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Automated Arduino Based Temperature Control and Resistance Change Reading System for Gas Sensors

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AUTOMATED ARDUINO BASED TEMPERATURE CONTROL AND RESISTANCE CHANGE READING SYSTEM FOR GAS SENSORS

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ABSTRACT

Semiconductor gas sensors detect gases by a chemical reaction that takes place when the gas is in contact with the sensor and sensitivity is affected by operating temperature and humidity. The accurate control of gas sensor's operating temperature is a fundamental aspect that determines the sensitivity and selectivity of gas sensors. A variety of gas sensors are developed so far, and each has different working temperature requirement ranging from 200°C - 400°C for functioning at the finest. This research mainly focuses on the package design criteria of semiconductor gas sensor substrate being developed by Arizona State University. To maximize the sensor's sensitivity, stability, and accuracy; the package design needs to regulate the gas sensing material at a preset temperature of 200°C using automated temperature control system. To achieve these requirements, we developed a system that contains a microcontroller, micro-heater, and temperature control circuit with temperature sensors(thermocouples) to control the temperature measurement and read the resistance change of the gas sensor using Proportional Integral Derivative (PID) Controller algorithms. This paper proposes an invention of smart package design for gas sensor technology. It uses the Arduino microcontroller for processing and controlling the circuit operation and PID controller algorithm to automatically control the temperature by using PWM control of the metal ceramic heater and temperature sensor. This technology utilizes the principle of Wheatstone bridge to read the resistance change of the gas sensor and used an instrumentational amplifier (INA125P) to amplify the voltage reading from the circuit. In

addition to the sensor’s performance, the designed package considers low-cost fabrication, portability, energy consumption and regulation of low voltage for operation.

DEDICATION

This thesis is dedicated to God and all the people who helped and supported me to accomplish my goal.

ACKNOWLEDGMENTS

First, I would like to thank my academic advisor, Dr. Hai Xiao for believing in me and giving me the opportunity to work in his lab. This master's degree could not be achieved without his kindness and support. Second, I would like to thank Dr. Hongxin Hu and Dr. Harlan Russell for being my committee members, all Clemson's ECE faculty and staff especially Dr. Richard Brooks, Courtney Honeycutt, Jennifer Gooch, and students in my research lab for supporting me in many cases. Third, I would like to thank my family and friends who supported me throughout this journey.

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Chapter 1

Introduction

Gas sensor is a device that measures the concentration of gases in the environment. The key elements of gas sensors for representing its performance are sensitivity, selectivity, response time, stability, fabrication cost and energy consumption. Sensitivity is one of the major performance metrics for the gas sensor as it measures the change in measured output signal per gas concentration unit. Higher sensitivity is the preferred attribute while designing gas sensor. Selectivity is the ability of the gas sensor that determines if the sensor can react to particular group of gases or a specific gas. Response Time is the time required by the sensing material to respond to one step concentration and to modify the output from zero to a certain concentration value [1]. Stability, on the other hand, is the most important attribute in making gas sensor as it helps to overcome the effects of disturbances and attain an equilibrium state.

For this project, we focused on the design criteria of semiconductor gas sensors. Tin dioxide (SnO_2) is a common material used in semiconductor gas sensor, and its resistance is about 50kΩ. This resistance will change when it is in contact with some gases and this change in resistance is used to calculate the gas concentration. For instance, SnO2 will drop to 3.5kΩ when it is in contact with 1% methane. Semiconductor gas sensors are usually used to detect H_2, O_2, CO and alcohol vapor and their working temperature range from 200°C to 400°C. Since the sensitivity and selectivity of those sensors are highly affected by operating temperature, our design focused on maintaining the accurate temperature for gas sensors. Additionally, lower cost fabrication price, stand-alone functionality, and energy consumption are the other important features we considered while working with the design package.

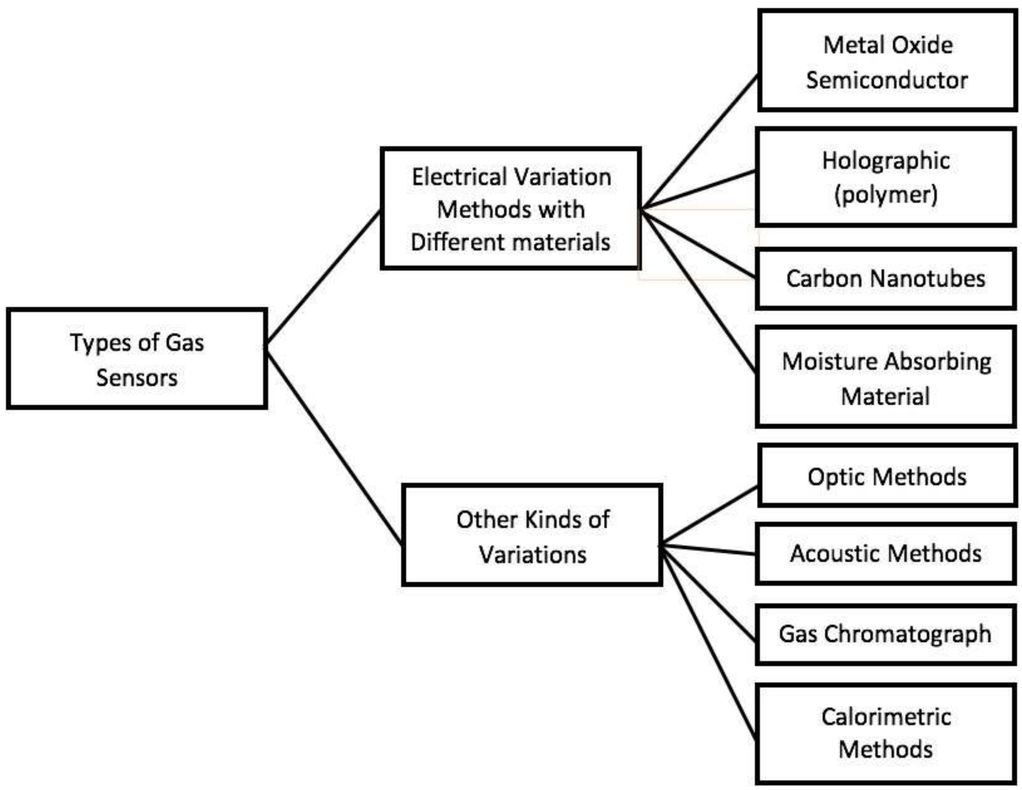

Figure 1: Types of Gas Sensors [30]

1.1 Background

Gas sensors identify the presence of unique type of gases in an environment. They are beneficial to protect the safety of the atmosphere, usually in a lab setting where the use of various gases is fundamental for research purposes. Moreover, mostly these gases might be harmful to human beings and animals; therefore, gas sensors play a major role in detecting and notifying the users about the presence of these particular gases.

As shown on Figure 1, gas sensors are classified based on the kind of gas they detect (toxic, flammable, combustible, gas leak, oxygen depletion), their operation mechanism (semiconductors, oxidation, catalytic, photoionization, infrared, and so forth), and their portability. Type of gases includes Infrared point sensors, Combustible gas sensors, Photoionization sensors, Ultrasonic sensors, Electro Chemical gas sensors, and Semiconductor gas sensors. Also, these sensors are used in a wide range of applications such as monitoring of combustible gases [25], preventing fires by detecting gas leaks [29] and flammable gases, identifying solvents in a reaction, etc. These sensors are mostly found in industry, in a lab for research purposes, plants, manufacturing, aircraft facilities, wastewater treatment facilities, homes, etc.

Electrochemical gas sensors [26] oxidize or reduce the gas by allowing it to form a contact with the electrode present in the gas sensor through a chemical reaction. Catalytic Bead gas sensors are usually used to detect combustible gases by the presence of beads on the opposite sides of Wheatstone bridge circuit and by heating up these beads the combustible compound gets oxidized, and there will be a change in resistance that can be measured to be detected. Photoionization gas sensors use UV energy to ionize the chemicals in the gas to be detected. Infrared point [27] gas sensors detect gases by using radiation that passes through the gases to be detected.

Holographic gas sensors detect polymer by using light reflection techniques. Carbon nanotubes sense various gases such as diesel fumes and ammonia. They have quick detection response time and low detection limits. A calorimeter detects the heat of a chemical reaction, heat capacity or physical change.

In Semiconductor gas sensors [28], a chemical reaction is present to detect the specific gases for which there exists a change in resistance due to the contact between the gas and the material (example: SnO_2) present in the gas sensor. On this research project, we focused on designing technology for satisfying the semiconductor gas sensors specific requirements.

1.2 Motivation

This research project is a collaborated effort among Arizona State University, Clemson University, and GEIRI. The agreement among these three organizations is as follows. Arizona State University will be developing the gas sensing material on a substrate. Clemson University will take Arizona State University material with the substrate and package it into a sensor including the heater, circuit, and Electromagnetic Interference (EMI) shielding. Arizona State University will take the packaged sensor and integrate it with the gas extraction unit, and GEIRI will facilitate the system testing and tech transfer.

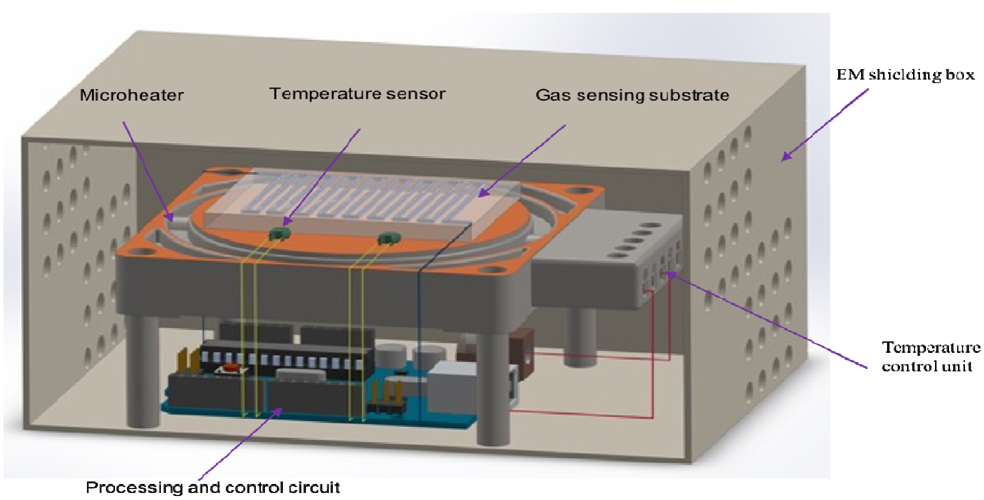

Figure 1.2: Proposed Package Design for the Gas Sensor

We want to design a package that is identical to the design Figure 1.2 as our ultimate goal. We want to design a technology that integrates processing and control circuit to monitor the temperature sensors and temperature control unit, the gas sensing substrate, and the micro-heater using Electromagnetic shielding box.

