Measuring altitude using an environmental sensor (Bosch BME680)

Scientific Seminar

Autonomous Vehicle Engineering (B.Eng.)

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List of Abbreviations

IIR	Infinite Impulse Response
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
SPI	Serial Peripheral Interface
I2C	Inter integrated Circuit
TWI	Two Wire Interface
EEPROM	Electrically Erasable Programmable Read Only Memory
SCL	Serial Clock
SDA	Serial Data
SDI	Serial Data Input
SDO	Serial Data Output
CE	Chip Enable
MOSI	Master Output Slave Input
MISO	Master Input Slave Output
SCLK	Serial Clock
SS	Slave Select

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Acknowledgments

I would like to express my gratitude to Prof. Dr-Ing. Thomas Schiele, whose constant supervision and advice have been key to overcoming the challenges that I faced.

I would also like to thank my family who have provided support and encouragement throughout my academic journey.

Finally, I would like to thank my friends who accompanied me at this stage.

Abstract

The BME680 sensor is a high precision developed by Bosch Sensortec. This sensor is recognized for its robust four-in-one functionality, providing accurate temperature, humidity, air quality (gas), and pressure readings.

In this paper we dive deep into the capabilities of the BME680 sensor with specific focus on the working principle of the barometric pressure sensor. The barometric pressure sensor uses the piezoresistive phenomenon. Piezoresistive phenomenon which is the change of resistance of material when pressure is applied, this pressure also changes the dimensions of the material which affects resistance.

We also explore the usage of Wheatstone bridge in the sensor, how does it affect the pressure readings and its temperature compensation and sensitivity. Additionally, the Digital to Analog Converter is illustrated which is used to convert the analog signal to digital signal to be compatible with the modern device. Also, the IIR filter inside the BME680 is mentioned showing it working method and advantages.

1. Introduction

1.1 Background

The of sensor technology is increasingly dominating the world we live in today. These innovative tools can be found almost anywhere, from our homes and workplaces to our vehicles and even public spaces. Their functionality extends to various practical uses that significantly contribute to our everyday convenience, safety, and efficiency [1].

Looking at our daily surroundings, sensors in the form of simple alarm clocks wake us up. In advanced smart homes, sensors are used to automate processes such as meal preparation via programmed cooking appliances. Moreover, the use of temperature and humidity sensors, not to mention smoke detectors, have become common in offices and workplaces, proving the influence of sensor technology in enhancing occupational safety [1].

Vehicles have not been left behind in benefiting from this technology. Modern cars are filled with various types of sensors such as the oxygen sensor for fuel efficiency and emission control, as well as object detection sensors for enhanced safety and accident prevention [2].More complex workplaces use sensors in tasks as crucial as explosive detection, and for those whose professions involve travel, airport security utilizes sensors for identifying concealed objects [1].

Beyond the individual use of sensors, it is worthy to mention their importance on a larger scale at local, state, national, and global levels These technological tools come into play in controlling traffic lights, mitigating congestion and ensuring the smooth flow of traffic [1].With advancement in the logistics industry, the efficient monitoring of vast warehouse spaces relies heavily on multiple sensors. These sensors measure temperature, detect smoke, and perceive motion, transforming warehouse control into an automated, real-time operation as seen in modern Intelligent Warehouse Systems [3].

The fast rise of sensor technology in our lives highlights their absolute necessity not only in everyday living but also usefulness in scientific research, industrial applications, and societal advancements. Indeed, the universal inclination towards sensor technology confirms their significance, and shows why we will continue to witness their growth, improvement, and integration with our daily lives [1].

1.2 Objectives

To comprehensively understand the features and capabilities of the BME680 environmental sensor and its specific attributes. provide an explanation of the correlation between atmospheric pressure and altitude.

To explain the fundamental working principle of the BME680's built-in pressure sensor, specifically detailing how differences in atmospheric pressure are measured.

