Hochschule Bremerhaven

M.S in Embedded Systems Design
Maritime Systems

Under the guidance of
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Laboratory Report
Acceleration Measurement

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Abbreviation

Summary

The goal of the experiment is to calculate the height of the floors by measuring the acceleration of an elevator trip.

The experiment includes multiple phases, including designing and simulating a circuit in LTspice, creating a circuit on a PCB, programming a microcontroller, measuring acceleration data, processing it, and recording it on an SD card with the help of a microcontroller.

To improve accuracy, several elevator rides were taken and the data examined. The measurements were then shown in MATLAB, and the floor height was determined by calculating the standard deviation of all the readings.

1. Overview

The circuit is built using a ADXL355 [1] from Analog Devices was used to measure the acceleration. A Zener diode (BZX85C4V7) [2] used for stabilizing the direct current voltages for operating the sensor. An operational amplifier (TLC272) [3] for amplification of the output signal and also an active low pass filter. Finally, the remaining components values are calculated assuming the Amplification value suited.

Before starting with the assembly of the circuit on the Printed Circuit Board (PCB), the circuit was simulated in LTspice to observe the behavior of design with the calculated values of the components.

Once done with the LTspice simulation for observing the frequency response of the circuit as expected with the circuit components selected. The components are soldered onto a PCB. After which instead of directly placing the sensor module on the PCB, it is tested with the power supply and a designed board used for depicting the sensor output voltage.

DSOX 2002A Oscilloscope from Agilent [4] is used for measuring the frequency response and the step function.

Then the designed circuit was integrated with an ATmega 32 microcontroller [5] which uses a C-code for storing the analog data which uses an Analog to Digital Converter (ADC) to store the data in SD card. The acquired data values are sent to the RS232 to save onto the SD card.

Then with help of batteries the whole circuit is powered and the acceleration readings are collected for the height of the floors to be calculated.

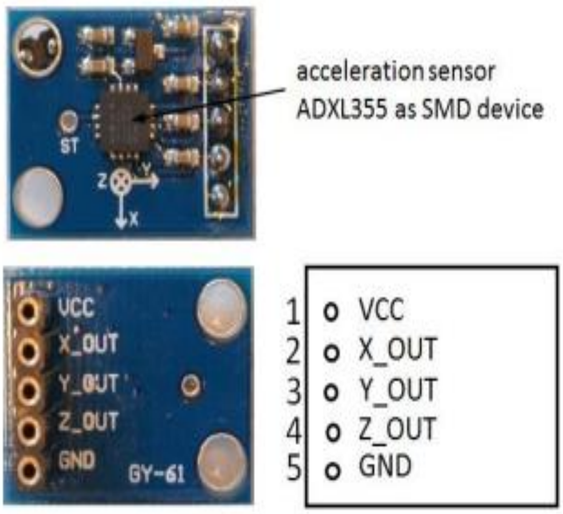
2. Hardware basics

The following hardware components were included in this experiment:

2.1 Acceleration sensor/ Sensor module

Analog Devices' ADXL335 [1] is the acceleration sensor utilized in the experiment. It works on the basis of a mass pendulum in a micro electric mechanical system (MEMS). When the pendulum is distracted, internal capabilities are altered, affecting the output voltage. The level of the output voltage becomes the measure of acceleration because the relative movement of the pendulum is changed by the sensor's acceleration. These two variables are proportional to one other. The ADXL335 [1] is a three-axis acceleration sensor. Only one axis is necessary in this experiment.

With a typical sensitivity of $s = 300\ \frac{mV}{g}$ and a 0 g bias level of V_{off} = 1.5 V, the acceleration sensor can measure static and dynamic acceleration within a full-scale range of ±3 g. It can detect gravity's static acceleration as well as dynamic acceleration caused by motion, shock, or vibration in tilt-sensing applications. Figure 1 indicates the pin connections on the sensor module.



Pin	name	declaration
1	VCC	supply voltage: 1.8 V to 5 V
2	X_OUT	X channel analog output
3	Y_OUT	Y channel analog output
4	Z_OUT	Z channel analog output
5	GND	ground

Figure 1 Sensor module and pinout of ADXL335 [1]