The package design criteria for the gas sensor possess three basic requirements specified as follows. First, to maximize the sensor sensitivity, we need to optimize the interaction (surface areas) of the gases with the nanostructured gas sensing materials (semiconductors). Second, to maximize the sensor stability, we need to maintain the gas sensing material at preset temperature using automated temperature control and third, to enhance the sensor accuracy, we need to minimize the noise and interference. Based on these standards, we designed the temperature monitoring and resistance change reader package for the gas sensor using automated micro-heater and N-Channel MOSFET transistor, temperature control circuit (MAX31856) and thermocouples, Arduino microcontroller, Wheatstone Bridge and INA125 Instrumentation Amplifier and the principle of PID controller algorithm.

1.3 Arduino Microcontroller

Arduino is an open source platform based on user-friendly hardware and software. Arduino hardware refers to Arduino boards that use variety of microprocessors and controllers equipped with multiple digital and analog input/output (I/O) pins interfaced to various expansion boards (shields) such as Ethernet shields, GPS Logger shield, and

Wireless communication shields for several applications. On the other hand, the open-source Arduino software (IDE) makes it easy to write code and upload it to the board. The software can be used by any Arduino board and uses C/C++ programming language.

Arduino continues to be extensively used platform primarily for simple projects and complex scientific experiments and for applications of products of IoT applications, wearable, 3D printing, and embedded environments. Its simplicity, open-source, easy-to-use and flexibility attributes for beginners as well as for advanced users make it a suitable electronic platform for students, teachers, and researchers. Additionally, Arduino has several advantages over other existed microcontrollers. Most of the Arduino boards are a low-cost module that costs less than $50. The other advantage of Arduino is its cross-platform. Most microcontroller systems are limited to a specific operating system; however, Arduino software (IDE) runs on Windows, Mac OS, and Linux operating system. For this project, we used Arduino Uno board to perform analog and digital signal processing and transmission.

1.4 Theory of Wheatstone Bridge

For several sensors, a fundamental change in the sensor is a change in the resistance. For instance, in thermistor (temperature sensor), the resistance is dependent on the temperature. Thermistors are divided into two types. Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC). With NTC, resistance decreases as temperature increase and in the case of PTC, resistance increases as temperature increases. Similarly, on this research, the Wheatstone bridge is used to read the resistance change of the gas sensor with an instrumentational amplifier to amplify the voltage reading.

Variable low resistance measurements are usually needed for research purposes such as to study sensor applications and to measure such unknown resistance; we use electrical circuits such a Wheatstone bridge. Wheatstone Bridge is a simple circuitry used to measure the resistance of unknown resistor value by comparing it with the values of known resistors. As illustrated in Figure 1.4, a Wheatstone bridge is a circuit setup of four resistors arranged in a diamond shape. In which three of the values of the resistors (R1, R2, R3) are known and one resistor has an unknown value (usually a variable resistor R4), and the resistors are connected to a voltage supply terminal (Vs). On this research, this electrical circuit is particularly used because of its simplicity and ability to measure accurate resistance precisely. By measuring the unknown resistance, we can convert the resistance change into a voltage change to make a voltage measurement.

How Wheatstone Works? When R1 and R2 have the same value on the left side of the bridge and, R3 and R4 have equal value on the right side of the bridge, the voltage reading at point C will be equal to the voltage reading at point D. In this case, the voltage difference (ΔV) is zero, and this condition is called balanced situation.

On the other hand, when the value of R4 is changed, the voltage at point D will have a different value, thus ΔV will have a new value other than zero and this circumstance is known as an unbalanced situation.

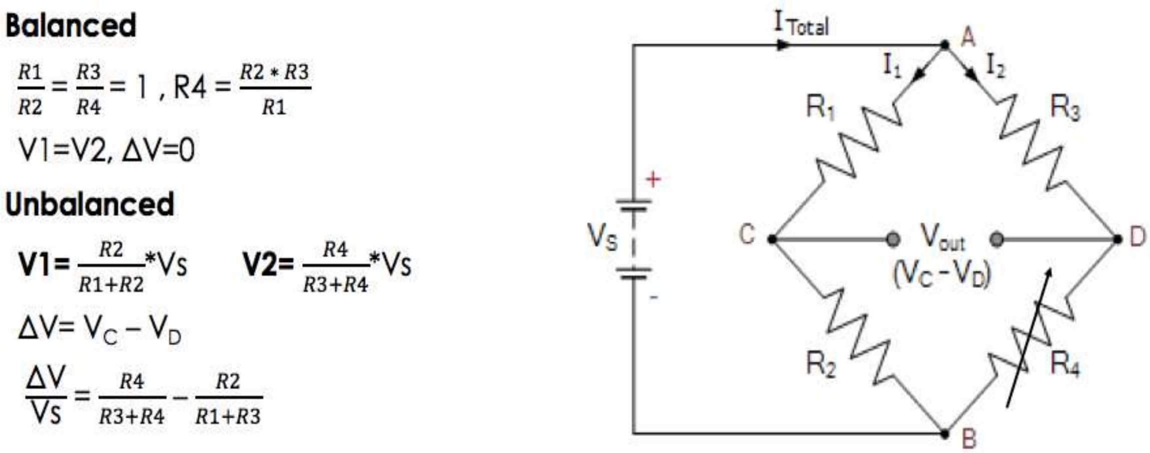

Figure 1.4: Wheatstone Bridge

1.5 INA125 – Instrumentation Amplifier

INA125 is the instrumentation amplifier that is used for our system. This amplifier uses low power, a precision voltages of 2.5V, 5V, or 10V and provides complete bridge excitation and precision differential-input amplification on a single integrated circuit. INA125 has two options for power supplies. It can be operated either on a single supply (+2.7V to +36V) or dual (±1.35V to ±18V) power supplies. In INA125, a single external resistor can set a gain between 4 to 10,000. As this chip is laser-trimmed for low offset voltage (250μV), and low offset drift (2μV/°C), and due to its high common-mode rejection ratio (100dB at G = 100) feature, it is a widely-used amplifier for industries, factory automation, and general purpose instrumentation.

INA125's reference voltage is accurate to ±0.5% (max) with ±35ppm/°C drift (max), and the Sleep mode is used to shutdown and save power at duty cycle operation.

As shown on Figure 1.5, this chip has 16-pins, and each of them has different purposes. This instrumentation amplifier is excellent when used with Wheatstone bridge to amplify small voltage reading in sensor application.

