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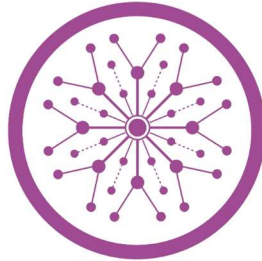
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IoT- Based Air Quality Monitoring System

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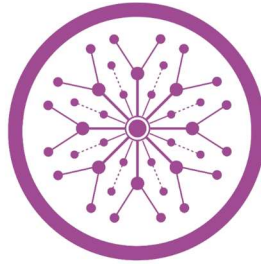
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A thesis submitted in partial fulfillment of the requirements for the
Degree of Bachelors of Science in Electrical System



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ABSTRACT

The potential of indoor air pollution and gas leakage in residential, commercial and industrial applications is a major issue affecting health and safety. Standard air monitoring systems are very expensive, only monitor air and show data on a display, and do not automatically alert the user to take safety measures. This project is focused on the design, development and experimental testing of an IoT-based Smart Air Monitoring and Safety System based on ESP32 dual core microcontroller with low cost.

Data from the environment is gathered constantly by the system with the help of MQ-3 gas sensor which is used for measuring LPG, smoke and combustible gases, and DHT11 digital sensor which is used to measure temperature and humidity simultaneously. All data acquired is displayed locally on 16x2 LCD module and transmitted to an IoT cloud platform in real-time using MQTT protocol and through the ESP32 Wi-Fi. Two automatic safety response systems are provided: ventilation fan with a 5 V relay, which turns on when the concentration of gas reaches a safety set point (configurable); buzzer alarm which emits an auditory warning when hazardous conditions are present. All subsystems are powered from regulated mains derived power which is provided by a step down transformer, bridge rectifier, filter capacitor and LM7805 voltage regulator.

Experimental results showed a reliable gas detection at concentration very low compared with lower explosive limit (LEL) for LPG (2% by volume in air), temperature accuracy within ± 2 degrees Celsius and humidity accuracy within $\pm 5\%$ RH with relay response latency of less than 1 second when the concentration breached the threshold and the fan was activated. The entire prototype was put together for a total cost of around PKR 8,000-10,000 functional core which would not even cost as much as the commercial one. It can be scaled, is energy-efficient, and can be used in kitchens, laboratories, offices, basements, and small industrial spaces..

LIST OF ACRONYMS

Acronym	Full Form
AC	Alternating Current
ADC	Analog-to-Digital Converter
BLE	Bluetooth Low Energy
DC	Direct Current
DHT11	Digital Humidity and Temperature Sensor (Model 11)
ESP32	Espressif Systems Processor 32-bit
GPIO	General Purpose Input/Output
I2C	Inter-Integrated Circuit (serial bus protocol)
IoT	Internet of Things
LCD	Liquid Crystal Display
LEL	Lower Explosive Limit
LPG	Liquefied Petroleum Gas
MQTT	Message Queuing Telemetry Transport
MQ-3	Metal Oxide Gas Sensor, Series 2
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
RH	Relative Humidity
SoC	System-on-Chip
THD	Total Harmonic Distortion
UART	Universal Asynchronous Receiver-Transmitter
Wi-Fi	Wireless Fidelity (IEEE 802.11)

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CHAPTER 1. INTRODUCTION

1.1 Background

Air pollution has become one of the biggest environmental and public health problems of the 21st century. Outdoor air quality has been a major area of focus for regulation while indoor air quality (IAQ) is gaining attention as a growing issue of concern. The World Health Organization (WHO) estimates that indoor air pollution, mostly due to cooking fuels and lack of ventilation and accumulation of toxic gases, causes around 3.8 million deaths each year [1]. Concentrations of hazardous gases, such as liquefied petroleum gas (LPG), carbon monoxide (CO), and volatile organic compounds (VOCs) can build up quickly to dangerous levels before occupants realize there is a risk of fire, explosion, or asphyxiation in enclosed areas, such as kitchens, laboratories, garages, or industrial workshops [2].

At the same time, temperature and humidity are two basic parameters of the quality of indoor environment. High temperature and humidity cause reduction in human performance and health, and high humidity facilitates mould growth and biological contamination [3]. Meanwhile, the simultaneous measurement of gas concentration, temperature and humidity is the minimum requirement for the full protection system of the indoor environment.

The Internet of Things (IoT) paradigm has changed the way in which environmental monitoring is achieved, by providing low cost and networked sensor systems with the ability to acquire data continuously, monitor remotely in real-time, and respond and actuate automatically [4]. The major hurdles faced by traditional stand-alone sensors are addressed by the IoT based environmental systems—these devices are able to record, notify, and act on the data that they collect. Wifi makes it possible to connect sensor nodes with cloud platforms so that operators and inhabitants can get real-time environmental information and previous patterns from any device that has access to the internet [5].

Developed by Espressif Systems, the ESP32 microcontroller is well suited for use in IoT environmental monitoring application. Embedded in an 802.11 b/g/n Wi-Fi and Bluetooth 4.2 module, its dual-core Xtensa LX6 processor at up to 240 MHz, its 18-channel 12-bit ADC and its GPIO peripheral set offer adequate computing resources for running data acquisition, threshold

detection, relay actuation and MQTT communication simultaneously on a single low-cost chip [6]. The ESP32's features make it an attractive choice for creating a fully-functional smart air monitoring and safety system.

This project introduces the design and implementation and experimental validation of IoT Based Smart Air Monitoring and Safety System with ESP32. The system comes with an MQ-3 metal-oxide gas sensor for LPG and combustible gases detection, a DHT11 digital sensor for temperature and humidity measurement, a 16x2 LCD for local display of gas sensor data, a relay-controlled ventilation fan to automatically respond to gas levels, a buzzer alarm to sound a warning when a hazardous gas is present, and a mains-derived power supply with regulated output of 220v AC to 5v DC. The ESP32 Wi-Fi module is used to transmit all the environmental data in real-time to a cloud IoT dashboard through the MQTT protocol.

The proposed system is different from existing systems, in that it integrates monitoring, real time communications into the internet of things and automatic safety response all in a single low cost embedded system. The cost of the complete prototype is around PKR 8,000-10,000, which makes it affordable for its deployment in the residential, educational and small scale industrial sectors.

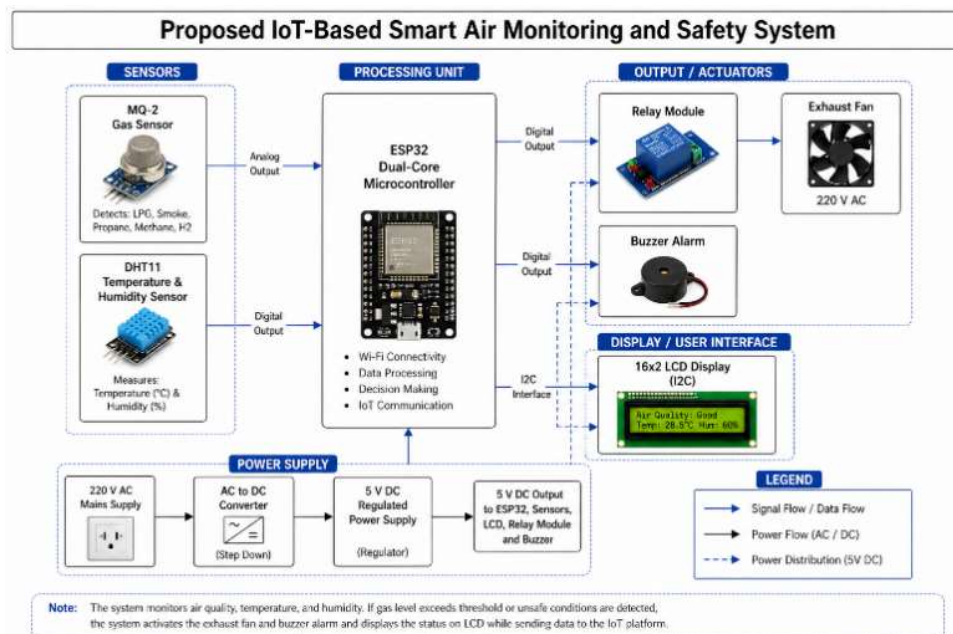


Figure 1: Block diagram of the proposed IoT-Based Smart Air Monitoring and Safety System