1.3 Overview of Seminar Paper

In this section a quick look will be given at the main structure of this paper, which is entitled "Measuring altitude using environmental sensor BME680" and it aims to measuring the altitude using the pressure information provided by BME680. This document consists of 5 main chapters other than the list of abbreviations, list of figures, abstraction, and acknowledgments which the report begins with. The main chapters are:

1. **Introduction**
   This chapter explains the background on which this research was conducted, the motives that led to the necessity of conducting it and explains that goal it aims to achieve.

2. **Theoretical Knowledge**
   This chapter presents the scientific basis and the basic concepts that must be known to ease understanding.

3. **Conclusions**
   This chapter summarizes the outcomes of this research.

4. **References**
   This chapter mentions all the resources that were used to conduct this research.

5. **Appendices**
   Here it contains the code and diagram for connecting Arduino UNO R3 with BME680 using I2C.

2. Theoretical Knowledge

2.1 BME680

2.1.1 Introduction

The BME680 is an all-in-one environmental sensor specially engineered for applications in mobile devices and wearables where the need for compact size and low energy consumption is a major concern. This addition to Bosch Sensortec's array of environmental sensors represents a first, as BME680 is offering high precision and linearity in its integrated sensors for measuring pressure, gas, humidity, and temperature [4].

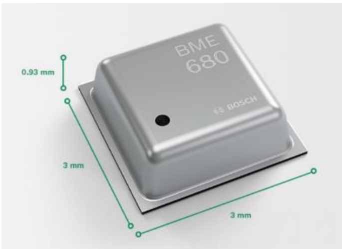


Figure 1 BME680 Sensor

The ability to measure parameters such as pressure, temperature, and humidity are adjustable features that can be either enabled or disabled according to the user's needs. Nevertheless, it is strongly advised against disabling the temperature measurement functionality. The reason behind this recommendation is that temperature measurements play a crucial role in reducing the effect of temperature on the measurement of other environmental parameters [4].

Once the measurement functionality is turned on, users have the choice from an array of options. In the context of data measurement, oversampling and IIR filter serves as an effective strategy for significantly lessening noise within the data, which ultimately enhances the accuracy of the results [4].

Furthermore, it's important to note that the resolution of the measured temperature and pressure data is heavily influenced by the configurations of both the IIR filter and the oversampling settings. For instance, the activation of the IIR filter causes the resolution of the pressure data to be set at 20 bits [4].

In contrast, if users choose to disable the IIR filter, they will notice that the resolution of the pressure data can vary within a range, more specifically, from 16 to 22 bits. Despite these factors influencing the resolution of pressure data, it should be noted that the resolution of humidity data retains a fixed value, consistently offering a 16-bit output from the ADC, irrespective of other settings or configurations [4].

2.1.2 Working Principle

The pressure sensor utilizes the piezoresistive effect, which refers to the change in electrical resistance resulting from the application of external pressure. The pressure instigates a transformation in the lattice structure, which in turn, impacts the resistivity. Essentially, the applied pressure leads to reconfiguration in the structural formation, causing the change [5]. The applied force on the material changes the dimensions of the material which has an influence in the resistance of the material.

$$R = \rho \frac{L}{A}$$

Equation 1 Resistance

Stress, denoted as σ, originates from the application of force on a material, leading to alterations in its geometry. It is mathematically expressed as the applied force (F) divided by the material's cross-sectional area (A). which on the other hand causes strain ε. Strain is the change of material's dimension caused by applied Force. It is mathematically expressed as the change of length(ΔL) divided by original length(L) of material [6].

$$\sigma = \frac{F}{A}$$

Equation 2 Stress

$$\varepsilon = \frac{\Delta L}{L}$$

Equation 3 Strain

We have taken to concern the change of material length which is longitudinal strain we have also to deduce the lateral strain which causes the change in the cross-sectional area. The relation between longitudinal strain and lateral strain is proportional and the constant of proportionality is Poisson's ratio (V). This shows that lateral strain can occur without applying lateral stress [7].

$$V = -\frac{Lateral\ Strain}{Longitudinal\ Strain}$$

Equation 4 Poisson's Ratio

We can deduce that the force applied on the material will have a huge effect on its resistance. The resistance (R) is the opposition to current flow. The resistance is measured in ohms. The resistance is directly proportional to the resistivity (ρ) of material and length (L) and inversely proportional to the cross-sectional area (A). The resistivity of conductor is resistance of conductor with unit length and unit cross sectional area [8].

