wiki/Exponential_smoothing?oldformat=true (Accessed: December 26, 2022).

[3] *MEMS accelerometers* (no date) *Silicon Sensing*. Available at: https://www.siliconsensing.com/technology/mems-accelerometers/ (Accessed: December 26, 2022).

[4] *MEMS Capacitive vs Piezoresistive Pressure Sensors – What are their differences?* (2021) *ES Systems*. Available at: https://esenssys.com/capacitive-piezoresistive-pressure-sensors-differences/ (Accessed: December 26, 2022).

[5] BOSCH, "https://www.bosch-sensortec.com/media/boschsensortec/downloads/datasheets/bst-bhi260ab-ds000.pdf," 2020, p. 137.