2.2 Microcontroller ATmega32

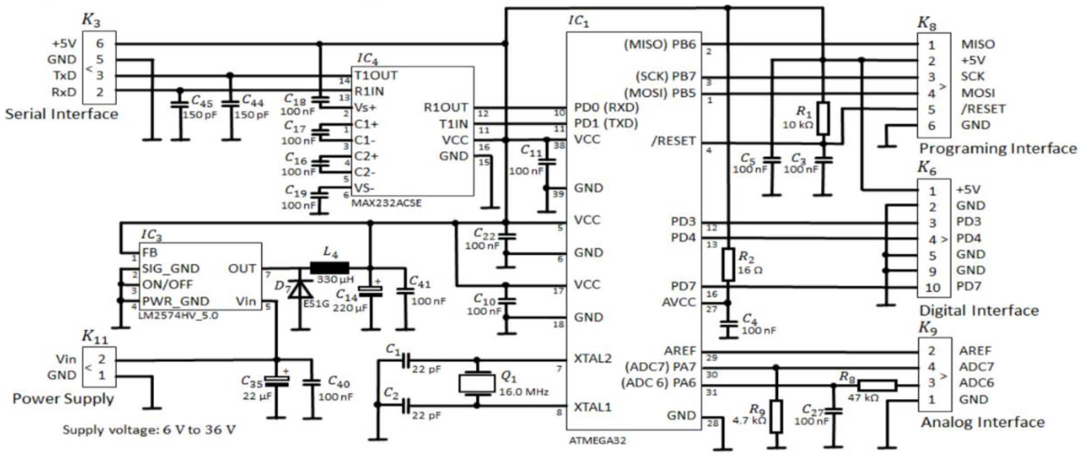


Figure 2 Microcontroller ATmega32 circuit diagram [2]

The Atmel® AVR® ATmega32 is a low-power CMOS 8-bit microcontroller based on the Automatic Voltage Regulator (AVR), enhanced Reduced Instruction Set Computer (RISC) architecture. In this experiment, the ATmega32 [5] microcontroller was used.
The board is suited for the experiment since it has an inbuilt 10-bit analog to digital converter (ADC), an RS232 communication port, and digital inputs and outputs. The above Figure 2 shows a circuit schematic for the microcontroller board.

2.3 Circuit assembly

The circuit design has two stages (see Figure 3). The former consists of subtracting amplifier and later stage is inverting amplifier and active low-pass filter. The purpose of this circuit is to measure acceleration. The offset voltage of the accelerometer in the test circuit is 1.5 V. The elevator acceleration was set to between +1.5 g and -0.5 g, resulting in a maximum output voltage of 1.95 V and a minimum output voltage of 1.35 V from the sensor.

A Zener diode provides the appropriate voltage to the sensor module M_1. The module provides a variable output voltage on pin 2 that is proportional to X-direction acceleration. Pin 5 serves as a ground (GND) for both the power supply and the output signal. The desired amplification converting the sensor module's output voltage to the test circuit's output voltage V_{acc} can be shared across both amplification stages. The subtracting amplifier's positive input can be adjusted to zero to erase the sensor module's offset voltage. The trimmer P_1 may be used to modify the voltage divider.

The second amplifier phase is made up of an active second-order low-pass filter with multiple negative feedback. This low-pass filters out high-frequency acceleration impulses. This is required since the Analog signal will be transformed to a digital signal later.

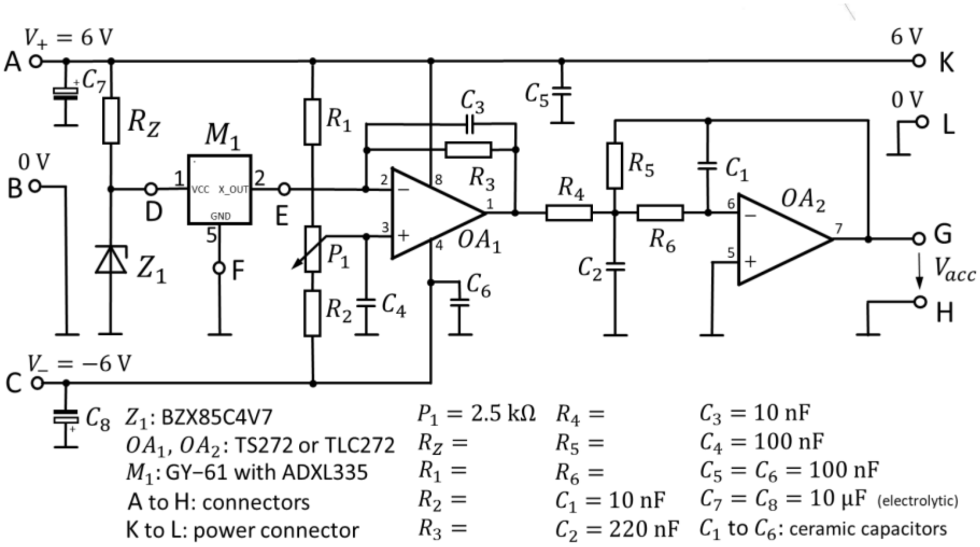


Figure 3 Schematics of the test circuit with sensor module and operational amplifiers [2]

The power supply for the microcontroller experimental board used for data acquisition can be provided through connectors K and L. Figure 4 shows the test circuit diagram.