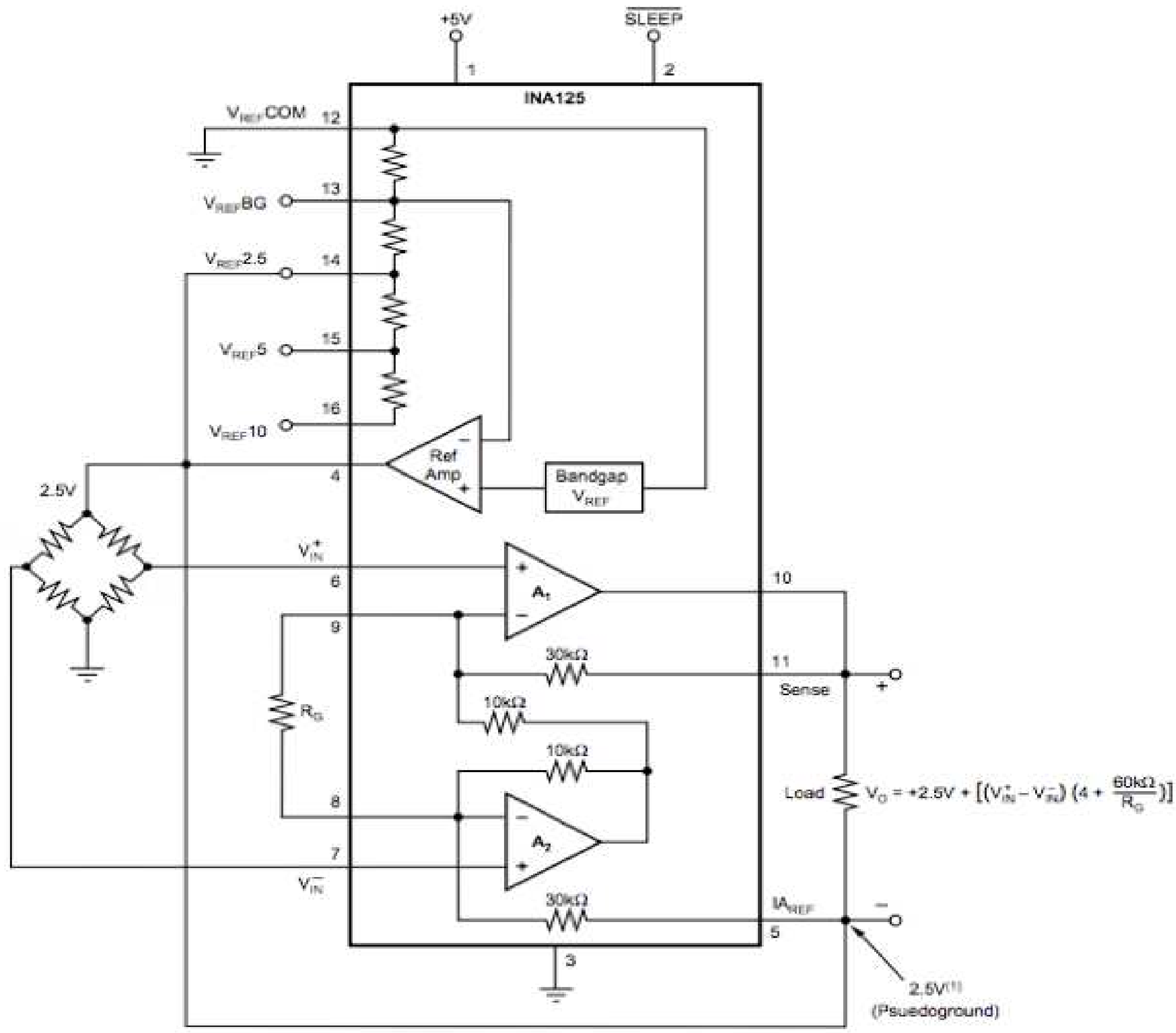

Figure 1.5: INA125 – Instrumentation Amplifier Circuit

1.6 N – Channel MOSFET Transistor

N - channel MOSFET transistor is one of the fundamental types of transistor used in heater control section of the circuit and can be used to switch a lot of power, over 60A of current and 30V voltage. Since N - channel MOSFET are packaged in TO-220, heat sinking is easy and also can fit into any breadboard. However, due to very low RDS(on), heat sinking can be avoided for high loads, and the T0-220 package for this transistor can dissipate up to 2Watts of power without heat sink to switch at least 15A of current. As the threshold voltage of this type of transistor is low, direct control from microcontroller running on 2.8V, 3.3V or 5V logic is possible. This transistor can be applied to inverter application, high-frequency synchronous buck converters for computer processor power and high frequency isolated DC-DC converters with synchronous rectification for telecom and industrial use.

1.7 MAX31856 – Thermocouple Amplifier

MAX31856 is a universal thermocouple amplifier chip used with the thermocouple and provides high accuracy thermocouple temperature readings. This chip includes automatic linearization correction for eight thermocouple types (K, J, N, R, S, T, E, and B). It is also useful to read the internal temperature reading of the microcontroller interfaced and can be protected against overvoltage conditions up to ±45V. The output data from MAX31856 is formatted in degree Celsius, and this converter resolves temperatures to 0.0078125°C, allows readings as high as +1800°C and as low as -210°C (depending on thermocouple type). For fault detection processes, line frequency filtering of 50Hz and 60Hz is included in the SPI compatible interface along with a selection of thermocouple type.

The MAX31856 amplifier has a broad range of application for temperature controllers, as industrial equipment in industrial ovens, furnaces, and environmental chambers. As illustrated in the Figure 1.7, MAX31856 has 14 pins: AGND, BIAS, T-. T+, AVDD, DNC, DRDY, DVDD, CS, SCK, SDO, SDI, FAULT, DGND.

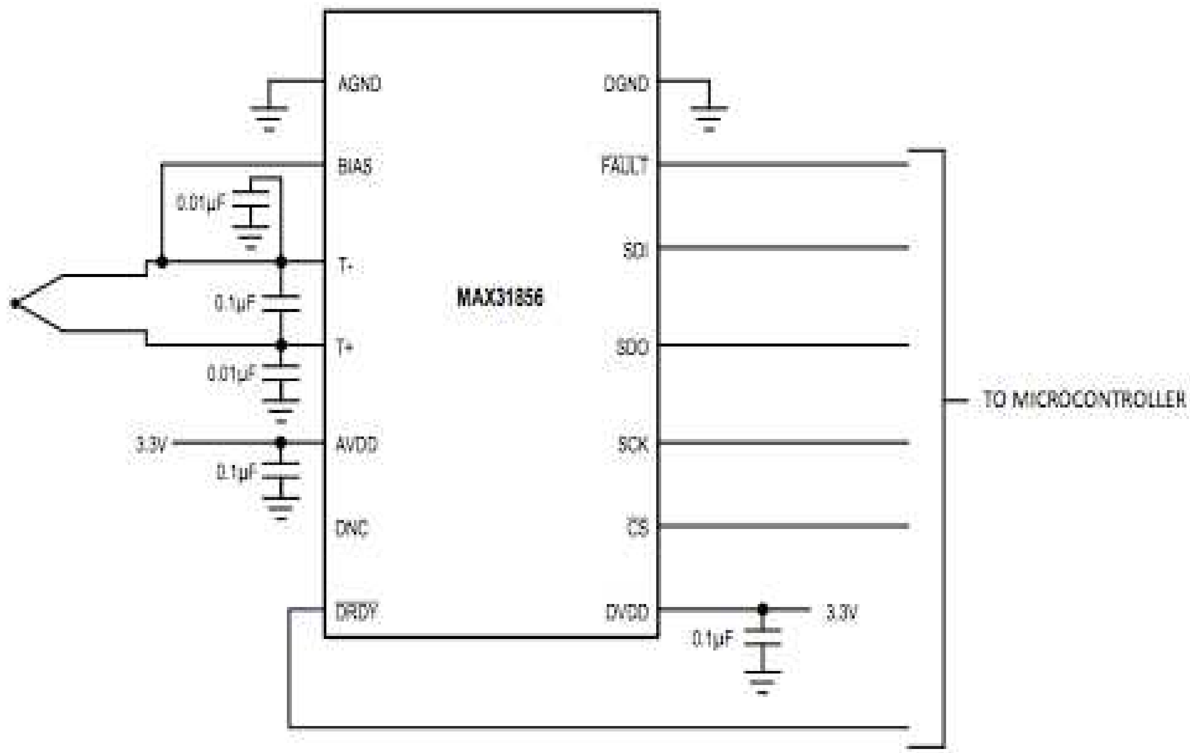

Figure 1.7: MAX31856 – Thermocouple Amplifier Pins

1.8 PID Controller

Proportional Integral Derivative (PID) Controller is a control loop feedback mechanism commonly used in an industrial system. PID continuously calculates the error value e(t) as the difference between desired set point and measured variable (input) and applies a correction based on proportional, integral, and derivative terms. The controller attempts to minimize the error value overtime by adjusting the output. The four major parameters in PID algorithm are Input, Output, Set-point and Tuning parameters. Input is the variable we are trying to control. The output is the variable that will be adjusted by PID Controller. Set-point is the desired value we want to maintain, and the tuning parameters (Kp, Ki, Kd) are the parameters that dictate the dynamic behavior of the PID and affect how PID will change the output through time.

PID implementation is performed in three basic step. First, tell the PID what to measure ("the input") and in our case, it is the temperature reading from thermocouples. Second, tell the PID where that measurement should be ("the set point) and third, choose the correct tuning parameters. Consequently, the PID will subtract the measurement from the desired set-point to calculate e(t) and adjusts the output by trying to make the input equal to set point.

1.9 PID Tuning Parameters

There are three tuning parameters in PID controller algorithm known as Proportional, Integral, and Derivative. Proportional produces the output value that is proportional to the current error value. This parameter is responsible for correcting the present values of the error, and if the error is significant and positive, the control output will also be large and positive. Too high proportional gain makes the system unstable. The second one is Integral, which is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. An Integral parameter is responsible for the past values of the error and is proportional to both magnitude and duration of the error. The other parameter is Derivative, which predicts the system behavior and improves the settling time and stability of the system. The Derivative is accountable for the possible future trends of the error based on its current rate of change.

1.10 Organization

The outline of this thesis is as follows: Chapter 1 introduces the motivation behind this project, introduction of the design, Arduino microcontroller, Wheatstone bridge and PID controller algorithm. Chapter 2 discusses the related works that have been done and the existing solutions similar to our design goal. Chapter 3 describes the system design and methodology. It also includes the components used and their specification, system's block diagram, system's circuit diagram and PID manual tuning method. Chapter 4 presents the actual setup and the PID implementation results with their performance analysis and limitations. Chapter 5 concludes and summarizes the overall system with discussion and future work.

Chapter 2

Related Work

2.1 Gas Sensors Study Discussions

A research paper on Application of Temperature Modulation for MOS Gas Sensors mentions that modulating the working temperature of a gas sensor improves the sensitivity and selectivity [31] due to the change in kinetic of the gas sensor when the temperature is altered. This is because when the working temperature is optimized, the working voltage will also be changed periodically. So, the sensor's temperature is also determined by the voltage applied across the heater.

There has been an increasing concern regarding the development of gas sensors especially semiconductor gas sensors. This is because of their ability to monitor and detect harmful gases such as carbon monoxide (CO) and methane (CH_4). The need to detect toxic gases has evolved into detecting greenhouse gases that cause global warming [20]. There are common materials used in the semiconductor gas sensors such as tin–oxide, tungsten–oxide, or indium–oxides to form a reaction with the gases to be detected [24]. These materials are operated at an elevated temperature of 200 °C–400 °C. The gas sensors are being exploited at the temperatures as mentioned above for the fact that the oxides show resistance changes when operated at those temperatures. Nowadays, gas sensors are integrated with microcontrollers to develop smart gas detectors.

2.2 Existing Solutions

Most gas sensors require their system to be set at a certain temperature level to function and become sensitive enough to sense the respective gases [4]. This situation is the reason why most researchers focused on fabricating stable and sensitive temperature controllers for their corresponding sensors. The optimal temperature for the gas sensors developed in some research studies is maintained by usually embedding a heater on the gas sensor [4].

Accurate control of gas sensor's operating temperature is a fundamental problem in gas monitoring system [5] as the heating characteristics determine the sensitivity and selectivity of the gas sensor. Thus, there are several research studies conducted regarding with the temperature control system of the gas sensor. However, these systems employ various fabrication mechanisms and are not optimized for an individual sensor [5]. This situation limits the usage of the temperature controller with other gas sensors as the temperature controller is mostly set to read or adjust a specific temperature, use a specific voltage or have a certain power consumption.