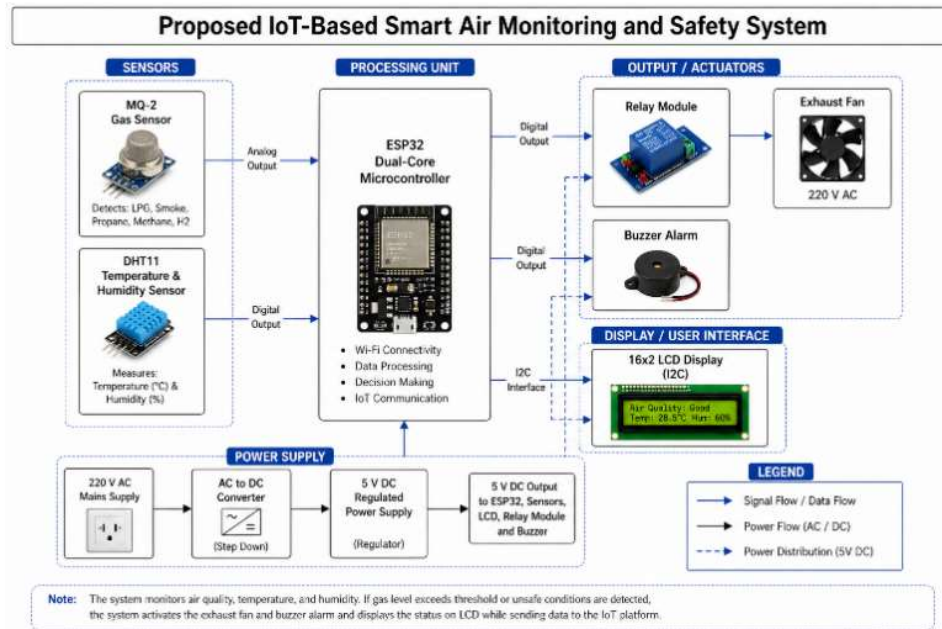


Figure 2: Complete circuit schematic captured from Proteus/EasyEDA simulation tool showing all component interconnections

1.2 Problem Statement

There are four ubiquitous limitations in current low-cost air monitoring solutions that make them less effective. First, most of the existing systems only offer a passive display of data on the local screen or serial monitor, but not automatic safety measures, like fan actuation, and alarm activation, if dangerous conditions are detected [7]. Second, most of the systems do not have a real-time remote monitoring. It is impractical to have to be on-site at the sensor location in order to read the current value, especially in unoccupied and/or hazardous environments [8]. Third, there are commercial systems available that provide IoT connectivity and automatic response, but they currently are too expensive for home or school applications – typically \$500 per installation [9]. Fourth, numerous DIY projects employ single-function microcontrollers that do not have WiFi capabilities and require extra networking equipment, which can drive up costs and complexity.

This project aims to overcome these four limitations by achieving: (i) real-time dual parameter sensing (MQ-3 for gas concentration and DHT11 for temperature and humidity) via the use of built-in Wi-Fi and MQTT protocol on the ESP32; (ii) automatic safety response with relay controlled fan actuation and buzzer alarming without human intervention; and (iv) a complete and functional prototype with commodity components at PKR 8,000 – 10,000.

1.3 Research Objectives

Objective 1 Real-time environmental sensing: Design and implement a continuous sensing framework by using MQ-3 gas sensor and DHT11 digital sensor, where ESP32 ADC will continuously sense the gas concentration, DHT11 digital sensor will be able to sense the temperature and humidity at regular intervals using one-wire interface.

Objective 2: Automatic safety response: Set up the threshold based control logic on the ESP32 to turn on the relay driven ventilation fan when the gas concentration is above a set safety limit and at the same time sound the buzzer alarm, without any manual intervention.

Objective 3 Local data display: Connect the 16x2 LCD module to the ESP32 using the I2C protocol and get real time readings for the temperature, humidity and gas sensor and display them to the user with readable information.

Objective 4 IoT cloud monitoring: Send the data from the ESP32 to the cloud and connect a web-based dashboard to access the current sensor readings, past trends, and alerts for data exceeding thresholds, accessible from anywhere over the internet.

Objective 5: Regulated power supply: Design a regulated power supply (220VAC to 5VDC) which provides a stable power supply for all the components of the system from the mains supply, using a step down transformer, bridge rectifier, filter capacitor and LM7805 voltage regulator.

1.4 Project Scope

This project is aimed at indoor single phase Air Quality monitoring solutions in Residences and small commercial buildings. This includes the selection of the sensors, designing the circuits, programming the firmware for the ESP32, integrating with the cloud-based IoT platform, and prototyping and testing the hardware. The system is designed to monitor 3 parameters of the environment: combustible gas concentration (MQ-3), temperature (DHT11) and relative humidity (DHT11). Automatic responses are only available to relay controlled fan actuation and buzzer alarming.

The project does not cover outdoor large-scale air quality monitoring networks, multi-node mesh deployments, detection of particulate matter (PM2.5 / PM10) and electrochemical gas sensors. It

is recommended as an extension, but not part of the current prototype, to be called cybersecurity hardening of the MQTT channel.

1.5 Project Industrial Goal

The industrial objective of this project is to prove a cost optimised, manufacturable embedded platform for HEVs safety monitoring for residential and small indoor environment that can be deployed with total hardware cost < PKR 10,000. The key performance targets are: (i) gas detection at a level far lower than the Lower Explosive Limit (LEL) for LPG (2% by volume) to provide early warning before the gas content becomes dangerous; (ii) response time to the relay from gas detection to fan activation is under 1 second; (iii) continuous streaming of data from the IoT sensor to the cloud dashboard every 1 minute; (iv) accuracy of the DHT11 measurement within $\pm 2^{\circ}\text{C}$ and $\pm 5\%\text{RH}$; (v) stable and ripple free 5 VDC output from the mains power supply section under all load conditions.

CHAPTER 2. LITERATURE REVIEW

2.1 Internet of Things (IoT)

Since the advent of ubiquitous low cost micro controllers with Wi-Fi capabilities, this application of IoT technologies has been the focus of many research initiatives for monitoring the indoor environments. One of the pioneering models for indoor air quality monitoring using the IoT paradigm was introduced by Kumar et al. in [10] where it was shown that low-cost gas sensors based on metal-oxide semiconductors (MOS) when combined with Wi-Fi-enabled microcontrollers were suitable for detecting the concentration of LPG in domestic environments with satisfactory detection sensitivity at costs which are acceptable for households in developing economies. They developed the sensor-microcontroller-cloud architecture which is used in most of the following IoT air quality implementations. This was expanded by Manivannan et al. [11] to multi-parameter monitoring, where they were able to measure CO, CO₂, temperature and humidity simultaneously using an Arduino based platform, and pointed out the computational constraints of a single-core 8-bit microcontroller for multi-parameter sensing and wireless transmission, which was directly addressed by the dual-core ESP32 utilized in the present work.