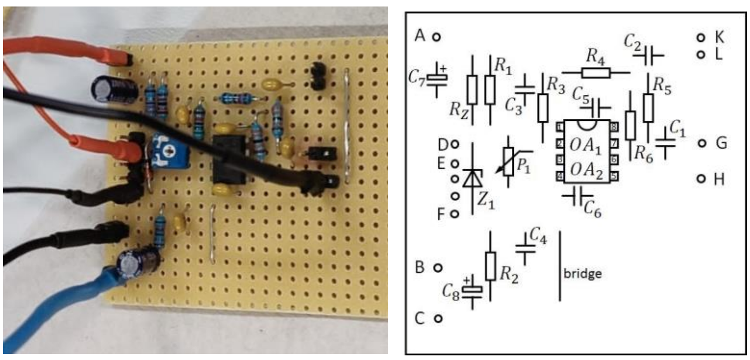


Figure 4: Positioning of the components on the experimental printed circuit board

3. Measurement of the cut-off frequency

A waveform is generated with the help of an Agilent oscilloscope. There are two ways to calculate the frequency response of the circuit.
The following two approaches were used to determine the cut-off frequency.

1 Comparing the frequency response with the step response.
2 Creating a sign wave with the frequency response of a waveform generator

3.1 Using sine wave

An alternating current (AC) voltage is supplied to the circuit as replacement of the sensor module. The internal resistor of the sensor must be simulated using an external resistor. Then the output voltage is observed by changing the frequency.

The gain at the cut-off frequency can be derived with the direct current (DC)-gain:

$$g_c = \frac{g_0}{\sqrt{2}} = \frac{7.08}{\sqrt{2}} = 5.006 \quad (1)$$

The gain g_c can be found at $f_c = 9.5$ Hz (see Figure 5)

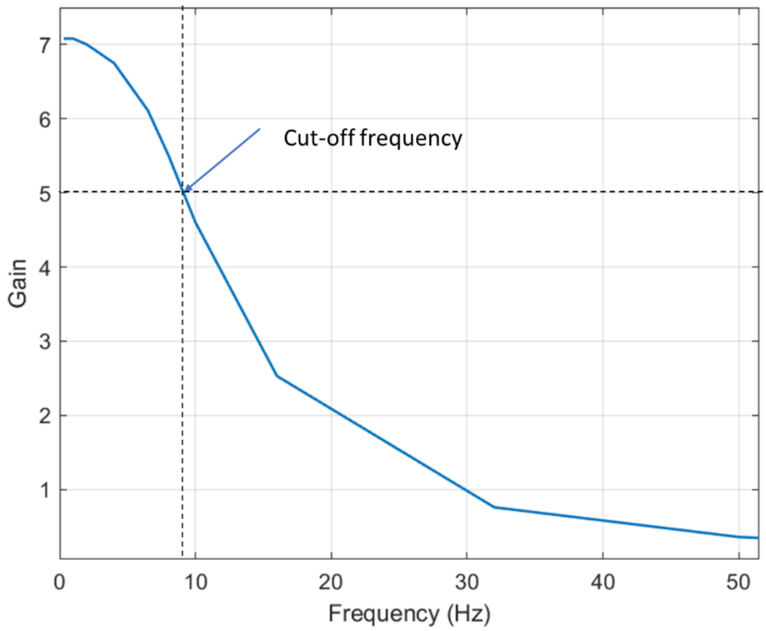


Figure 5 Sine wave frequency response

3.2 Using step response

Another way to calculate the cut-off frequency is using step response. Below diagram shows the square wave step response for the experimental circuit in oscilloscope screen.

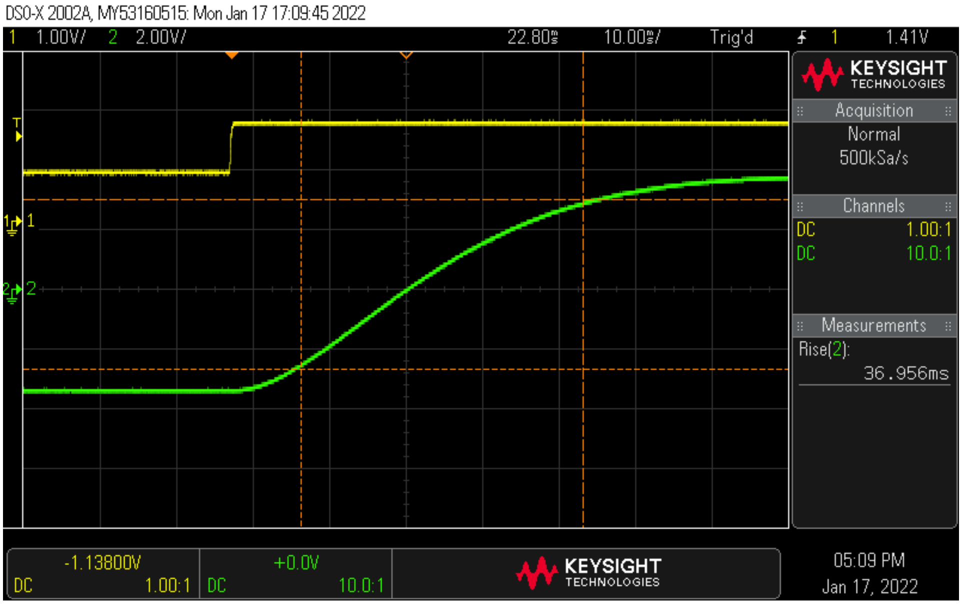


Figure 6: Step response of the experimental frequency

Slew rate t_s is the time between 10% to 90% of the output voltage which is measured automatically by the oscilloscope [4]. The cut-off frequency can be calculated as follows.