The action of applying stress on a material induces force, which in turn results in both longitudinal and lateral strain. This strain alters the length and the cross-sectional area of the material. So, it could be understood that the strain would lead to an extension in length and a reduction in area. This change inevitably leads to an escalation in the resistance of the material. Now we can say that resistance is equal to resistivity multiplied by new length and divided by new cross-sectional area. Alterations in the structural form cause shifts in the positions of the internal atoms, leading to a change in the average spacing between atoms in the lattice. This change subsequently impacts the mobility of charge carriers and consequently influences the resistivity of the material [9].

$$R = \rho \frac{L + \Delta L}{A - \Delta A}$$

Equation 5 New Resistance

The process of translating resistance changes in a sensor, which are caused by pressure, into output voltages is facilitated by the integration of a Wheatstone bridge circuit. This circuit represents the traditional way used for determining differences in voltages experienced within electrical circuits. In a Wheatstone bridge setup, four resistors are interconnected and amongst these, one is employed as a sensing resistor which undergoes changes owing to variable conditions. An input voltage is supplied across two specific points, or junctions, that are distinctively separated by these resistors. Subsequently, the voltage drop that happens across the two remaining junctions [10].

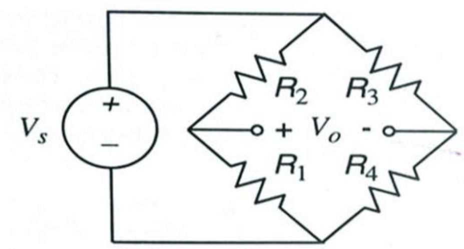


Figure 2 Wheatstone Bridge

$$Vo = \frac{R1\ R3 - R2\ R4}{(R1+R2)(R3+R4)}$$

Equation 6 Wheatstone Bridge Output

In Wheatstone bridge circuit the unknown resistor is compared with well-defined resistors, making it suitable for detecting slight changes in resistance. Wheatstone bridge circuit can help in reducing noise and thermal effects [10]. It's important to highlight that the signal produced by a Wheatstone Bridge is analog.

The majority of signals utilized in the fields of science and engineering, such as varying voltages over time, are analog. This is the primary reason why ADC and DAC are employed, as they enable digital computers to interface with these signals. The process of changing an analog signal to a digital one involves two critical steps called sampling and quantization.

Sampling is the act of taking samples from the analog signal to change it from continuous time to discrete time. The frequency at which sampling occurs is dictated by the Shannon sampling theorem or also called the Nyquist Sampling theorem. This theory suggests that for accurate sampling of a continuous signal, the frequency of sampling should be double the highest frequency in the analog signal. The usage of sampling frequency that doesn't follow the theorem will cause a phenomenon called aliasing which will make the reconstruction of the signal impossible [11].

Quantization is the process of turning signal values from a continuous value into discrete values. If we have a signal with values ranging from -1 to +1, the specific value of a sample could be anything within this range, presenting an infinite number of possibilities. This potentially infinite precision can cause a quantization error, which is typically the addition of a certain degree of random noise. Any given sample can have an error of up to ± the least significant bit. The resolution of an ADC is the number of bits it uses it significantly influences the quantization error. As the number of bits rises, the precision improves, reducing the potential error [11].