Existing solutions focused on building the temperature control system for their specific gas sensors with consideration of intended gas sensor's size, power consumption, reliability, stability, and portability. Most of them use different temperature reading techniques and heating methods. For instance, some measures the temperature using simple voltage divider circuit [3] and controls the heater either as Pulse Width Modulation (PWM) output or as an electrical heater that is responsible for measuring the temperature as a change of electrical resistance and heat the sensor by setting an electric voltage [7]. Others control the temperature by designing specific micro-heater by making copper layer strip on PCB and using etching method [6].

2.3 Summary

On this chapter, we tried to discuss the related research studies on temperature controller system for gas sensors. Even though there are several kinds of research conducted on temperature controller for various gas sensors, our system used a different circuit setup and approach which is suitable for our specific gas sensor requirement. This is because most of the existed technologies are developed for lab experiment purposes and possess fixed operating voltage and current. We used an inexpensive, simple and robust temperature sensors (thermocouples) to obtain a real-time and precise temperature reading integrated with an instant heating element (metal ceramic heater) and utilized the principle of Wheatstone bridge for resistance change reading. We also considered the size of the packaged system, the fabrication cost, stability, portability and low power consumption while designing the system.

Our system uses a PWM (Pulse Width Modulation) to control the turning on and off of the heater while using PWM effectively controls the heater it also has a disadvantage when used alone since it introduces a significant noise to the system [4]. This problem is avoided by using a PID (Proportional Integra Derivative) control by adjusting the constant correct parameters of Kp, Ki, and Kd. Using PID algorithm increases the persistence of the automatic temperature control [4].

Chapter 3

System Design & Methods

3.1 Components Used & Specifications

In this section, we introduced various components used to build the system and their specifications. Our system comprises three basic circuit modules, and as listed in Table 3.1.1, different kinds of components are used for various purposes due to certain specifications.

Components Used	Application/ Purpose
Arduino Uno (Atmel ATmega328P Microcontroller)	Heater Control, Temperature Measurement, Resistance Change Reading
Thermocouple (K-Type)	Temperature Measurement
Universal Thermocouple Amplifier (MAX31856)	Temperature Measurement
Metal Ceramic Heater (HT19R)	Heater Control
N-Channel Power MOSFET Transistor	Heater Control
Power Supply(24V)	Power up the Heater
Resistors/ Potentiometer	Wheatstone Bridge Application, Resistance Change Reading
USB Cable	Communication Interface
Instrumentational Amplifier (INA125P)	Wheatstone Bridge Application, Resistance Change Reading
Software (Arduino IDE, C++, PID Controller Algorithm)	Entire system
Others – Jumper wires, Bread Board	Entire system

Table 3.1.1: Components and Specifications

The most fundamental component used for signal processing and transmission is Arduino Uno microcontroller board, which is based on ATmega328P microcontroller. As shown in Figure 3.1, an Arduino Uno has six analog inputs and 14 digital input/output pins of which six can be used as PWM outputs. The Arduino Uno is programmed using Arduino Software (IDE). It has built in serial communication interface and USB cable that can be utilized for connection with PC and to power up the board. External power supply can also be used to power-up the board. In this project, this board is used with the thermocouple, Metal Ceramic Heater and for the application of Wheatstone bridge along with Instrumentational amplifier for measuring the temperature, controlling the heater and reading the resistance change of the gas sensor, respectively.

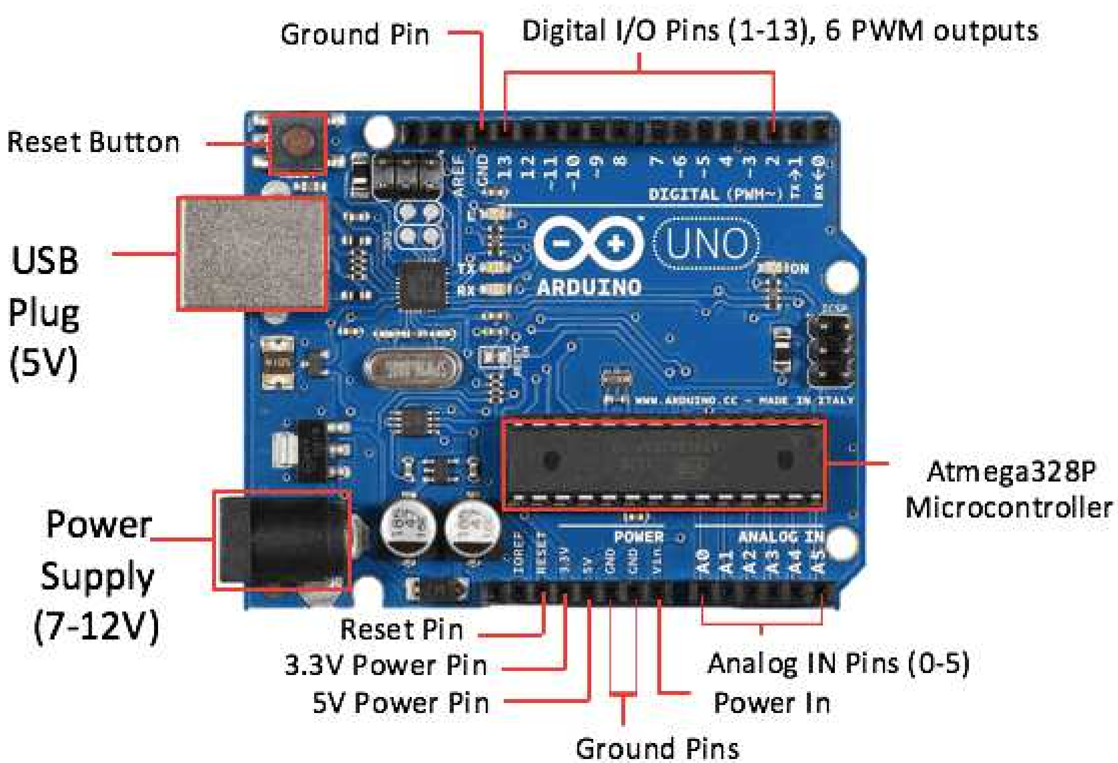

Figure 3.1.1: Arduino Uno Microcontroller Board [8]

The K-type Thermocouple and Universal Thermocouple Amplifier(MAX31856) manufactured by Adafruit are used with Arduino Uno board for measuring the temperature. K-type Glass braid insulator thermocouple as displayed in Figure 3.1.2, is a 1 meter long, 2.18 mm thick and weighs 7.18g. This thermocouple measures the temperature up to 500 ℃ (900°F) and best used with universal thermocouple amplifier (MAX31856).

Figure 3.1.2: K-Type Thermocouple Wire **Figure 3.1.3: MAX31856 - Thermocouple Amplifier [9]**

Thermocouples are very sensitive and require a good amplifier. MAX31856 board has a chip itself, 3.3V regulator and level shifting circuitry. It has an easy interface with any microcontroller and can handle K, J, N, R, S, T, E, B thermocouple types. It has internal temperature reading and can output from -210℃ to +1800℃ in 0.0078125° resolution. As shown in Figure 3.1.3, MAX31856 board's Serial Peripheral Interface (SPI) logic pins (SCK, SDO, SDI, CS, FLT, DRDY) have pin header used to plug it into any breadboard. The logic pins require four digital I/O pins for connection with Arduino. SCK (SPI Clock pin) is input to the chip, SDO (Serial Data Out) is used for data sent from MAX31856 to the processor and SDI (Serial Data In) is for data sent from the processor to the MAX31856 and CS is the Chip Select Pin. This board's FLT (Fault Output) and DRDY pins are utilized for advanced usage.

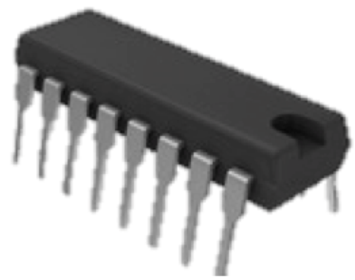

Figure 3.1.4: INA125 – Instrumentation Amplifier

For reading the resistance change of the gas sensor and apply the principle of Wheatstone bridge, we used resistors, potentiometers, and Instrumentation Amplifier (INA125P) manufactured by Texas instruments. We used three resistors each with a value of 5kΩ and one potentiometer with a value of 1-10 kΩ. Since we cannot read the resistance change directly, we convert the resistances to a voltage using Wheatstone bridge. The voltage from the Wheatstone bridge is too small to be read by the Arduino directly. Hence, we used INA125 shown in Figure 3.1.4, which is a low power, high accuracy instrumentation amplifier with a precision voltage reference of 1.24V, 2.5V, 5V or 10V. This amplifier is chosen because it has low noise, low quiescent current, low offset voltage, low offset drift, and high Common Mode rejection of 100dB. INA125 has a wide range of application for pressure and temperature bridge amplifiers, industrial process control, factory automation, multichannel data acquisition, battery operated systems and for general purpose instrumentation.

	Heater 1	Heater 2 (HT19R)
Size	18mm X 12 mm X 1.2mm (L X W X H)	23mm (Outer Diameter), 4.0mm (Inner Diameter), 1.3mm (Thickness)
Working Voltage	12 V	24 V, 12 V, 6 V
Current	5.71A - 8A	0.8 A,0.4A,0.2A
Dissipated Power	68 – 96 W	19 W $\pm$ 20%, 4.8 W, 1.2 W
Maximum Temperature	580 ^oC	400 ^oC
Resistance Change	1.5 – 2.1 Ω	30 $\Omega \pm$ 10%

Table 3.1.2: Heater Comparison

As illustrated in Table 3.1.2, we used two different kinds of heaters labeled as Heater 1 and Heater 2 (HT19R). Heater 1 uses small voltage when compared to Heater 2, but it needs to be driven by high current values of 5.71A-8A to give us the maximum temperature. It also has high power consumption which is 68-96W. HT19R on the other side uses more voltage than Heater 1 to output the maximum temperature. However, due to a higher resistance value, it can be driven by a small amount of current 0.2A - 0.8A. It also has a lower power consumption of 1.2W – 19W and this makes it preferable Metal Ceramic heater for our system.