$$f_c = \frac{1}{3 \cdot t_s} = \frac{1}{3 \cdot 36.956 \text{ ms}} = 9.02 \text{ Hz} \quad (2)$$

Both determination of the cut-off frequency fits into the designed cut-off frequency.

4. Acceleration measurement in the elevator

During the elevator travels, the battery was attached to the power supply connection on the experimental circuit. In order to achieve stability during the measurement, the experimental circuit was put and fastened with a wooden block. Using the RS232 interface, the measured data was sent and recorded to a micro-SD card. Figure 7 depicts the results of the elevator rides. After the circuit's functioning was confirmed, software measurements of acceleration during an elevator trip were recorded. In housing T of the University of Applied Sciences Bremerhaven, five elevator rides between the ground and 1st floor were recorded. A calibration process was carried out before each journey in order to later calibrate the recorded data to the acceleration values of 0 g and 1 g.

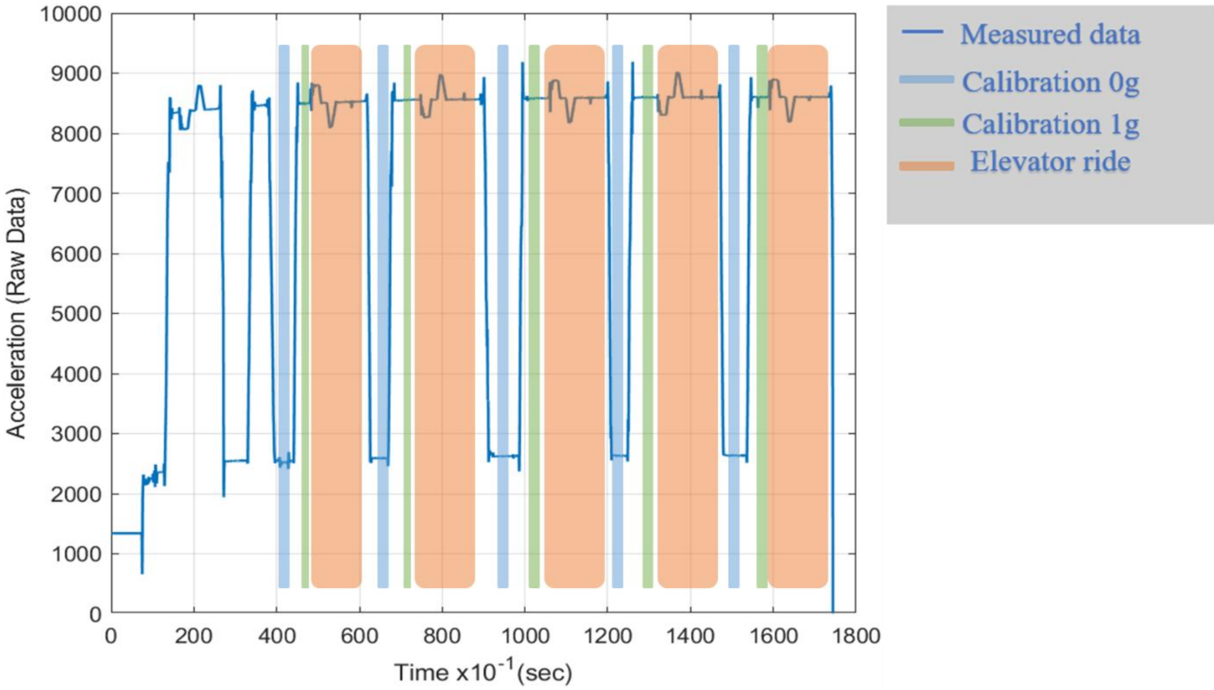


Figure 7: Overview of recorded data

The first reading was discarded due to erroneous data.

a. At time 40s (color blue) acceleration due to gravity is 0 g. Sensor axis is in horizontal direction.
b. At time 43s (color green) acceleration due to gravity changes to 1 g. Sensor axis is tilted to vertical direction.
c. Between 45s to 65s (color orange section) is acceleration during elevator trip.

The following plot is repletion of the above steps. Calibration was performed after reaching every floor.

4.1 Calibration process

Raw data captured can't be used directly for the calculation. The data logged contains the time and the output d_{acc} from the ADC. This is nothing but the acceleration data in other means. Two known accelerations were collected before each trip to calibrate the recorded data.