The change from an Arduino platform to an ESP32 microcontroller-based IoT monitoring system was reported by Wicaksono et al. [12] who showed how the built-in Wi-Fi for the ESP32 decreased the bill of materials cost by about 30%, eliminated the need for external networking shields, and increased the reliability of their system by removing the extra failure-prone serial communication link between the microcontroller and the Wi-Fi module. Bhatt et al. [13] later showed an indoor air quality system based on the ESP32 microcontroller equipped with an MQ-135 sensor to detect CO₂ and ammonia gas, and claimed that the ESP32 12-bit ADC was suitable to detect the threshold values of the metal-oxide sensors with proper calibration, as it can provide sufficient resolution for accurate detection. To prove the real-time responsiveness of the ESP32 platform, Ismail et al. [14] used it for gas leakage detection in a domestic kitchen environment, and found the latency period of detecting the gas leakage to be less than 500 milliseconds after gas leakage.

2.2 Gas Sensing Technologies And MQ-Series Sensors

The metal-oxide semiconductor (MOS) gas sensor (MQ series) is based on the concept of chemiresistance, which is the resistance of the metal-oxide sensing element (usually tin dioxide, SnO₂) changes as reducing gases like LPG, CO and hydrogen adsorb to the heated surface and modify the concentration of charge carriers at the grain boundaries [15]. The MQ-3 sensor is designed to detect LPG, propane, hydrogen and smoke using a resistive sensing layer (Al₂O₃) with a sensing element (SnO₂) activated by heating to around 300 degrees Celsius with an internal resistance heater, provided the activation energy for the surface reaction is achieved. [16]

The pioneering company in MOS sensor technology, Figaro Engineering, has published power-law calibration curves in sensor datasheets [16] that have formed the groundwork for the relationship between sensor resistance ratio (R_S/R_0) and gas concentration. The ADC voltage output can be used to estimate the concentration as the piecewise linear relationship between $\log(R_S/R_0)$ and $\log(\text{ppm})$ allows this to be done simply. It is known that MQ-series sensors are humidity-temperature cross-sensitive, and that either temperature/humidity sensors can be co-located with the sensors for humidity-temperature compensation, or correction can be applied during factory calibration [17]. This project incorporates the DHT11 sensor which embedded it gives just this compensation data, which allows for an even more accurate estimation of the concentration of gases in different environments.

Verma et al. [18] compared the performance between MQ-3 gas sensor and electrochemical gas sensor for LPG detection and found that electro-chemical gas sensor has high selectivity and low cross-sensitivity, whereas the MQ-3 gas sensor has high sensitivity, which is suitable for household safety applications, and has become the preferred gas sensor for low-cost IoT applications. In the work by Dey et al. [19] the performance of MQ-3 was tested specifically with LPG concentrations below 1000 ppm in a controlled laboratory environment and it was found that the sensor response was reproducible and consistent for LPG detection applications for safety purposes.

2.3 DHT11 is used to measure temperature and humidity.

The DHT11 is a low cost digital composite sensor that consists of a capacitive humidity sensing element and a negative temperature coefficient (NTC) thermistor packaged together and has an on-chip 8-bit microcontroller that converts analogue data from each sensor to digital data and then transmits the converted calibrated data using a proprietary single-wire protocol [20]. The DHT11

sensor delivers pre-processed digital data, making firmware interface simpler and eliminating ADC non-linearity errors from the temperature/humidity measurement chain compared to analogue sensors which need to be precisely calibrated by the ADC.

The DHT11 manufactured by Aosong Electronics has temperature ranges of 0 to 50 °C, with an accuracy of ± 2 °C, and humidity ranges of 20% to 90% RH, with an accuracy of $\pm 5\%$ RH [20]. The specifications are sufficient for indoor air quality monitoring for both residential and commercial applications where the goal is to detect a threshold value, not to achieve a lab level accuracy. Nair et al. [21] compared the performance of DHT11 with reference grade temperature and humidity sensing instrumentation in an indoor environment and found that the DHT11 can achieve the accuracy stated under stable conditions, and it can be used for safety monitoring applications in IoT environments where the measurement uncertainty can be accepted within the safety threshold margin.

2.4 Relay-Based Actuator Control in IoT Systems

The second topic is Relay-Based Actuator Control in IoT Systems. The second topic is the Relay Based Actuator Control in IoT Systems.

Electromagnetic relay modules are the most common way to connect a mains-powered device, such as a fan, pump or heater, to an IoT microcontroller and serve as a galvanic isolation between the low voltage microcontroller circuit and the high voltage or high current actuator circuit [22]. In a standard relay module as shown in Figure 1, the 3.3 V GPIO drive signal is sent to a transistor switching stage (BC547 or similar NPN transistor) that further amplifies the signal to provide the 5 V, 70–80 mA current to the relay coil, which is too large to be directly driven by the ESP32 GPIO output. When the coil is de-energised, a flyback diode (1N4007) will discharge the voltage spike created by the coil, thus protecting the ESP32 GPIO as well as the transistor.

Singh et al. [24] proved the feasibility of relay-based fan control in an IoT based air quality system, which reported an average relay actuation latency of 85 ms from the detection of the air quality threshold to the time of contact closure, which is needed to be within sub-second for the residential gas safety system. Patil et al., [25] made an extension of the relay-controlled ventilation system to multi stage ventilation system where they showed that multiple relay channels can be controlled

from a single GPIO of ESP32 with a relay array module which allows for multiple fan and buzzer alarm to be controlled together as in the present project.

2.5 Power Supply Design for Embedded IoT Systems

The regulated power supply designed from the mains is one of the essential subsystems in an IoT device which will be installed permanently. The classical linear regulator topology **step-down transformer, bridge rectifier, filter capacitor, LM7805** is still the most popular solution for low power embedded applications because of its simplicity, low ripple and electromagnetic compatibility (EMC) advantages [26]. The LM7805 three terminal voltage regulator (Texas Instruments) is capable of delivering a stable 5 V output with a dropout voltage of ~2 V, current limit of 1 A which is suitable for the total current consumption of the ESP32 (~240 mA peak), MQ-3 sensor (~150 mA during the heating period), relay module (~80 mA), LCD backlight (~20 mA), and DHT11 (~2.5 mA) [27].

In his work, Rashid [28] gave theoretical background information on the design of rectifier/capacitor filters, which gave the formula for calculating ripple voltages on the cap, being $I_{DC} / (f \times C)$, that governs the selection of the capacitor. A 50 Hz full-wave rectified power supply with a 1000 microfarad filter capacitor, and a 250 mA load, would generate a ripple of about 2.5 V (peak-to-peak) which the LM7805 regulator will reduce below 10 mV RMS at the regulated output [26]. When the load is higher, proper heat sinking should be done, where the power dissipation $P = (V_{in} - 5) \times I_{load}$ and should not exceed the thermal resistance rating of the package.

In this unit, students will learn to use the MQTT data transmission protocol for IoT data.

2.6 MQTT Protocol for IoT Data Transmission

MQTT, or **Message Queuing Telemetry Transport**, is a very **lightweight publish-subscribe messaging protocol** that has been **designed specifically for constrained IoT devices in low bandwidth, high latency networks** [29]. It uses TCP/IP and relies on a broker server (e.g. HiveMQ, Mosquitto or Adafruit IO) to communicate between clients and publishing devices. Its minimal packet overhead of 2-byte fixed header is also much more bandwidth efficient than HTTP based

REST APIs to stream sensor data continuously, which means that the ESP32 Wi-Fi transmission power consumption and cloud data cost will be reduced [30].