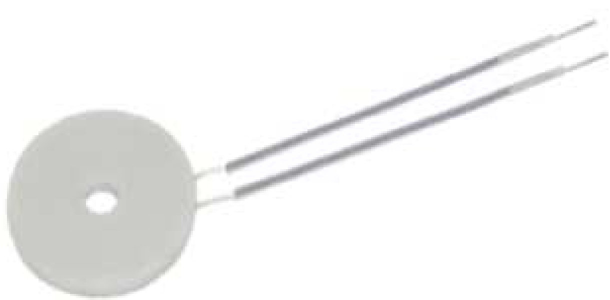

Figure 3.1.5: HT19R - Metal Ceramic Heater

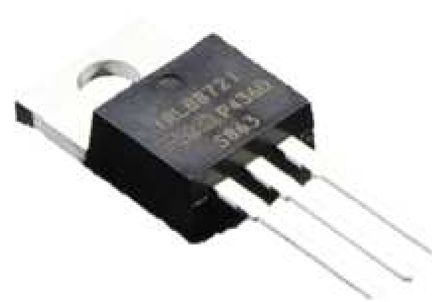

Figure 3.1.6: N – Channel MOSFET Transistor

To control the heating element of the gas sensor, we used metal Ceramic Heater (HT19R) as described in Figure 3.1.5, power supply (24V), resistor (10KΩ) and N-channel Power MOSFET Transistor as shown in Figure 3.1.6. HT19R consumes 19W at 24V, 4.8W at 12V and 1.2W at 6V. Its resistance is 30 Ω and using ohms' law; we found its current from 0.2A, 0.4A,0.8A. This heater is chosen because of its low power consumption, instant heating and its ability to heat up 400℃. Since the heater needs high operating voltage, we could not use the voltage from the Arduino. We used an external power supply that outputs 24V voltage and drives current up to 2A. Additionally, we used N-channel Power MOSFET transistor which can switch over 60A and 30V for application of PWM heat control.

3.2 Software

Arduino Integrated Development Environment (IDE) is used to write the C++ code needed to control the individual circuits, namely temperature control, heater monitoring and resistance change reading circuits. In the beginning, three parts of code were written separately for the respective circuit setups mentioned previously, and after obtaining the results, we combined the three pieces in one general source code. Arduino PID Library – Version 1.2.1 by Brett Beauregard was used to implement the PID algorithm. However, few modifications were used to fit it into our system and get the the good results. Additionally, Adafruit MAX31856 Arduino Library written by Limor Fried was used for working with the MAX31856.

3.3 System Block Diagram

On this section, we discuss the overall block diagram of the system. As shown in Figure 3.3, the three core parts of the system temperature measurement, heater control and resistance change reader with the components used are represented explicitly. The Arduino reads the temperature of the gas sensor using thermocouple and thermocouple amplifier. It also controls the heater using PWM output and MOSFET transistor. The Arduino also reads the resistance change of the gas sensor from the Wheatstone bridge and amplify it with the instrumentation amplifier. Instructions are programmed, and commands are sent using Arduino IDE and the results of those readings are displayed on PC using serial monitor and plots are shown using Arduino serial plotter.

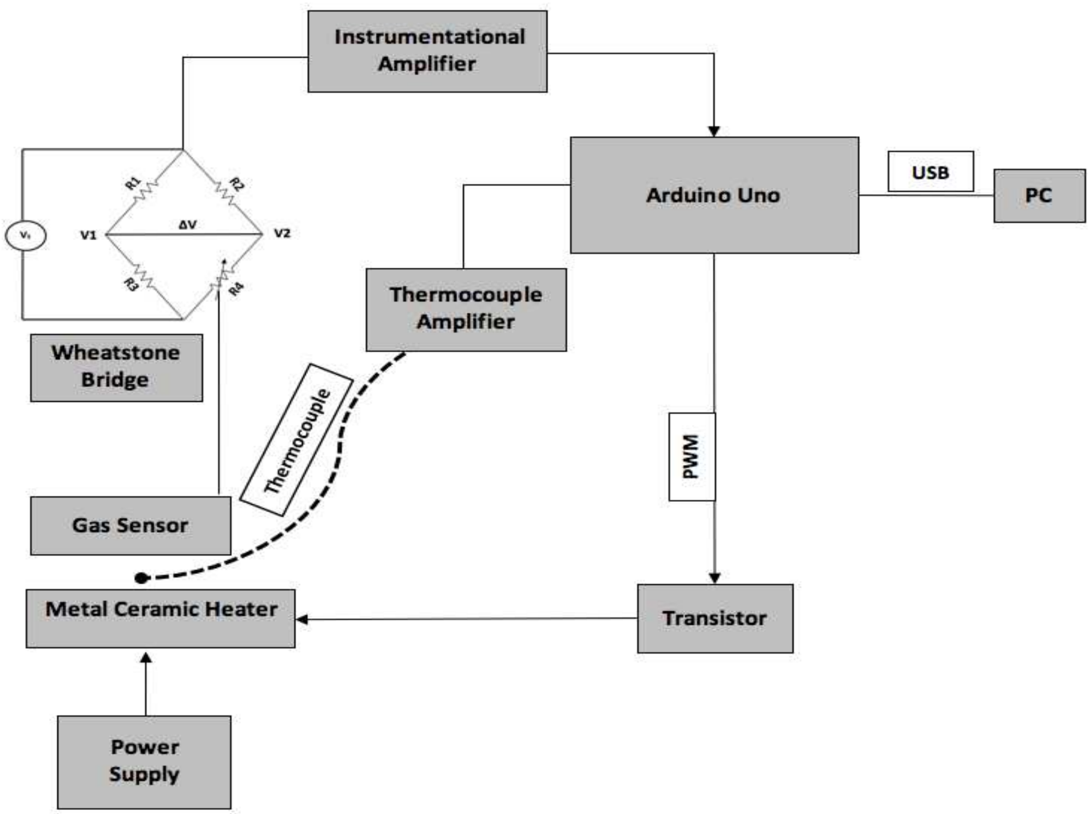

Figure 3.3: System Block Diagram

3.4 System Circuit Diagram

In this section, the system's circuit diagram is explained in detail. As shown in Figure 3.4.1, the PC is connected to the Arduino Uno through USB cable and the board encompasses three basic connections. The digital pins on the board are used to control the temperature whereas the analog pin is reading the resistance changes.

For temperature measurement section of the circuit, MAX31856 has two pin terminal blocks identified as T+ and T-, and with common-mode bias voltage provided by BIAS output, these terminals are used to connect the K-type thermocouple wires directly. On the other side of the chip, there are nine pin headers used to plug the MAX31856 to the breadboard. For SPI communication purpose, we used four pins: SCK, SDO, SDI, and CS of this amplifier that required four Digital I/O pins from the Arduino. SCK is a Serial Clock Input pin used as an input for the chip. SDO is a Serial Data Output pin used for sending data from the MAX31856 to the Arduino. SDI is a Serial Data Input pin used for receiving data from the Arduino to the MAX31856 and CS is Chip select pin used to enable serial interface when setting to low.

For the heater control part of the circuit, the Metal Ceramic Heater is driven by external voltage supply as it requires 24V, the heating element is controlled by N-channel MOSFET transistor and PWM pin of the Arduino board is used. PWM control is a method commonly used for controlling power across loads. The Gate pin of the transistor is connected to a resistor and PWM pin of Arduino. As adjusting the delay determines the duty cycle, the controlling of the pulse width be performed by using the

PWM pin of Arduino. The Drain pin is connected to one leg of the heater, source pin is grounded, and the other leg of the heater is connected to the power supply.