By tilting the sensor 90° to the floor, the first calibration point is 0 g. The sensor axis was then tilted in the direction of gravity to detect 1 g. To get a stable value, both calibration points were measured for 3 seconds. Both calibration stages were averaged arithmetically.

The below equation is used to calculate the acceleration.

$$a = k_1 \cdot d_{acc} + k_0 \tag{3}$$

Where,

a = Acceleration
k_1 = co-efficient for proportionality
d_{acc} = Output of analog to digital converter
k_0 = co-efficient of the offset (m/s^2)

By choosing two appropriate calibration sites of 0 g and 1 g, the coefficients k_0 and k_1 are calculated.

	Trip1 (d_{acc}($value\ can\ be\ seen\ in\ the\ raw\ data$))
Mean 0 g	2550
Mean 1 g	8596

Substituting these values in equation (4), we can derive following two equations.

For 0g: $$0\, m/s^2 = k_1 \cdot 2550 + k_0 \tag{4}$$

For 1g: $$9.81\ m/s^2 = k_1 \cdot 8842 + k_0 \tag{5}$$

From equation (5) and equation (6), we get,

$$k_1 = \frac{9.81\ m/s^2}{8842 - 2550} = 1.559\ \times 10^{-3}\, m/s^2$$

Substituting k_1 we get k_0

$$k_0 = -k_1 \cdot 2550 = -4.1375\, m/s^2$$

The actual acceleration can be determined by using k_0, k_1, and d_{acc} for all of the recorded values (Refer to equation 3).

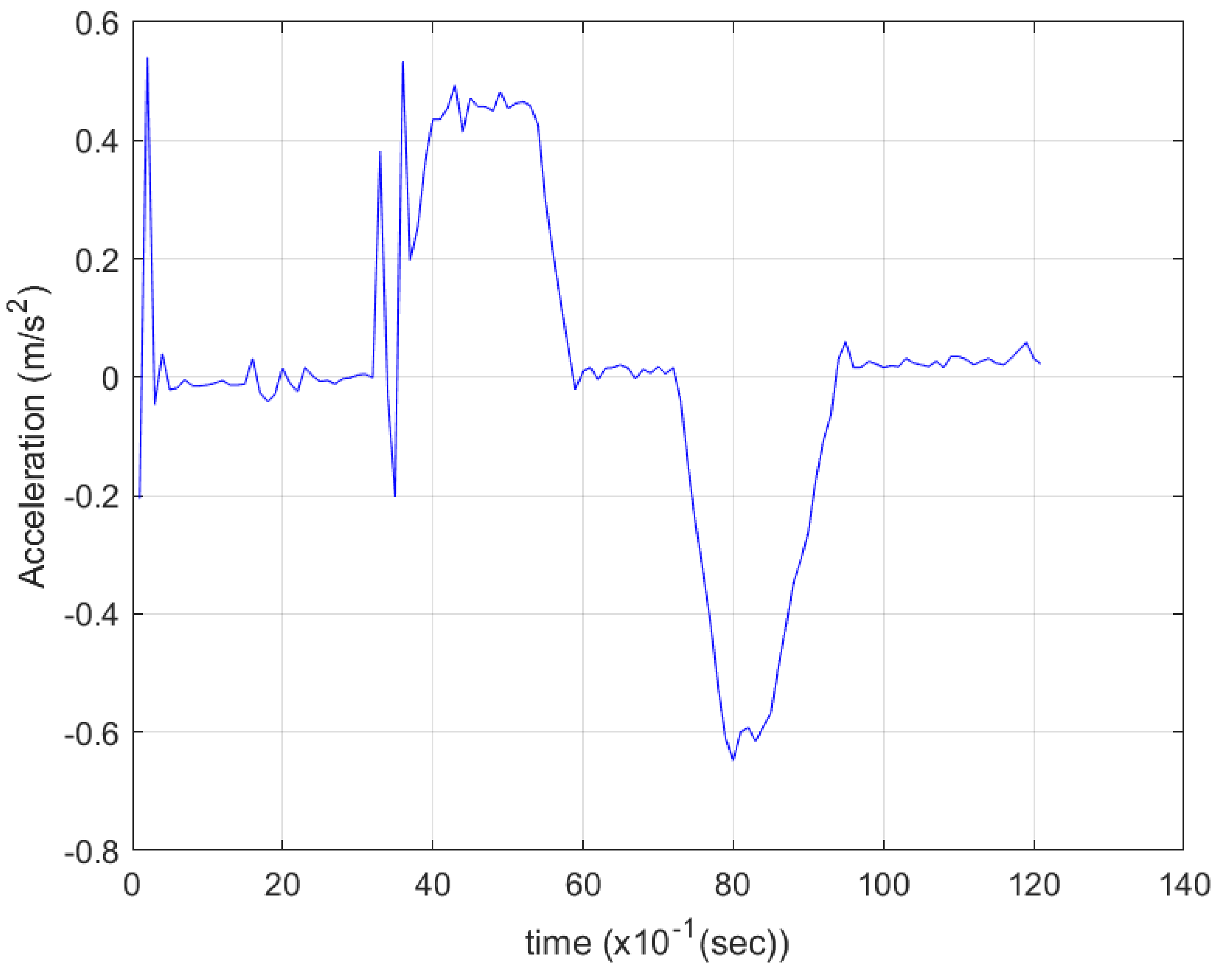


Figure 8 Acceleration Data

As a result, the raw acceleration data is transformed to m/s^2after calibration, as illustrated in Figure 8.