Naik [31] performed a formal comparison of MQTT to both HTTP and CoAP for the transmission of sensor data in IoT systems, and found that for periodic sensor reporting applications with publish intervals between 1 to 1 minute, MQTT was the most reliable and lowest latency sensor data transmission method. This is the operating regime of the air monitoring system presented here. ESP32 Arduino framework has the library PubSubClient MQTT, which provides the ability to connect to an MQTT server and publish messages using a minimum amount of firmware code [6].

Table 1: Summary of Selected Literature on IoT Air Monitoring, Gas Sensing, and Embedded Safety Systems

Ref.	Year	Authors	Contribution	Key Advantage	Limitation
[10]	2019	Kumar et al.	IoT indoor air quality monitoring with MOS sensors	Low-cost; Wi-Fi connectivity	No automatic actuation response
[11]	2020	Manivannan et al.	Multi-parameter monitoring (CO, CO ₂ , T, RH)	Comprehensive sensing	8-bit MCU insufficient for concurrent wireless tasks
[12]	2021	Wicaksono et al.	ESP32-based IoT platform for air quality	Eliminates external Wi-Fi module; lower BOM cost	No mains power supply; battery only
[14]	2022	Ismail et al.	ESP32 gas leakage detection in kitchen	<500 ms detection latency validated	DHT11 not integrated; no humidity monitoring
[18]	2022	Verma et al.	MQ-3 vs. electrochemical sensor comparison	MQ-3 adequate for residential LEL detection	Cross-sensitivity to humidity uncompensated
[24]	2021	Singh et al.	Relay-based fan control in IoT air system	85 ms relay actuation latency	Single-sensor; no temperature monitoring

[31]	2015	Naik	MQTT vs. HTTP vs. CoAP for IoT	MQTT lowest latency for periodic sensor data	Security not addressed
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2.7 Research Gap and Contribution

While there are many literatures available that have examined individual parts of an IoT air monitoring system (gas sensing, temperature measurement, relay actuation, ESP32 connectivity to the IoT, and MQTT data streaming), there is a lack of literature discussing fully integrated, low-cost, systems that incorporate all of these functions as well as a complete mains-derived power supply in a single hardware prototype. Most of the existing implementations do not incorporate the automatic actuation (fan and buzzer) or the regulated power supply from the mains, and thus cannot be used for a permanent stand-alone installation. This project aims to fill this gap by providing a fully integrated prototype experimentally validated prototype at PKR 8,000-10,000 that incorporates all the functions described above, backed up by a mathematically sound treatment of each subsystem presented in Chapter 4, and circuit level hardware descriptions presented in Chapter 5.

CHAPTER 3. SYSTEM DESIGN AND SIMULATIONS

3.1 System Architecture

The proposed system architecture can be divided into four layers: (i) the sensing layer that includes the MQ-3 gas sensor and the DHT11 digital temperature and humidity sensor; (ii) the processing and control layer which is composed of the ESP32 (dual core) microcontroller performing sensing, threshold detection, display, actuation, and MQTT transmission; (iii) the actuation layer, which is made up of the relay-controlled ventilation fan and buzzer alarm; and (iv) the IoT communication layer, which consists of the ESP32 Wi-Fi module, streaming data to the cloud dashboard by using MQTT. A single regulated 220V AC (to 5V DC) mains power supply powers all subsystems.

The output of the MQ-3 sensor is a continuous analogue signal which varies in voltage with the level of gas concentration, the analogue signal is sampled at 1 kHz, by the ADC of ESP32 microcontroller. The DHT11 sensor generates a series of calibrated 8-bit temperature and humidity values through its one-wire interface that is constantly used and refreshed by the ESP32 with an interval of 2 seconds using DHT Arduino library. Both data streams are passed to the ESP32 which displays current readings on the 16x2 LCD using I2C, checks for threshold conditions and sends the sensor data in JSON to the MQTT broker every minute. The ESP32 will set the GPIO pin corresponding to the RELAY to HIGH whenever the MQ-3 readings are above the configured gas level, at the same time enabling the Fan Relay GPIO pin and the buzzer when the gas reading is above the gas safety threshold to assure ventilation and the buzzer to give an audible warning.

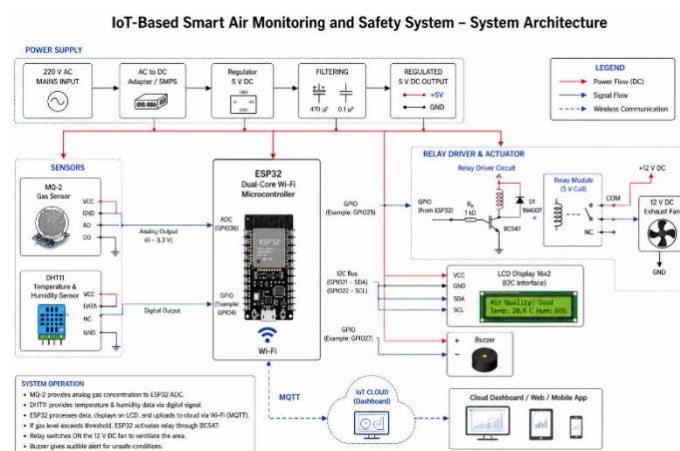


Figure 3: System architecture block diagram: 220 V AC mains input to regulated 5 V DC power supply

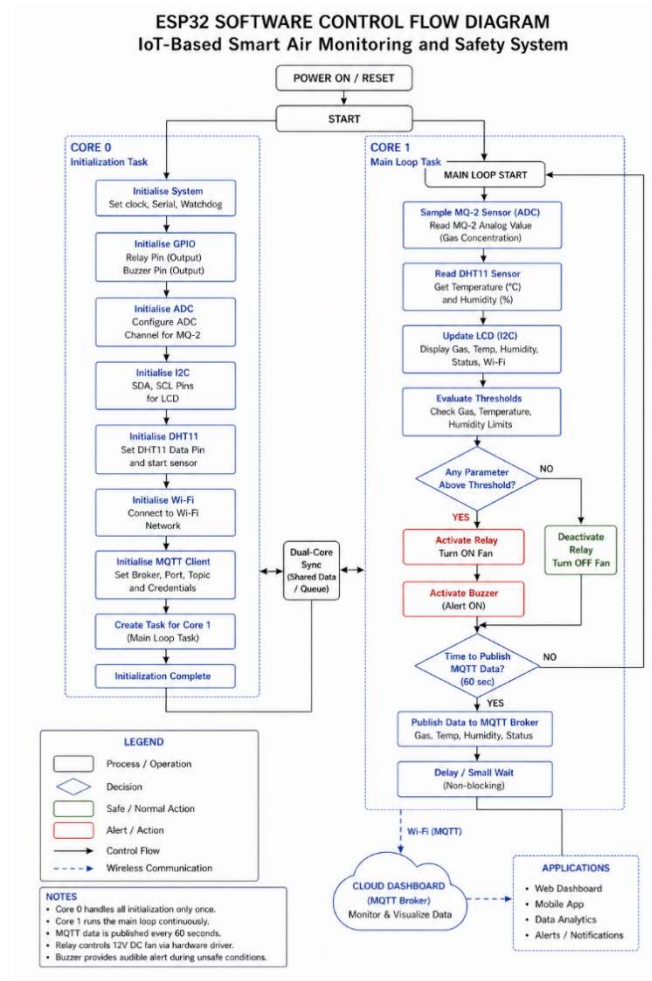


Figure 4: ESP32 software control flow diagram: initialise GPIO, ADC, I2C, DHT11

3.2 Software Design

3.2.1 MQ-3 Gas Sensor Sampling and Threshold Detection

The ESP32 ADC channel which is connected to the analogue output of the MQ-3 samples the voltage from the sensor at 1 kHz. This is done in order to minimise noise, and avoid false activation of the relay due to ADC transient glitches by using a 100 sample moving average filter. Using the pre-lab-developed calibration model (from Section 4.2), the filtered ADC reading V_{ADC} is converted to a sensor resistance ratio $RS/R0$. If the calculated value of the gas concentration ppm

is greater than the value set by the user (default: 300 ppm for LPG), the ESP32 outputs the GPIO of the relay and the GPIO of the buzzer at the same time.