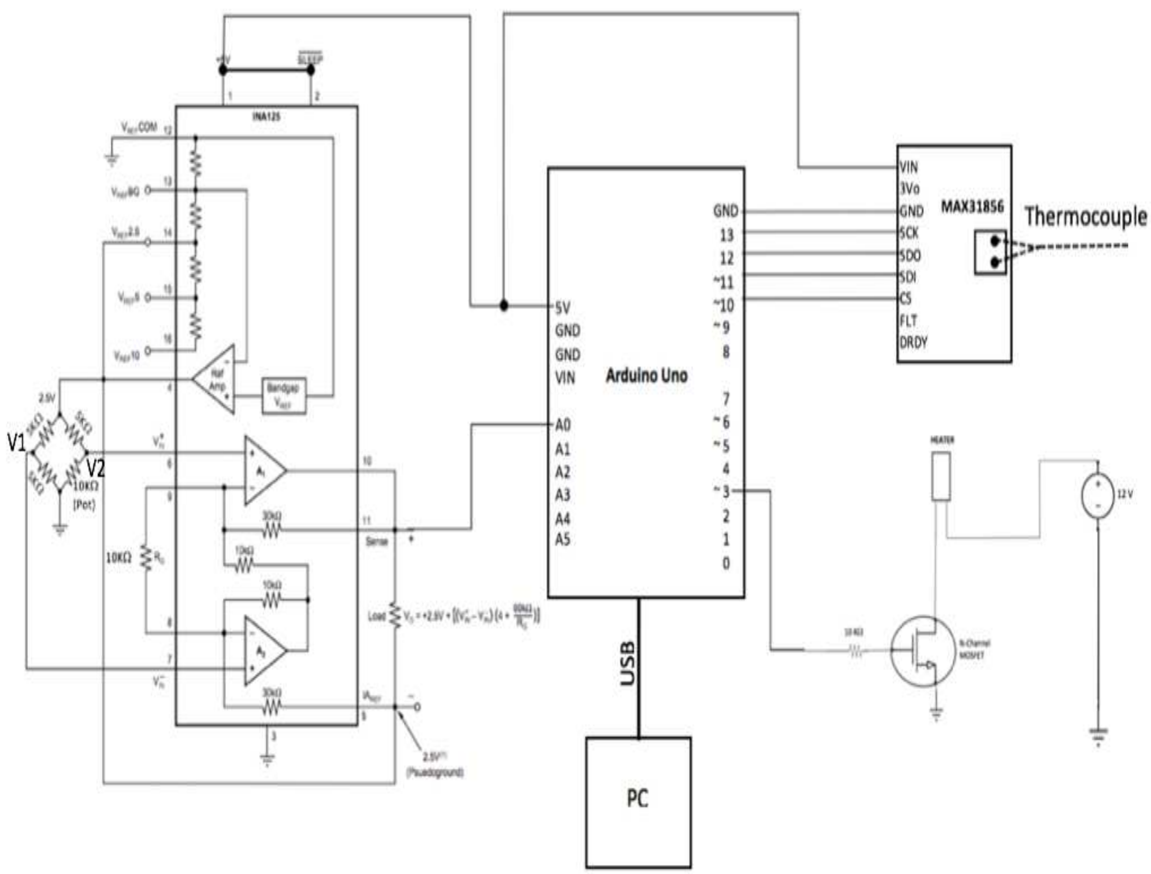

Figure 3.4.1: System Circuit Diagram

On the resistance change reading part of the circuit, the Wheatstone bridge is connected to the instrumentation amplifier (INA125), and the output from the amplifier is the analog input for the Arduino and A0 pin is used. As displayed in Figure 3.4.2, INA125 has 16 pins: V+, Sleep, V-, V_{REF}OUT, IA_{REF}, V_{IN+}, V_{IN-}, R_G, V_{REF}10, V_{REF}5, V_{REF}2.5, V_{REF}BG, V_{REF}COM, Sense, Vo, and 2 R_G pins. V+ and Sleep pins are connected to 5V of Arduino to power up the chip. The precision voltage reference provides a reference output of 2.5V, 5V or 10V on pin 14, 15, 16 respectively and reference output will be available if one of the voltages are connected to V_{REF}OUT (pin 4). V1 and V2 voltages of the Wheatstone bridge circuit are connected to the V_{IN+} and V_{IN-} pins of the chip. IA_{REF} refers to the instrumentation amplifier reference terminal, which is grounded and connected to pin 11 (sense) with a load resistance of 12Ω in series to assure excellent common mode rejection (CMR) of 80dB with a gain of 4 (G = 4). Vo and Sense are connected to output the analog voltage sent to the microcontroller. R_G is the gain resistor connected between pin 8 and 9 to set the gain. The gain is calculated using the following formula: $G = 4 + \frac{60K\Omega}{R_G}$

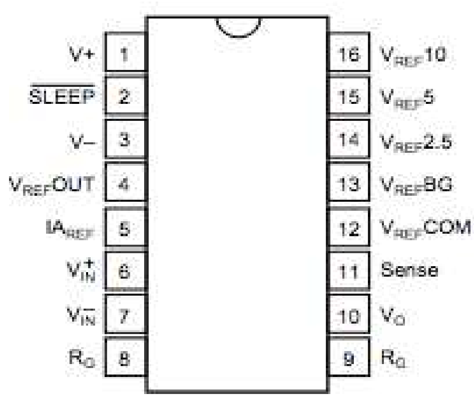

Figure 3.4.2: INA125 – Instrumentational Amplifier Pin Representation

3.5 PID Manual Tuning Method

There are several tuning methods: Manual tuning, Ziegler Nicols, Tyreus Luyben, and Cohen-coon tuning methods available while working with PID algorithm. All tuning methods have advantages and disadvantages, and for this project, we used manual tuning method. This method is helpful to find the right tuning parameters; however, it is relatively time-consuming. Manual tuning is performed using three main steps. First, set the Ki and Kd values to 0 and increase the Kp value until the output oscillates as shown in Figure 3.5.1. Second, increase Ki until the offset is corrected as depicted in Figure 3.5.2 in sufficient time and too much Ki value will cause instability. Third, increase Kd until the loop removed the overshoot and unnecessary oscillations, and at this step, the system output should be stabilized and aligned with the set-point as shown in Figure 3.5.3.

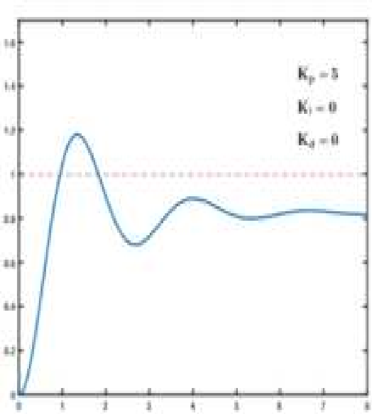

Figure 3.5.1: Adjusting K_p Value [23]

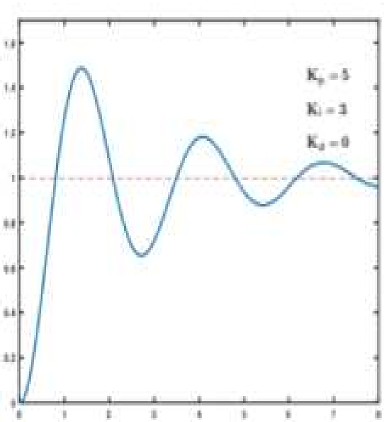

Figure 3.5.2: Adjusting K_i Value [23]

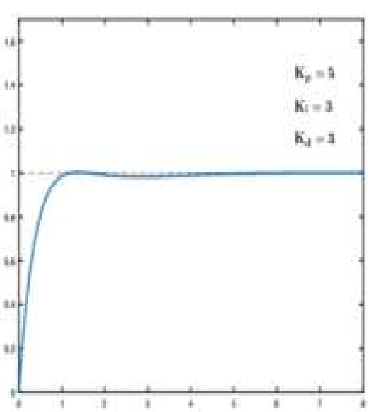

Figure 3.5.3: Adjusting K_d Value [23]

There are five basic characteristics of tuning parameters needed to be considered while working with PID algorithm. Rise time, overshoot, settling time, steady-state error and stability as illustrated in Table 3.5. Rise time is the time it takes for the output to increase beyond 90% of set-point for the first time and Kp and Ki decrease the rise time. Overshoot determines how much the peak level is higher than the steady state. Kp and Ki increase the overshoot whereas Kd decreases it. Settling time is the time it takes for the system to converge to steady state. Ki increases the settling time, yet, Kd decreases it. Steady state error is the difference between the steady state output and desired output and Kp decreases the steady state error and Ki eliminates it. Stability is the ability of the system to achieve stable state and remove unnecessary oscillations, and both Kp and Ki degrades the stability while small Kd improves the stability.

Response	Rise Time	Overshoot	Settling Time	S-S Error	Stability
K_P	Decrease	Increase	Small change	Decrease	Degrade
K_I	Decrease	Increase	Increase	Eliminate	Degrade
K_D	Small Change	Decrease	Decrease	No effect in theory	Improve if K_D small

Table 3.5: PID Manual Tuning Characteristics [21] [22]

Chapter 4

Experiments and Results

In this chapter, the actual set up of the circuit and the PID implementation results are presented in detail. The circuit is implemented on a breadboard using a microcontroller, temperature heater, metal ceramic heater and other components.

4.1 Actual Circuit Setup

The figure below shows the actual setup of our system. The resistance change reading section is denoted by the green circle in Figure 4.1. The temperature reading is shown in the yellow circle, and the red circle represents the heater control section.

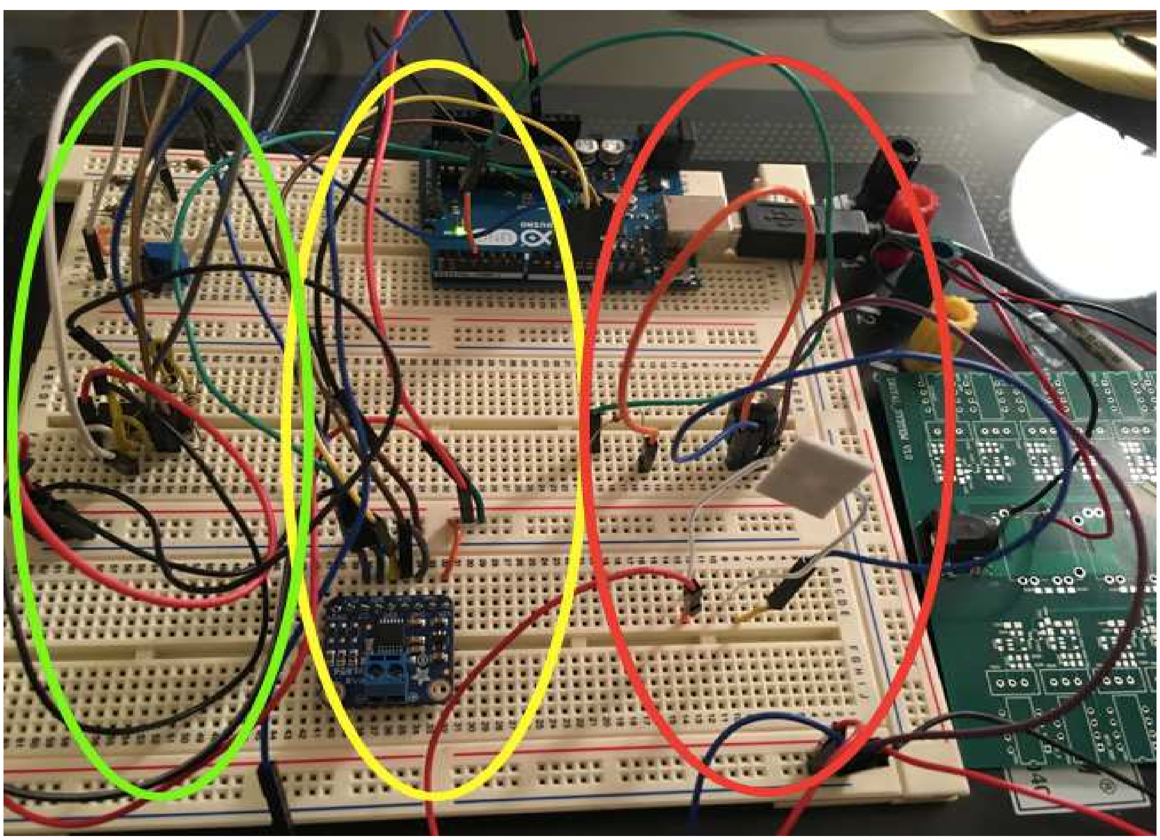

Figure 4.1: Actual Circuit Setup

4.2 PID Implementation Results

As shown in the graph below, the PID algorithm is implemented to control the system's temperature at a preset value of 200°C. The temperature control has a duration of 90 seconds to test the PID achieve and sustain the temperature of the system at the specified set point. Since the manual tuning method is utilized, various PID constants (Kp, Ki, Kd) were tested to find the perfect tuning parameters to give accurate results. Even if the manual tuning was tedious and time-consuming, we found the exact parameters needed for our system. Thus, Kp is set to 220, Ki is set to 95 and Kd is set to 301.5. As shown in Figure 4.2.1, the initial temperature of the system was 25°C, and after few seconds, the system adjusts the output based on those tuning parameters to maintain the set-point (200°C) with an offset of 1°C and 3.5°C rarely.