The acceleration data for a single-direction movement, such as moving from the ground floor to 1st floor, is displayed below.

4.2 Derivation of velocity and displacement

Using fundamental physics and mathematics concepts, the height of the floors can be computed from the acceleration data.

As we all know, an object's acceleration is defined as the rate at which its velocity changes, and velocity may be further defined as the rate at which its displacement varies over time.

The mathematical formula for acceleration (a), velocity (v), and displacement (s) are provided below.

$$a = \frac{\mathrm{d}v}{\mathrm{d}t} \text{ and } v = \frac{\mathrm{d}s}{\mathrm{d}t}$$

From the above equations we have

$$v = \int_0^t a \cdot \mathrm{d}t + v_0 \text{ and } s = \int_0^t v \cdot \mathrm{d}t + s_0$$

Where,

s_0 = Initial displacement at time t = 0
v_0 = Initial velocity at t = 0

Since we have discrete time systems, the above equations are replaced by summation:

$$v_k = \sum_0^k a_i \cdot \Delta t + v_0 \tag{6}$$

Where,

v_k = Velocity at instance T
a_i = acceleration at instance i
Δt = Time between two measurements

$$s_k = \sum_0^k v_i \cdot \Delta t + s_0 \tag{7}$$

Where,

S = Displacement at instance T
v_i = acceleration at instance i
Δt = Time between two measurements

Using these equations, the velocity and the displacement can be calculated from the acceleration data acquired.
The Figure 9 shows the Velocity graph calculated from the equation (7).

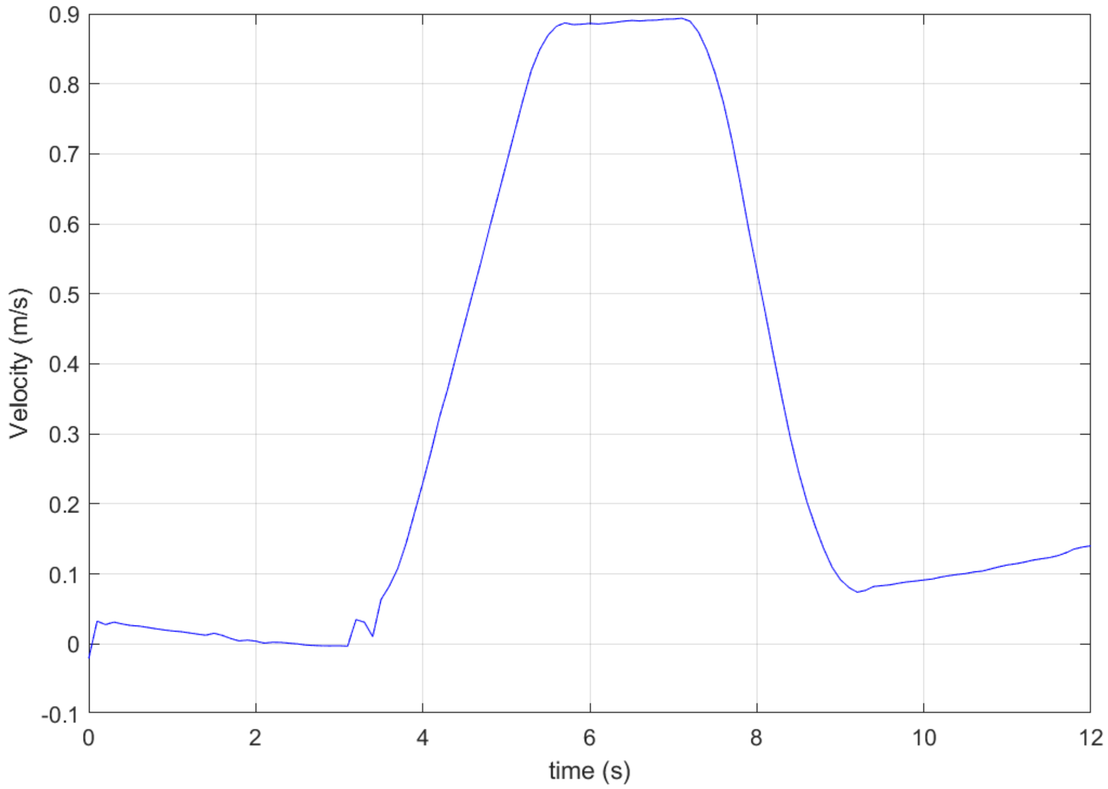


Figure 9 Velocity of Initial trip

4.3 Correction of the temporal drift

The velocity graph shows a temporal drift as the velocity never reaches to 0 even after elevator has stopped at time around 12s. This is because of linearly increasing error due to incorrect calibration. It is corrected by subtraction of the linearly increasing value.