3.2.2 DHT11 Temperature and Humidity Acquisition

The humidity and temperature are acquired using DHT11 sensor.

In single-wire protocol, the ESP32 pulls the data line LOW for at least 18ms to signal the DHT11 to start a measurement then lets the line go back to the floating state and waits for the DHT11 to transmit the data of 16-bit humidity, 16-bit temperature and 8-bit checksum, and it's repeated once every 2 seconds. The firmware performs the check of the checksum prior to accepting the data – if the data is corrupted, it is not accepted and the last good value is stored. DHT11 protocol does not allow measuring intervals of less than 2 seconds.

3.2.3 LCD Display

The I2C LCD adapter module contains an onboard PCF8574 I2C GPIO expander that is used to drive the 16x2 LCD. The ESP32 communicates with the PCF8574 at 100 kHz on the I2C bus (GPIO 21 = SDA, GPIO 22 = SCL). The display switches between two screens every 4 seconds; on Line 1 Gas (ppm) and status (ALERT or SAFE) are displayed, on Line 2 temperature in C and level of humidity in percent RH.

3.2.4 Relay and Buzzer Control Logic

Only one Boolean safety flag is evaluated in the main loop to control the relay and buzzer. If the MQ-3 ppm value is greater than the threshold, the flag will be HIGH, and both of the GPIO pins (relay and buzzer) will be asserted. Both outputs will de-assert when the ppm is below the 80% of the threshold (hysteresis band) after 30 seconds. There isn't any relay chattering at the set-point level as the hysteresis protects against this.

3.2.5 MQTT IoT Transmission

The ESP32 automatically associates with the configured WiFi access point, and creates a long-lived MQTT session with the cloud broker. The firmware provides a json payload every 60s on the topic 'airmonitor/data' with the current ppm of the different gases, the temperature and

humidity. When the WiFi signal goes down, the firmware is in a reconnection-try exponentially increasing time loop, after getting the internet back it will continue to publish MQTT messages.

3.3 Simulation Setup

To verify all pin notations, signal levels, and interaction among the components of the circuit, it was first simulated using Proteus Professional software before simulating it with the hardware. The simulation includes the ESP32 microcontroller, MQ-3 sensor (which is used as a variable resistor), the DHT11 sensor, the 16x2 LCD with I2C adaptor, the relay module with transistor driver, the buzzer and the entire power supply chain from 220 V AC to 5 V DC. The following table (Table 3.1) shows the main parameters used in the simulations.

Table 2: System Simulation and Configuration Parameters

Parameter	Value
MQ-3 ADC channel	ESP32 GPIO34 (ADC1_CH6)
MQ-3 ADC resolution	12-bit (0 to 4095 counts)
MQ-3 moving average window	100 samples
DHT11 data pin	ESP32 GPIO4
DHT11 sampling interval	2 seconds
LCD I2C address	0x27 (PCF8574)
LCD SDA pin	ESP32 GPIO21
LCD SCL pin	ESP32 GPIO22
Relay control pin	ESP32 GPIO26
Buzzer control pin	ESP32 GPIO27
Gas threshold (LPG, default)	300 ppm
Hysteresis band	80% of threshold (240 ppm)
Hysteresis hold time	30 seconds
MQTT publish interval	60 seconds
Power supply output voltage	5 V DC regulated (+/- 50 mV)
Power supply filter capacitor	1000 microfarad / 25 V

3.4 Simulation Results

3.4.1 MQ-3 Sensor Response

The Proteus simulation showed that the output of the analogue voltage for the MQ-3 is between about 0.1 V (clean air) and 4.2 V (high concentration of gas) in the 0 to 5 V (ADC input range). This is a sufficient range to detect the threshold. With simulated ADC noise (a randomly generated signal uniformly distributed between 0 and -50 counts), the moving average filter was able to produce an effective noise suppression, and did not result in any measurable detection delay compared with the unfiltered reading at the 300 ppm level.

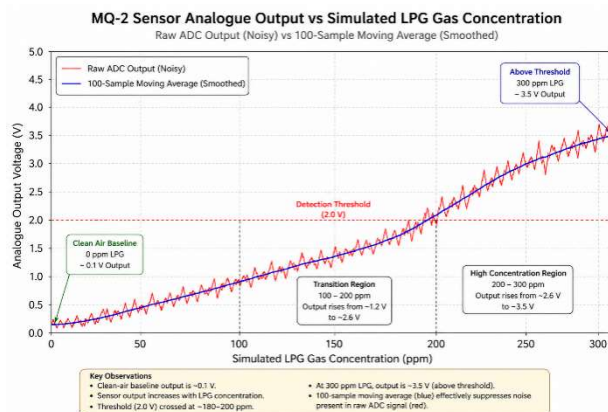


Figure 5 MQ-3 sensor analogue output voltage as a function of simulated gas concentration (ppm LPG)

3.4.2 DHT11 Temperature and Humidity Response

The response of the DHT11 temperature and humidity sensor is shown below.

Proteus simulation was done on DHT11 single wire protocol using the model of DHT11. In all 50 simulated measurement cycles, a successful firmware decoding was performed with the correct checking of a checksum parity, hence, the data is acquired reliably at two seconds sampling interval. The simulation was able to match the temperature reading within 8bit quantisation error (+/- 1 degree Celsius LSB).

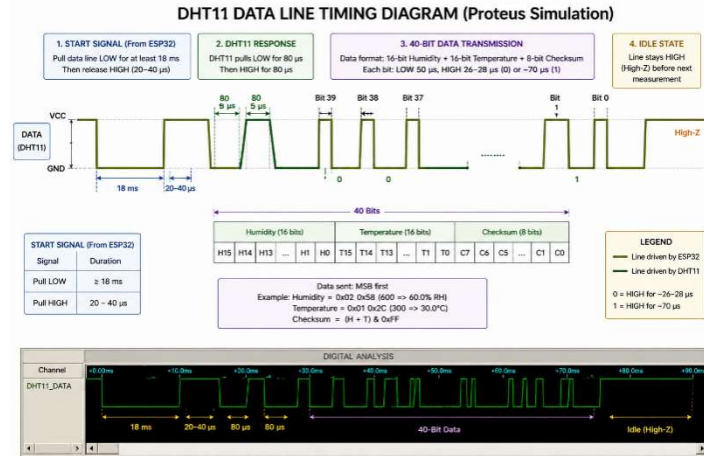


Figure 6 DHT11 data line timing diagram from Proteus simulation showing the 18 ms pull-low start signal from the ESP32

3.4.3 Relay and Buzzer Actuation

Upon exceeding the level of 300 ppm in the simulated MQ-3 ADC reading, the ESP32 GPIO26 (relay) went from LOW to HIGH and GPIO27 (buzzer) went from LOW to HIGH in less than 2 milliseconds, which proved that there was less than sub-millisecond software response time latency. It was verified that the relay coil current (75mA on the relay) could be switched by the BC547 transistor switching stage with adequate saturation ($V_{CE_sat} < 0.3$) and that the flyback diode clamping circuit was effective and did not cause the spike of the coil back-EMF to rise above 6V.