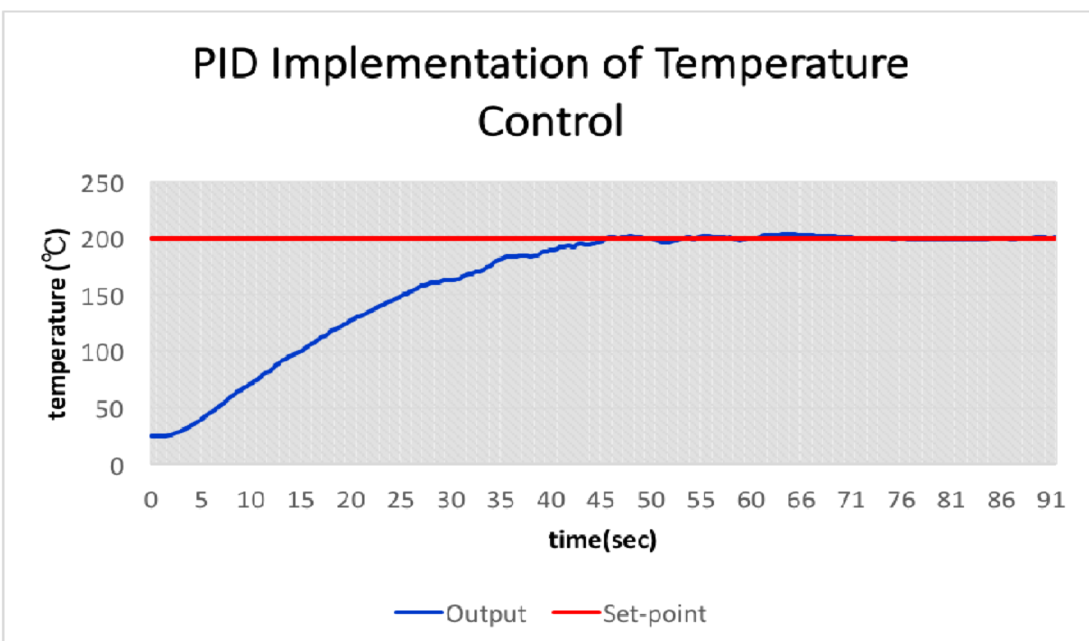

Figure 4.2.1: Temperature Control, Duration: 90 Seconds, Initial Temperature:25°C, Set- Point:200°C

The temperature control rises linearly until it is close to the set point and starts to settle once it is above 90% of the rise time. The PID algorithm uses proportional control to remove present values of the error by multiplying the error value with a proportional constant, and uses its integral value to remove the past values of the error by multiplying the sum of the instantaneous error with the integral constant and finally adjusts overshoot and unnecessary oscillations by multiplying the derivative of the error with a derivative constant.

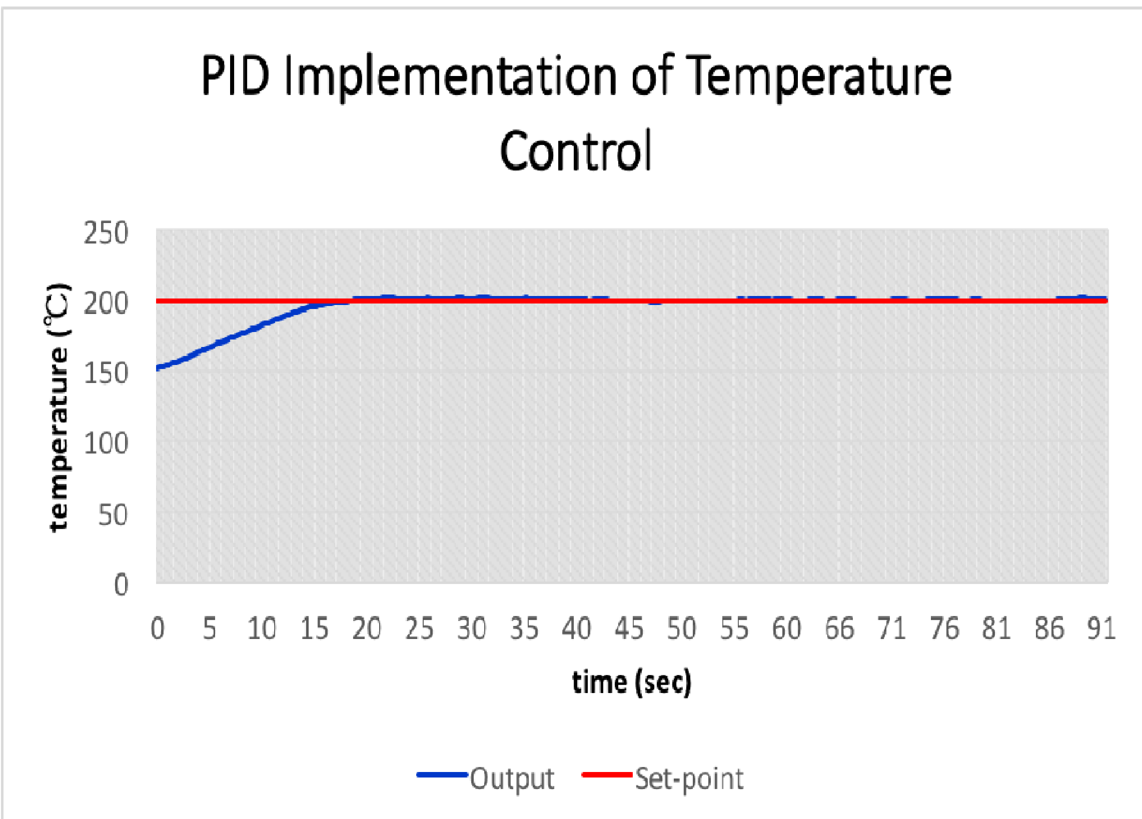

Figure 4.2.2: Temperature Control, Duration: 90 Seconds, Initial Temperature:150°C, Set-Point:200°C

On Figure 4.2.2, the PID algorithm is implemented the same way as the previous one. However, the system's initial temperature is altered to 150°C. We changed the initial temperature value to test the system's stability when the initial temperature range is changed and test if the system can maintain the desired temperature. Thus, the designed temperature control system yields better results for sustaining set point of 200°C without adding adaptive tuning methods.

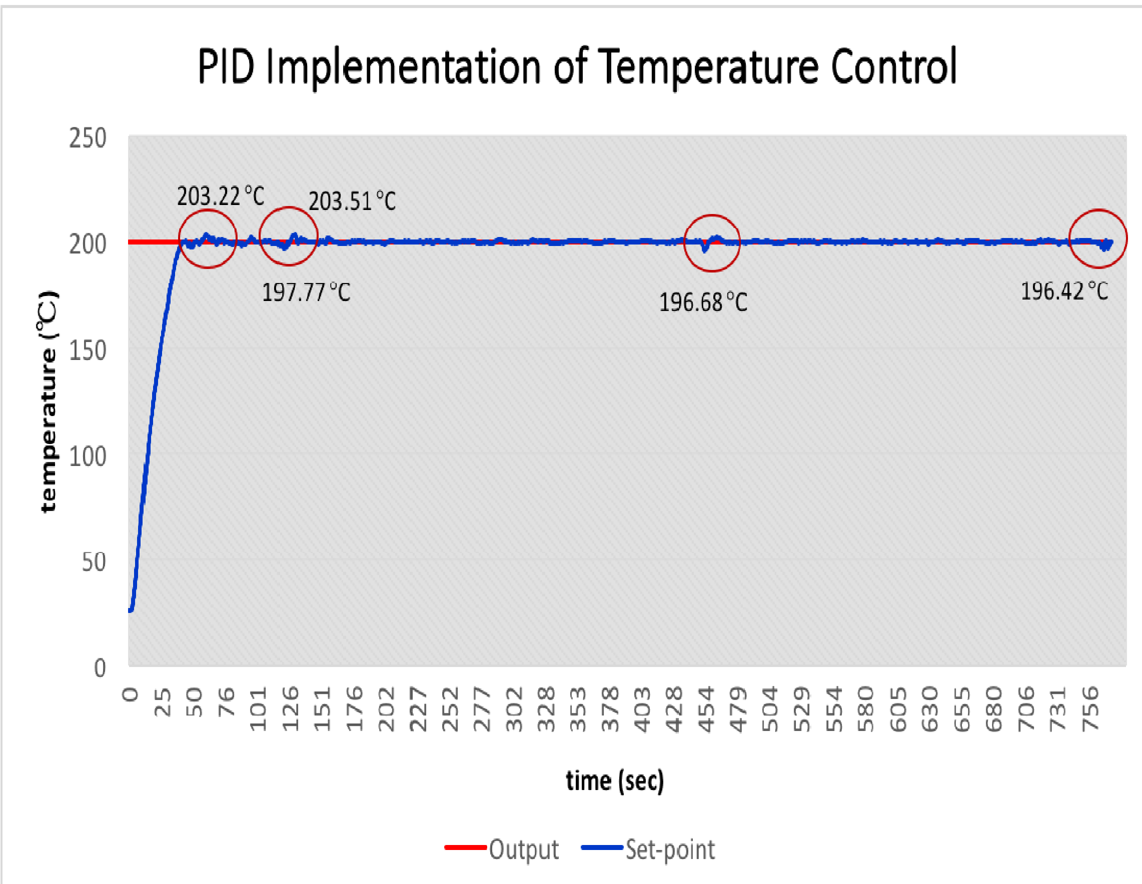

Figure 4.2.3: Temperature Control, Duration: 750 Seconds, Initial Temperature:25°C, Set- Point:200°C

After obtaining the above results, we wanted to test our system if it could give us same results when running for a long time. We run the system for more than 750seconds to make sure whether the designed system sustains the desired temperature with accuracy and constancy. Thus, we realized that the temperature control maintains the set point temperature with an offset of 1°C most of the time, however, has ± 3.5°C offset rarely (Table 4.2). As depicted in Figure 4.2.3, the temperature goes to 196.42°C and 203.51°C at worst case scenarios.