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

Where,

m = Slope of temporal drift
y_n = Velocity Coordinate
x_n = Time Coordinate

$$m = \frac{0.13 - 0}{9.8 - 0} = 0.0132\, m/s^2$$

Thus, by plotting the temporal drift using equation of line ($y = m \cdot x$), and subtracting the velocity values in Figure 9, corrected velocity graph can be plotted as shown in Figure 10 below.

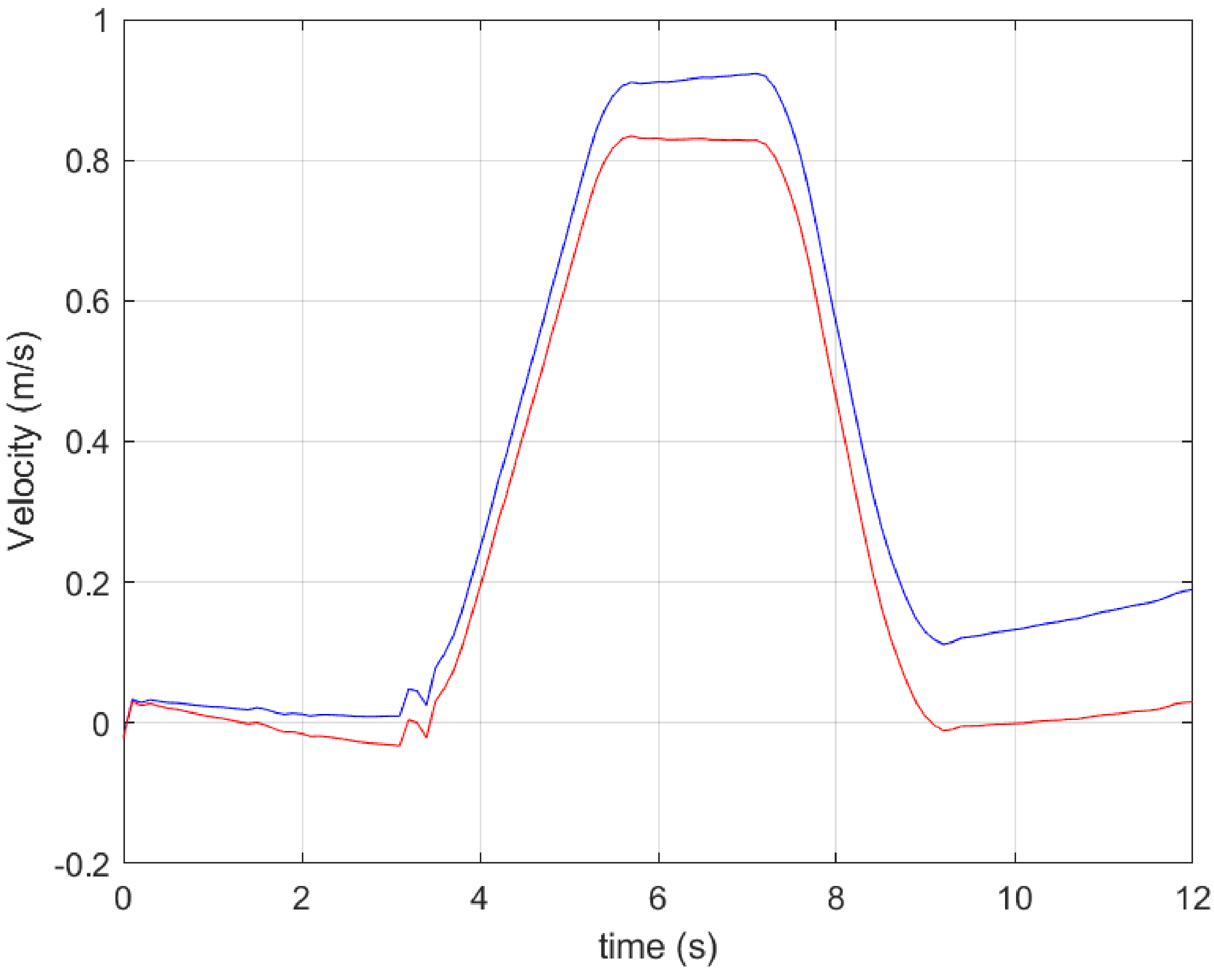


Figure 10: Corrected velocity during elevator trip from ground floor to third floor

4.4 Calculation of displacement

Using this equation (8), displacement s at all instances is calculated considering the velocity values from Figure 11 and Δt as 0.1 s, displacement graph is plotted for the elevator trip from ground floor to third floor as shown below.