Infinite impulse response (IIR) filter is used in BME680. It is used to suppress disturbances without causing more work load on the processor or causing additional interface traffic. It also reduces the bandwidth of the temperature and the pressure output signals and increases the resolution of output data to 20 bits. It is also important to mention that humidity and gas value inside sensor doesn't fluctuate rapidly and doesn't need low pass filter. The output of a next measurement in the sensor is filtered using the formula:

$$Xfilt[n] = \frac{Xfilt[n-1] * (c-1) + Xadc}{C}$$

Equation 7 IIR Filter

Here:

Xfilt[n]: is data coming from current filter memory

Xadc: is the data coming from the current ADC

Xfilt[n]: new value of filter memory and the value that will be sent to output registers

C: filter constant

Filters are a very important part in digital signal processing. The Filters have two main uses: signal separation and signal restoration. Signal separation is used when the signal is affected by interference, noise or other signals. Signal restoration is used when the signal has been distorted.

These filters can be analog filters or digital filters. Analog filters are cheap, fast and have a large dynamic range. On the other hand, digital filters have a huge superiority in performance.

2.1.3 Altitude Measurement

Altitude is a crucial parameter in a variety of human activities, most notably aircraft navigation. The safe and efficient operation of global air traffic relies heavily on accurate altitude measurements for route planning and maintaining secure air connections [12]. Altitude is the height of object or a point in relation to sea level [13].

The International Standard Atmosphere (ISA) describes how atmospheric pressure, temperature, density, and other atmospheric properties change with an increase in altitude under standardized conditions. It's observed that atmospheric pressure steadily declines as altitude increases [14].

We can express this relationship using the following formula:

$$H = \frac{T}{\tau}\left[1 - \left(\frac{P}{P0}\right)^{\frac{R\tau}{gM}}\right]$$

Equation 8 Altitude

Here:

H: altitude

T0: standard temperature at sea level (288.15 K)

L: standard temperature lapse (0.0065 K/m)

P: Atmospheric pressure at the altitude h

P0: Atmospheric pressure at the sea level (101325 Pa)

R: ideal gas constant (8.31447)

g: gravitational acceleration (9.8 m/s^2)

M: molar mass (0.0289644 kg/mol)

This equation provides an accurate approach to calculate the barometric altitude

But it has limitations, for example the temperature lapse rate is considered as a constant which might not be accurate, especially for high altitudes, such as in commercial planes. In reality, the temperature does not decrease in a linear manner as suggested by the temperature lapse rate [15].

2.2 Communication Protocols

Communication protocols are just a set of rules that define how should the device communicate with each other [16].The BME680 supports I2C and SPI communication protocols. Both of them are serial protocols which mean that data is sent bit by bit, also both of them are synchronized which means there is a clock in each of them.

2.2.1 Inter Changed Circuit

The Inter-Integrated Circuit (I2C, pronounced “I Squared C”) is a unique, highly efficient means of connecting microcontrollers with numerous peripheral devices, such as sensors, memory devices, and digital converters [17].This innovation made its debut under Philips and has since become a widely utilized standard in the semiconductor industry due to its versatility and efficiency [18].

One of the standout features of I2C is its suitability for instances of short-distance communication between devices. The protocol allows for the connection of low-speed peripherals to an embedded system or motherboard [18].

Where traditional methods of data transfer would require 8 pins or more, the I2C system achieves the same outcomes with just two pins. These two pins, known as SCL (Serial Clock) and SDA (Serial Data), are instrumental to the operation of I2C. The Serial Clock (SCL) is utilized to synchronize the data transfer between devices, while the Serial Data (SDA) is responsible for the actual transmission and reception of data [18].

The innovative use of just two communication lines in I2C has several significant benefits. Notably, it leads to a reduction in power consumption and device size. This streamlined approach proves particularly ideal for applications where space and power are major constraints. The fewer number of lines minimized power usage, and reduced system complexities all contribute in increasing the overall system efficiency [18].