Temperature Reading from Experiment	
Temperature Reading(°C)	Offset(°C)
199.46	-0.54
198.96	-1.04
200.44	+0.44
197.41	-2.59
203.22	+3.22
197.77	-2.23
196.42	-3.58

Table 4.2: Temperature Reading Results

```
potentiometerValue: 9.98289
analogValue(amplifiedVoltage): 3.99

potentiometerValue: 9.99511
analogValue(amplifiedVoltage): 4.00

potentiometerValue: 10.00733
analogValue(amplifiedVoltage): 4.00

potentiometerValue: 10.00733
analogValue(amplifiedVoltage): 4.00

potentiometerValue: 10.00733
analogValue(amplifiedVoltage): 4.00

potentiometerValue: 10.00733
analogValue(amplifiedVoltage): 4.00
```

Figure 4.2.4: Resistance Change Reading Results

The resistance change reading section of the circuit result is shown in Figure 4.2.4. Using the principle of Wheatstone bridge, we obtained the analog voltage reading by adjusting the potentiometer value and by comparing it with the three resistor values of 5kΩ. The potentiometer is a representation of the resistance change reading section of the gas sensor for this time and will be replaced by the gas sensor resistor pins in the future. Based on the voltage reading between the two terminals of Wheatstone bridge V1 and V2, the change in voltage (ΔV) is calculated. Since the ΔV value is very small to be read by the Arduino, it is amplified using the instrumentational amplifier INA125 and sent to pin A0 of the microcontroller. By principle, when the potentiometer value is at 5kΩ, the Wheatstone bridge is in a balanced situation; hence, the voltage at terminal 1 (V1) and terminal 2 (V2) are equal, and the analog voltage (ΔV) is 0V.

While experimenting, we measured the correct values of each resistors and found R1=R2=R3= 4.885kΩ, R4(potentiometer value) = 0-10kΩ and RG = 9.74kΩ. Gain is calculated as G = 4 + 60kΩ/RG = 10.16kΩ. The reference voltage(V_{REF}2.5) used is 2.49V; therefore, we compared the calculated value from the bridge with the results found from the experiment. Figure 4.2.4 shows the potentiometer value reading and the analog voltage (amplified voltage) from our experiment setup.

As shown below, the calculated value when the potentiometer value is set to 10kΩ gives a ΔV value of 0.39568V and multiplying this with the Gain value; we obtained the amplified analog voltage as 4.0199V. Comparing this value with the results found in Figure 4.2.4, we can conclude that the results for a resistance change reading section are correct.

$$V1 = Vs * \frac{R2}{R1+R2} \qquad V2 = Vs * \frac{R4}{R3+R4}$$

$$V1 = 2.492V * \frac{4.885k\Omega}{4.885k\Omega + 4.885k\Omega} = 1.246\ V$$

$$V2 = 2.492V * \frac{10k\Omega}{4.885k\Omega + 10k\Omega} = 1.674168V$$

$\Delta V = V2 - V1 = 1.64168V - 1.246V = 0.39568V$

when amplified,

$Vo = \Delta V * G(gain) = 0.39568V * 10.16 = 4.019V$

4.3 Performance Analysis

The system has satisfied the design criteria needed to maintain the gas sensor's accuracy, selectivity, and sensitivity. Performance is defined in terms of efficient and stable temperature control and resistance change reading system, and it is accomplished. Besides, the system achieves low power consumption by utilizing a maximum of 19Watts of power at 24V for the heating element. The entire design components cost less than $100, and this makes the cost-effective system design. The easy-to-use interface makes this technology suitable and preferable for people who want to use it for monitoring the temperature of gas sensors. Portability is the other important attribute for this design and is achieved by using Arduino microcontroller. We are using the PC to display the measurements for now, and this can be improved by adding wireless communication systems in the future, and this aspect will be discussed in detail in the future works section.

4.4 Limitations

Two major issues need to be addressed to improve the system's performance for better stability and accuracy, and to take this technology to the next level. As described earlier, the system has an offset temperature of 1°C most of the time and 3.5°C occasionally as shown in Table 4.2. We defined accurate temperature control system when the temperature has an offset of less than 1°C. Thus, we need more tuning efforts to remove those offsets and to use other tuning methods other than manual tuning might be the solution. The second issue we have is noise due to the contact area of the thermocouple wire with the ceramic heater. When the position of the thermocouple is placed at different parts of the metal ceramic heater, it yields different results. This limitation can be solved with the application of better packaging technique. Better packaging technique refers to the package design (Figure 1.1) displayed on the goal of the project.

Chapter 5

Conclusion, Discussion and Future Work

5.1 Summary

This research is performed to integrate a system that controls a gas sensor at its optimal preset temperature. The system also includes a resistance change reader for the gas sensor, to obtain the voltage reading of the gas sensor. To summarize this work, in chapter one the background, motivation organization and introduction of this research were discussed. In chapter two, some related works that are similar to our designed system are discussed. In chapter three, the system design and methodology with the components used and their specifications, the system's block diagram, and system circuit diagram of temperature control, heater control, and resistance change reading are discussed. Chapter four includes the results of the system with PID implementation, performance analysis and limitation of the results in detail. Chapter five, concludes the work with its, summary, conclusion, discussion, and future work.

5.2 Conclusion

In conclusion, our integrated board design has been completed and tested effectively. The system is intended to integrate the temperature measurement section using temperature sensors, heater control unit using PWM output and resistance change reading part using Wheatstone bridge principle for application of gas sensor technology. Results show that the design criteria have been satisfied to maintain the gas sensing material at a predetermined temperature of 200°C and read the resistance change of gas sensors successfully. However, there are few limitations regarding with accuracy and contact area of the heater with a temperature sensor that need to be addressed in future works by applying more tuning methods and effective design. This work can be extended and optimized to achieve its ultimate-goal and high-level performance.

5.3 Discussion and Future Works

This project has been an interesting area of study for me as it integrates the application of hardware and software design principles. The most challenging part of this project was using PID library to fit into my specific system, getting the correct tuning parameters and choosing the right components for the circuit design to satisfy my unique system requirement.

Based on the current system implementation, adding an improved packaging technique can be used to eradicate the current limitations and achieve high accuracy. This work can be extended by adding other components such as alarm system to notify the user if the temperature is below a certain level. Wireless communication and LCD-display can also be added to display the temperature reading and to make wireless communication so that the serial display on the PC will be avoided and the portability issue will be solved. For the future, fabricating the semiconductor gas sensor using 3D printing technology will determine the structure of the sensor and integrated with our system can be used to make unique and smart technology. Also, IoT feature can be added to this system for communication of the devices intelligently with each other and connect them to mobile devices to regulate and get a notification to mobile devices when the temperature is out of range.

APPENDICES

Appendix A

Glossary of Terminology

AGND – Analog Ground

AVDD - Analog Positive Supply

BIAS – Bias Voltage Source

CMR – Common Mode Rejection

CMRR – Common Mode Rejection Ratio

CS – Cheap Select

DC – Direct Current

DGND- Digital Ground

DNC - Do Not Connect

DRDY - Data Ready Output

DVDD - Digital Positive Supply

EMI – Electromagnetic Interference

FLT - Fault Output

GEIRI – Global Energy Interconnection Research Institute

GND – Ground

IA_{REF} - Instrumentation Amplifier Reference

IDE – Integrated Development Environment

INA – Instrumentation Amplifier

I/O – Input/ Output

IoT – Internet of Things

Kp – Proportional Constant

Ki – Integral Constant

Kd – Derivative Constant

MOSFETs – Metal-oxide semiconductor field-effect transistor

NTC –Negative Temperature Coefficient

PCB – Printed Circuit Board

PID – Proportional Integral Derivative

PTC –Positive Temperature Coefficient

PWM – Pulse Width Modulation

R_G – Gain Resistor

SCK – Serial Clock

SDO – Serial Data Out

SDI - Serial Data In

SPI - Serial Peripheral Interface

S-S Error – Steady State Error

T- – Thermocouple Negative Input/Terminal

T+ – Thermocouple Positive Input/Teminal

TO-220 – Transistor Outline

USB – Universal Serial Bus

V+ – Positive Voltage Pin

V- – Negative Voltage Pin

V_{IN+} - Voltage in Positive

V_{IN-} - Voltage in Negative

Vo – Voltage Output

V_{REF}BG – Reference Voltage Bandgap

V_{REF}COM - Reference Voltage Common

V_{REF}2.5 – Reference Voltage 2.5V

V_{REF}5 – Reference Voltage 5V

V_{REF}10 – Reference Voltage 10V

V_{REF}OUT – Reference Voltage Out

Vs – Source Voltage

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