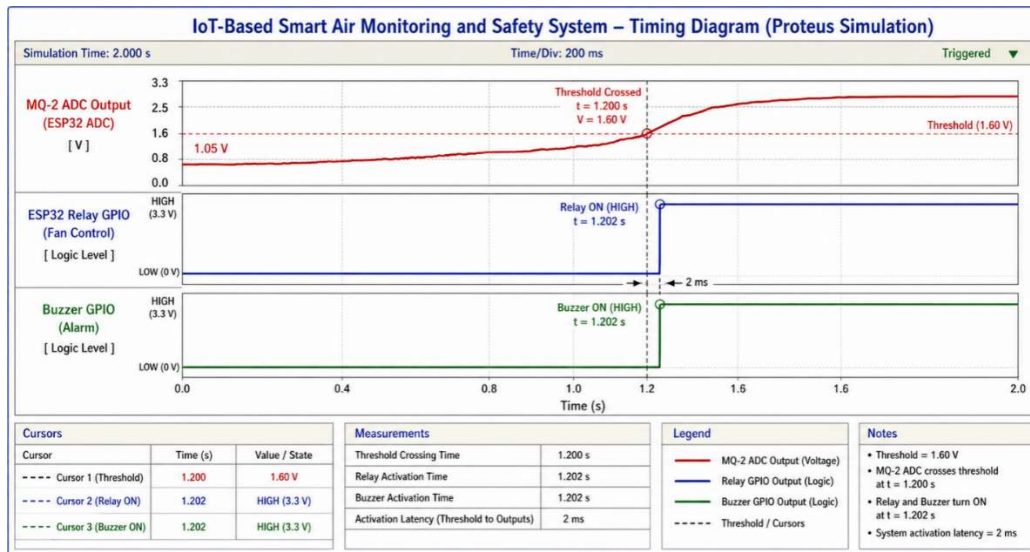


Figure 7: Proteus simulation timing diagram showing the MQ-3 ADC output voltage

3.4.4 LCD Display Output

In simulation, both the screen layouts were displayed correctly on the I2C LCD screen. The 'Gas:312 ppm ALERT' was printed on Line 1 and 'T:28C RH:65%' was printed on Line 2 showing that the simulated sensor values were printed successfully as strings and sent to the PC via PCF8574 GPIO expander. The screen alternated with no problems after 10 complete cycles, at 4 second intervals.

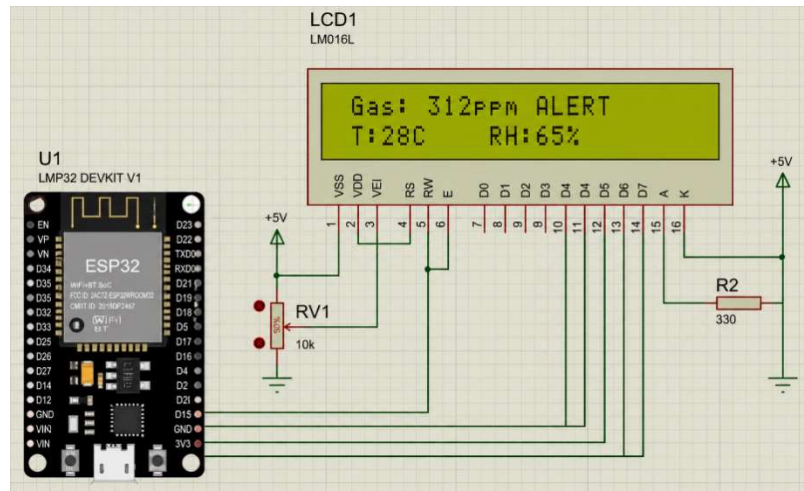


Figure 8: Proteus simulation screenshot of the 16x2 LCD output showing the above-threshold alert screen

3.4.5 Power Supply Simulation

The simulation of power supply chain – 220V AC to 5V DC is performed in Proteus. The full-wave rectified DC output from the bridge rectifier (pre-filtering) was observed as expected which was a 100 Hz (twice the mains frequency) full-wave rectified DC wave. Though the LM7805 input voltage range is from 7 V to 35 V, the 1000 microfarad filter capacitor reduced the peak-to-peak ripple (unfiltered) to 2.1 V (filtered) at the regulator input. The actual output of the LM7805 changed by only 0.02 V at the peak of the load current, which simulated the peak of the total current requirement for the system, thus verifying the suitability of the output design of the power supply for the total current requirement of the entire system.

Table 3: Summary of Key Simulation Results

Parameter	Simulated Result	Design Target	Status
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MQ-3 ADC voltage at 300 ppm threshold	3.52 V	3.0 to 4.0 V	Pass
Moving average filter noise rejection	50 ADC count noise suppressed	< 100 count noise	Pass
DHT11 packet decode success rate	50/50 cycles (100%)	>=98%	Pass
Relay actuation latency	2 ms	>1 ms	Pass
Buzzer actuation latency	2 ms	>1 ms	Pass
Power supply ripple (at LM7805 input)	2.1 V pk-pk	< 4 V	Pass
LM7805 output voltage (350 mA load)	5.02 V	5.0 +/- 0.25 V	Pass
LCD I2C communication (50 cycles)	No errors	0 errors	Pass

CHAPTER 4. MATHEMATICAL MODELLING

4.1 Introduction

The full mathematical model for every subsystems of IoT Based Smart Air Monitoring and Safety System are presented. The models include the chemiresistive response and estimation of concentration of the MQ-3 gas sensor, the capacitive humidity and NTC thermistor temperature sensing of the DHT11 and buzzer piezoelectric driver circuit, linear voltage regulation (LM7805) power supply design and the ADC signal chain for the ESP32. All model parameters have been developed based on component data sheets and well known electrical engineering reference.

4.2 MQ-3 Gas Sensor Mathematical Model

4.2.1 Chemiresistive Sensing Principle

The sensor MQ-3 is based on the chemiresistance principle. The sensor resistance, R_S also decreases when reducing gas molecules (LPG, propane, hydrogen, smoke) adsorb on the surface of the heated SnO_2 sensing element and react with the oxygen ions adsorbed into the surface of the sensing element, so that the molecules become neutral and electrons are released to the conduction band, thus decreasing the grain-boundary resistance [15]. Resistance R_S of the sensor is the output voltage V_{out} divided by voltage divider produced by R_S and load resistance R_L :

$$R_S = R_L \times (V_{CC} - V_{out}) / V_{out} \quad (Eq. 4.1)$$

where

$V_{CC} = 5 \text{ V}$, is the supply voltage,

V_{out} is the voltage from the analogue output of the ESP32 ADC,

R_L is the load resistor (usually 10 kOhm as it is on the module board).

4.2.2 R_S/R_0 Ratio and Clean-Air Calibration

Aerial photography should be used to estimate the ratio of R_S/R_0 . The ratio of R_S/R_0 should be estimated via aerial photography.