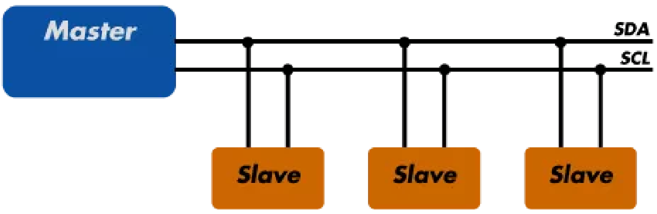


Figure 3 I2C Bus

Devices using the I2C protocol utilize usage of bidirectional open drain pins for both data transmission and synchronization. Each bus line in the I2C setup only necessitates a single 4.7 K Ω pull-up resistor. This type of configuration allows all devices to be linked as if by an AND gate logic. As per this logic, the default state of the line is high. Therefore, for a low to be transmitted, just one device needs to signal a low. Conversely, when none of the devices are signaling a low, the line retains its high state [18].

The I2C bus is capable of accommodating up to 120 unique devices, with every individual device referred to as a node. Within the I2C architecture, each node functions either in the capacity of a master or a slave [18].

The master node has two key duties. It is in charge of generating the system clock and also concluding any transmission. On the other hand, the slave node operates as a recipient of the clock and responds when summoned by the master node [18].

In an I2C system, it is important to note that both master nodes and slave nodes are equipped with data transmission and reception capabilities [18].

The operational modes within the I2C protocol are classified into four distinctive types: Master Transmitter, Master Receiver, Slave Transmitter, and Slave Receiver. Every node could potentially be in any one of these four modes at varying time periods, although they operate in only one mode at any given instance [18].

2.2.2 Serial Peripheral Interface

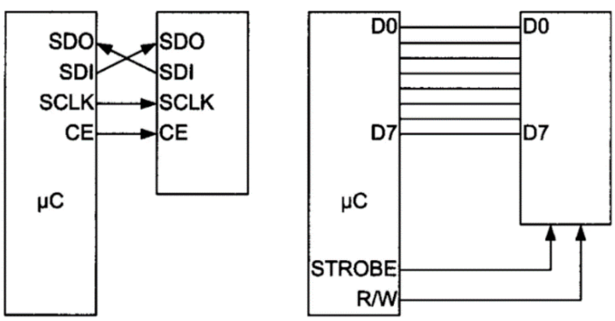
The Serial Peripheral Interface (SPI) is a bus interface connection that's incorporated into a wide variety of devices, including Analog to Digital Converters (ADC), Digital to Analog Converters (DAC), and Electrically Erasable Programmable Read-Only Memory (EEPROM). Developed by Motorola Corp. in the mid-1980s, the SPI is now widely adopted by many semiconductor chip corporations [18].

SPI devices have revolutionized data transfer by using only four pins: SDI, SDO, SCLK, and CE [17]. This is a significant improvement over the traditional method which requires the use of 8 pins or more. These four pins significantly reduce power consumption and package size, making the SPI well-suited for applications where space and power are crucial considerations [18].

The SDI and SDO pins are utilized for data transfer where the SDO (Serial Data Out) pin sends data out of the master device to the slave device, and the SDI (Serial Data In) pin receives data into the master device from the slave. The SCLK (Serial Clock) pin generates a clock signal to synchronize data transmission between the chips. The final pin, CE (Chip Enable), is responsible for initiating and terminating the data transfer [18].

These four pins collectively grant the SPI its identity as a four-wire interface. To elaborate, these pins are also interchangeably known as MOSI (Master Out Slave In), MISO (Master In Slave Out), SCK (Serial Clock), and SS (Slave Select) [18].

Interestingly, the SPI is configurable enough to be converted into a three-wire interface by coupling a single pin for data transfer (connecting SDO and SDI together). This transformation makes the SPI adaptable, conserving more space and power without compromising its efficiency in data transfer operations [18].



The Serial Peripheral Interface (SPI) encompasses two shift registers, one in the master device and the other in the slave device. This interface is characterized by the presence of a clock generator in the master that's responsible for generating the clock for both shift registers [18].