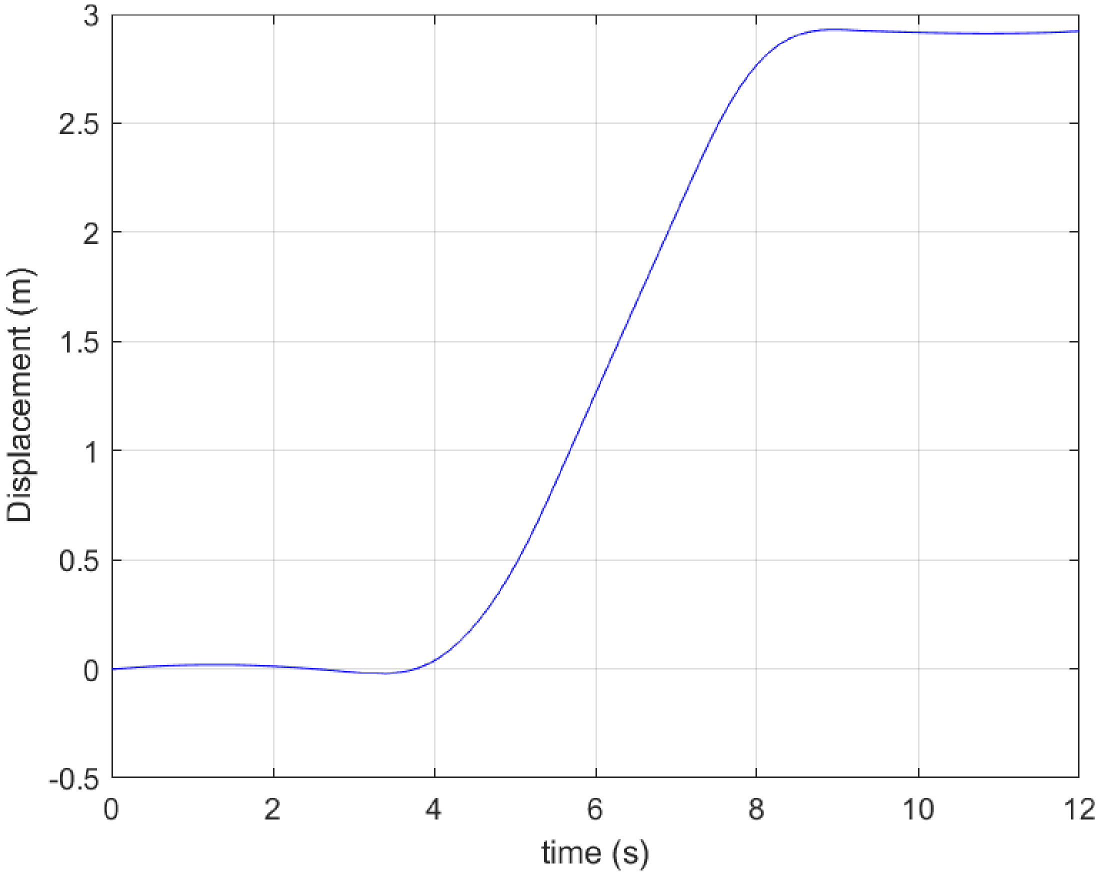


Figure 11 Displacement graph for the first trip

The final displacement is 2.89 m. This is the distance from ground floor to first floor.

5. Result

The first trip was excluded as there are erroneous values seen. The below table shows the height of the floor during each trip

Trip	Height
Trip 1 (Up)	2.89m
Trip 2 (down)	3.25m
Trip 3 (Up)	3.1m
Trip 4 (down)	3.15m
Trip 5 (Up)	3.5m

Table 1: Distance measurement during each trip

The mean distance ($\bar{s}$) of all of above trip as follows:

$$\bar{s} = \frac{1}{N}\sum_{i=1}^{5} S_i$$

$$\bar{s} = \frac{15.89\text{m}}{5} = 3.178 \text{ m} \tag{8}$$

Where,

N = Number of sample points
s_i = Measurement of i^{th} $point$

The standard deviation can be calculated as

$$\sigma = \sqrt{\frac{\sum_1^5 (s_i - \bar{s})^2}{N}}$$

Where,

σ is standard deviation
s_i = Measurement of i trips

$$\sigma = 0.199 \text{ m}$$

6. Conclusion

Overall, the experiment accomplished in monitoring the floor level using an accelerometer.

A circuit to condition the output signal of the accelerometer has been successfully calculated, constructed and tested. A suitable microcontroller program has been designed and integrated to record the data.

Finally, MATLAB was used to analyse the collected data in order to determine the floor level. With a standard variation of 0.199 m, the measured mean floor level is 3.178 m.

References

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[5] Atmel Corporation: Data Sheet ATmega32; 8-bit AVR Microcontroller with 32Kbyte In-System Programmable Flash; San Jose; Revision 2503Q-AVR-02/11; 2011.