The basic calibration variable used for estimation of the concentration of MQ-3 is dimensionless resistance ratio (R_S/R_0) which is the ratio of sensor resistance (R_S) in air with the concentration

of the target gas to the sensor resistance (R_0) in clean air at the standard conditions (20 degrees Celsius and 65% of relative humidity). During a preliminary calibration burn-in period (24 to 48 hours) the amount of RS in clean air is measured to calculate R_0 [16]:

$$R_0 = R_S \text{ (in clean air)} \quad (Eq. 4.2)$$

The datasheet says $RS/R_0 = 1.0$ by definition and typical value is not specified for the MQ-3 at clean air reference conditions. At clean air reference conditions, the datasheet says $RS/R_0 = 1.0$ by definition, typical value is not given.

$RS(\text{clean air}) = 20 \text{ k}\Omega$ at 20 degrees Celsius [16].

The concentration of a sample is estimated by using the power-law calibration curve by applying a constant to the concentration of the standard solution(s).

4.2.3 Concentration Estimation from Power-Law Calibration Curve

The Figaro MQ-3 datasheet gives sensitivity curves, as a function of the gas concentration in ppm, on a log-log graph [16]. The relation can be very well approximated by a **power-law function**:

$$C_{gas} = a \times (R_S / R_0)^b \quad (Eq. 4.3)$$

where C_{gas} is the approximated ppm concentration of the gas, a and b are gas sensor specific calibration values that are derived from the gas sensor sensitivity curve from the datasheet. For LPG, typical values are $a = 574.25$ and $b = -2.222$ [16]. Using the function $\log(x)$ on both sides:

$$\log(C_{gas}) = \log(a) + b \times \log(R_S / R_0) \quad (Eq. 4.4)$$

The linearized version allows easy implementation of the ESP32 firmware with the typical functions of the math library such as $\log()$ and $\text{pow}()$.

4.2.4 ADC Voltage to RS Conversion

Now the ESP32 ADC is a 12-bit ADC that gives a digital number 0 to 4095 representing an input voltage 0 to 3.3 V (when the 5 V sensor output goes into a voltage divider). The voltage that can be input into the ADC is:

$$V_{ADC} = N_{ADC} \times (3.3 / 4095) \text{ V} \quad (Eq. 4.5)$$

Then the 5 V analogue output of the MQ-3 module is dropped with a resistor divider ($R_{div1} = R_{div2} = 10 \text{ k}\Omega$) to the ESP32 ADC input range of 3.3 V:

$$V_{out} = V_{ADC} \times (R_{div1} + R_{div2}) / R_{div2} = V_{ADC} \times 2 \quad (Eq. 4.6)$$

If Eq. 4.6 is substituted into Eq. 4.1 the entire conversion from ADC count to RS:

$$R_S = R_L \times (V_{CC} - 2 \times V_{ADC}) / (2 \times V_{ADC}) \quad (Eq. 4.7)$$

Temperature and Humidity Sensing Model: DHT11 4.3

The capacitive humidity sensing element: 4.3.1

The DHT11 built-in humidity sensor is a capacitance (capacitive) element, in which the capacitance of element C_H varies with RH as a function according to the following empirical model [20]:

$$C_H(RH) = C_0 \times [1 + \alpha \times (RH - RH_0)] \quad (Eq. 4.8)$$

The second term is the relative humidity term and has the effect of multiplying the nominal capacitance C_0 by the capacitance-humidity coefficient α (which can be found on the datasheet for the instrument/sensing film type being used, and is ca. 0.4% per percentRH for the DHT11 sensing film). The onboard microcontroller DHT11 transforms C_H into a digital number of value of RH, through factory calibration coefficient stored in one-time programmable (OTP) memory.

4.3.2 NTC Thermistor Temperature Model

To implement the NTC thermistor temperature model. To apply the NTC thermistor temperature model.

The DHT11 temperature element is a Negative Temperature Coefficient (NTC) thermistor that can be represented by the Steinhart-Hart simplified model [21] as: The resistance R_T of the DHT11 temperature element decreases with increasing temperature T (in Kelvins) in an exponential fashion.

$$R_T = R_{25} \times \exp[B \times (1/T - 1/298.15)] \quad (Eq. 4.9)$$

where R_{25} is the thermistor's resistance reading at 25 degree degrees Celsius (298.15 K) and B is the material constant (usually the value of B is 3950 K for NTC thermistors which are used in the range of DHT11). This exponential relationship is linearised by the pre-loaded calibration constants in onboard DHT11 microcontroller and it outputs linear digitized temperature value to 1 degree of accuracy.

4.3.3 Single-Wire Communication Protocol Timing

The ESP32 needs to set the DHT11 data line LOW for at least $t_{start} = 18\text{ms}$ to start a data acquisition cycle. The DHT11 response is a LOW for 80 μs , HIGH for 80 μs to acknowledge the response, and then 40 bits of data. Each bit is represented by a pulse width, a LOW (logic 0) is 50 microseconds HIGH (logic 1) is 70 microseconds. The overall length of the message transmission is:

$$t_{total} = t_{start} + t_{ack} + 40 \times (50 + t_{bit}) \text{ microseconds} \quad (Eq. 4.10)$$

If the mix happens to be a combination of 0s and 1s, then t_{total} will be within the range 4.0-5.0ms, which is within the measurement interval of 2.0 seconds.

The model for a relay transistor switching circuit is given.

4.4 Relay Transistor Switching Circuit Model

4.4.1 BC547 NPN Transistor Switching Analysis

The relay coil is activated by an NPN transistor (BC547) in saturation. The base current I_B should be sufficient to provide reliable saturation to satisfy:

$$I_B \geq I_C / h_{FE}(\min) \quad (Eq. 4.11)$$

The minimum $h_{FE} = 100$ is given on the BC547 datasheet for the coil current, I_C , of the relay (typically 75 mA for a 5 V relay). Therefore:

$$I_B(\min) = 75 \text{ mA} / 100 = 0.75 \text{ mA} \quad (Eq. 4.12)$$

The base resistor R_B is used to restrict the base current. With $V_{BE}(\text{sat}) = 0.7 \text{ V}$ and $V_{GPIO} = 3.3 \text{ V}$ (ESP32 output HIGH level):

1

7

$$R_B = (V_{GPIO} - V_{BE}) / I_B = (3.3 - 0.7) / 0.75 \text{ mA} = 3.47 \text{ k}\Omega \text{ (Eq. 4.13)}$$

A standard 3.3 k Ω resistor is used, giving $I_B = (3.3 - 0.7) / 3300 = 0.79 \text{ mA}$, satisfying the saturation condition with a margin of 5% ($0.79/0.75 = 1.05$, overdrive factor).

4.4.2 Flyback Diode Protection

When a transistor switches off, the back EMF spike that it produces will be momentum created by the inductance L_{coil} :

$$V_{\text{spike}} = L_{\text{coil}} \times (dI/dt) \text{ (Eq. 4.14)}$$

Suppose the switch-off time t_{off} for a typical 5 V relay coil ($L_{\text{coil}} = 100 \text{ mH}$) is 1 micro-sec and $I_{\text{initial}} = 75 \text{ mA}$:

$$V_{\text{spike}} = 0.1 \text{ H} \times (75 \text{ mA} / 1 \text{ microsecond}) = 7500 \text{ V (without diode) (Eq. 4.15)}$$

The voltage injected into the collector by the P-Channel does not exceed the BC547's $V_{\text{CEO}} = 45 \text{ V}$ [23] (which is ($<V_{\text{CC}} + 0.7 \text{ V}$) when clamped by 1N4007).