The link between the master and slave devices is maintained through two vital pins known as MOSI (Master Out Slave In) and MISO (Master In Slave Out). Specifically, the MOSI pin connects the serial output pin of the master's shift register to the serial input pin of the slave's shift register. This connection allows data to be transmitted seamlessly from the master to the slave [18].

Conversely, the MISO pin connects the serial input pin of the master's shift register to the serial output pin of the slave's shift register. This configuration enables the slave device to send data back to the master device [18].

The master clock, generated by the master device, simultaneously provides the clock pulse to both the master and the slave shift registers [18].

One of the notable features of SPI is that the shift registers possess a size of 8 bits. This shows that after the production of 8 clock pulses, the data stored in the registers interchange between the master and slave devices. This exchange leads to the transmission and reception of the precise bit of data between the two devices [18].

3. Conclusion

Sensors have a huge importance in our world today. They exist everywhere from our homes to our work places and vehicles. They are used to make our life easier and help us do things better and faster.

BME680 is an advanced sensor designed by Bosch that can measure multiple parameters like pressure, humidity, gas and temperature in the environment. Also, its low power consumption and small size make it ideal to be used in wearables, smart homes and phones.

The pressure sensor in BME680 uses piezoresistive effect with help from Wheatstone bridge to measure and detect small changes in resistance value. The Output of the sensor is then filtered to reduce noise and fluctuations and then is changed to digital format so that the microcontroller can understand it.

The pressure sensor output can be used to measure the height or the elevation of a point from the sea level using proper mathematical equation. This deduction of altitude using pressure has some limitations with high altitudes.

The BME680 can communicate with other devices using I2C and SPI communication protocols.

4. References

[1] J. Vetelino and A. Reghu, Introduction to sensors, CRC Press, 2011.

[2] W. Fleming, "Overview of automotive sensors," *IEEE,* 2001.

[3] Q. Zhang, Y. Wang, G. Cheng, Z. Wang and D. Shi, "Research on warehouse environment monitoring system based on wireless sensor network," 2014.

[4] B. Sensortec, "BME680," Reutlingen, 2024.

[5] K. Seeger, Semiconductor Physics, 9th ed.

[6] J. Bird and C. Ross, Mechanical Engineering Principles, 3rd ed., 2015.

[7] P. P. Benham, R. J. Crawford and C. G. Armstrong, Mechanics of Engineering Materials, 2nd ed.

[8] R. C. Dorf, The Electrical Engineering Handbook, 2nd ed.

[9] P. B. Harika and S. Kundu, "Design of MEMS-Based Piezoresistive Pressure Sensor Using Two Concentric Wheatstone bridge Circuits for Intracranial Pressure Measurement," 2022.

[10] R. A. Rahim, A. N. Nordin, N. A. Malik, B. Bais, B. Y. Majlis and R. A. Rahim, "Fabrication of monolithic Wheatstone bridge circuit for piezoresistive microcantilever sensor," 2015.

[11] S. W. Smith, The scientists and Engineer's guide to Digital Signal Processing, 2nd ed., 1999.

[12] L. Gregor, L. Dražan and J. Veselý, "Aircraft altitude used for atmospheric pressure determination," 2015.

[13] "Definitions of elevation, height and altitude," Wellington, New Zealand, 2014.

[14] I. Ostroumov, N. Kuzmenko and O. Kyzymchuk, "Estimation of Geodetic Altitude from Barometric One with Actual Meteorological Aerodrome Report Data," 2022.

[15] M. Simonetti, "Modeling of Barometrict Measurements to support Geodetic Altitude Navigation," Institute for Communications and Navigation, Munich Germany , 2021.

[16] A. S. TANENBAUM and D. J. WETHERALL, COMPUTER NETWORKS, Pearson, 2011.

[17] S. Monk, Programming Arduino Next Steps, McGraw-Hill Education, 2019.

[18] M. M. Mazidi, The 8051 Microcontroller A Systems Approach, 1st ed., Pearson, 2014.

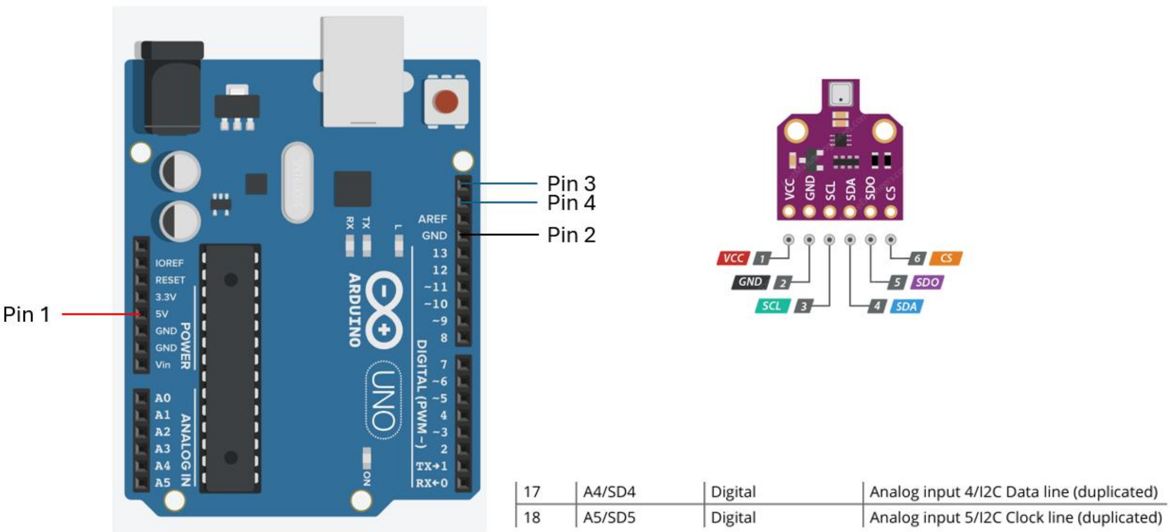
5.Appendices

5.1 Code for Arduino UNO R3 with BME680

```
/****************************************************************************
* Project : Measuring Altitude using BME680
* System : Arduino UNO R3
* Author : Asser Soliman
****************************************************************************
* Description
* This is a project in which we connect enviromental sensor BME680 with
* Arduino UNO R3 using I2C communication protocol and read pressure data
* which then can be used to get altitude using proper equation
***************************************************************************/

/******************** Includes Section Start ********************/
#include <Wire.h>
#include <SPI.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_BME280.h>
#include <LiquidCrystal.h>
/******************** Includes Section End ********************/

/******************** Definition Section Start ********************/
#define SEALEVELPRESSURE_HPA (1013.25)
/******************** Definition Section End ********************/

/******************** Variables Section Start ********************/
Adafruit_BME280 bme;
/******************** Variables Section End ********************/

/******************** Functions Section Start ********************/
void printValues()
{

  Serial.print("Pressure = ");
  Serial.print(bme.readPressure() / 100.0F);
  Serial.println(" hPa");

  Serial.print("Approx. Altitude = ");
  Serial.print(bme.readAltitude(SEALEVELPRESSURE_HPA));
```

```
  Serial.println(" m");

}
/******************** Functions Section End ********************/

/******************** Setup Section Start ********************/
void setup()
{
  Serial.begin(9600);

  while(!Serial);
  status = bme.begin(0x76);

}
/******************** Setup Section End ********************/

/******************** Loop Section Start ********************/
void loop()
{
    printValues();
    delay(2000);
}
/******************** Loop Section End ********************/

```

5.2 Hardware Connection Using I2C



17	A4/SD4	Digital	Analog input 4/I2C Data line (duplicated)
18	A5/SD5	Digital	Analog input 5/I2C Clock line (duplicated)

Figure 5 Arduino with BME680