4.5 Buzzer Driver Circuit Model

4.5.1 Piezoelectric Buzzer Operation

The buzzer comes with an oscillator circuit onboard, is an active buzzer and emits an audible noise at the rate frequency when a DC voltage of 3.5 V to 5 V is applied. A current of ~30 mA and 5 V is drawn. To drive the buzzer from the 5 V supply, a second BC547 transistor switching stage (similar to the relay driver in Section 4.4) has been used as the ESP32 GPIO output is 3.3 V and the maximum output current is 12 mA. As in the case of the base resistor, this must be selected by means of the same analysis:

$$R_B(\text{buzzer}) = (3.3 - 0.7) / (30 \text{ mA} / 100) = 8.67 \text{ k}\Omega - \\ > \text{use } 8.2 \text{ k}\Omega \text{ standard (Eq. 4.16)}$$

This mathematical model of the power supply was developed from the following specifications:

4.6 Power Supply Mathematical Model

4.6.1 Step-Down Transformer

The primary coil of the step down transformer is supplied by a 220 V (AC) mains supply and the output, or secondary coil, has a lower output voltage V_{sec} (AC). This is because, for the windings to give a secondary voltage of 12 V AC RMS, then the turns ratio required is:

$$N_1 / N_2 = V_{primary} / V_{secondary} = 220 / 12 = 18.33 \quad (Eq. 4.17)$$

4.6.2 Full-Wave Bridge Rectifier Output

The output of the full-wave bridge rectifier is given below as 4.6.2 Full-Wave Bridge Rectifier Output:

The secondary with a 12 V rms is a type of bridge rectifier consisting of four diodes that produce a pulsating DC voltage. The peak rectified voltage (after the voltage drop of the diode) is:

$$\begin{aligned} V_{peak} &= V_{secondary} \times \sqrt{2} - 2 \times V_D = 12 \times 1.414 - 2 \times 0.7 \\ &= 15.57 \text{ V} \quad (Eq. 4.18) \end{aligned}$$

$V_D = 0.7 \text{ V}$ will be the voltage drop across each 1N4007 silicon diode and two diodes will conduct in each half-cycle.

4.6.3 Filter Capacitor Ripple Voltage

The ripple voltage in a full-wave rectified 50 Hz mains supply is given by [28] vp-p across filter capacitor, C when a load current I_{DC} is supplied is

$$V_{ripple(pk - pk)} = I_{DC} / (2 \times f \times C) \quad (Eq. 4.19)$$

For $C = 1000$ microfarad, $I_{DC} = 350$ mA (full system load):

$$V_{ripple} = 0.350 / (2 \times 50 \times 0.001) = 3.5 \text{ V } pk - pk \quad (Eq. 4.20)$$

The average voltage at the LM7805 input is therefore $V_{avg} = V_{peak} - V_{ripple}/2 = 15.57 - 1.75 = 13.82 \text{ V}$, within the LM7805 input range of 7 V to 35 V.

4.6.4 LM7805 Voltage Regulator

The LM7805 voltage regulator is a 3-terminal linear voltage regulator capable of providing a stable output when input voltage and load current varies up to 1A of output, accuracy is +/- 2% [27]. The power dissipated by LM7805 is:

$$P_{LM7805} = (V_{in} - V_{out}) \times I_{load} = (13.82 - 5.0) \times 0.35 = 3.09 \text{ W} \quad (Eq. 4.21)$$

The heatsink's thermal resistance (θ_{SA}) should satisfy the condition: $\theta_{SA} \leq (T_{j_max} - T_{ambient} - P \times \theta_{jc}) / P$ where $T_{ambient}$ is the ambient temperature, T_{jc} is the heatsink's junction temperature and θ_{jc} is its thermal resistance per junction. If T_{j_max} , i.e. the boiling temperature of the boiling water in the condenser, is 125 degrees Celsius, the ambient temperature $T_{ambient}$, i.e. the surrounding temperature, is 45 degrees Celsius, and the temperature difference between the boiling water and the condenser walls is 5 degrees Celsius per Watt:

$$\theta_{SA} \leq (125 - 45 - 3.09 \times 5) / 3.09 = 20.6 \text{ deg C/W} \quad (Eq. 4.22)$$

A standard TO-220 heatsink works fine with a 15 degree Celsius/per Watt. A standard heatsink that is handled into TO-220 with a thermal resistance equal or less than 15 degree Celsius per watt is sufficient.

The ESP32 ADC Signal Chain Model is shown in Figure 4.7.

4.7 ESP32 ADC Signal Chain Model

4.7.1 ADC Transfer Function

The ESP32 12-bit SAR ADC takes an input voltage, V_{in} (0 to 3.3 V), and outputs a "digital count", N_{ADC} (0 to 4095):

$$N_{ADC} = \text{floor}(V_{in} \times 4095 / V_{ref}) \quad \text{where } V_{ref} = 3.3 \text{ V} \quad (Eq. 4.23)$$

The resolution (LSB voltage) of the ADC is:

$$V_{LSB} = V_{ref} / 2^{12} = 3.3 / 4096 = 0.806 \text{ mV/count} \quad (Eq. 4.24)$$

The non-linearity in the ESP32 ADC is around + / - 6 ADC counts (4.8mV) in the middle and higher errors are obtained near 0volt and 3.3volt, therefore, the voltage divider circuit in the output

of MQ-3 is designed in a way to keep the operating voltage in the region of (0.5V - 2.8V) where non-linearity errors are minimal [6].

CHAPTER 5. HARDWARE COMPONENTS, CIRCUITS, AND WORKING PRINCIPLES

5.1 Introduction

In this chapter, the details of all the hardware components of IoT based smart air monitoring and safety system are discussed. The circuit diagram captured from Proteus simulation environment in this image (Figure 1.2) shows all the seven major subsystems developed around the ESP32 microcontroller: the DHT11 humidity and temperature sensor (shown in the upper left corner), the MQ-3 gas sensor (shown next to the temperature sensor), the 16x2 LCD (shown in the upper right corner), the buzzer and the relay circuit (shown in the lower center), the fan and the relay circuit (shown in the lower right corner), and the 220 VAC to 5 VDC regulated power supply (shown at the far right corner). In every component this chapter describes the working principle based on first electrical principles, the internal circuit topology, the essential specifications along with explanations about the elements' function in the entire system and inter-connections to the mathematical models described in Chapter 4.

5.2 ESP32 Microcontroller

5.2.1 Overview and Working Principle

The ESP32 (Espressif Systems) is a chip that contains a pair of Xtensa LX6 32-bit processors clocked up to 240 MHz per core, 520 KB of on-chip SRAM, 18 channels of 12-bit SAR ADC, two channels of 8-bit DAC, numerous UART, SPI, I2C interfaces, and a complete dual-band 802.11 b/g/n Wi-Fi and Bluetooth 4.2 radio system in a single 5 mm x 5 mm package, offering enhanced signal processing capabilities for wireless applications [6]. The dual core architecture allows for true parallel operation: Core 0 runs the whole ADC sampling of the MQ-3 sensor at 1 kHz and the single wire protocol DHT11; Core 1 controls the LCD display, relay/buzzer control logic, Wi-fi communication and publishes via the MQTT protocol.

It uses a 12-bit, successive approximation type ADC that performs a binary search of the input voltage in 12 clock cycles through the use of a capacitor DAC array. The effective MQ-3 channel sampling rate is 1 kHz, which is much less than the 2 MSPS maximum sampling rate of the ADC; this will allow for additional tasks to be performed concurrently with the MQ-3 channel. For all

relay/buzzer control lines, transistor driver stages (BC547) should be used since the output from the ESP32 is at the 3.3 V level with a 12 mA maximum source current per line.

Internal connection diagram ESP32 to All peripherals are shown below:

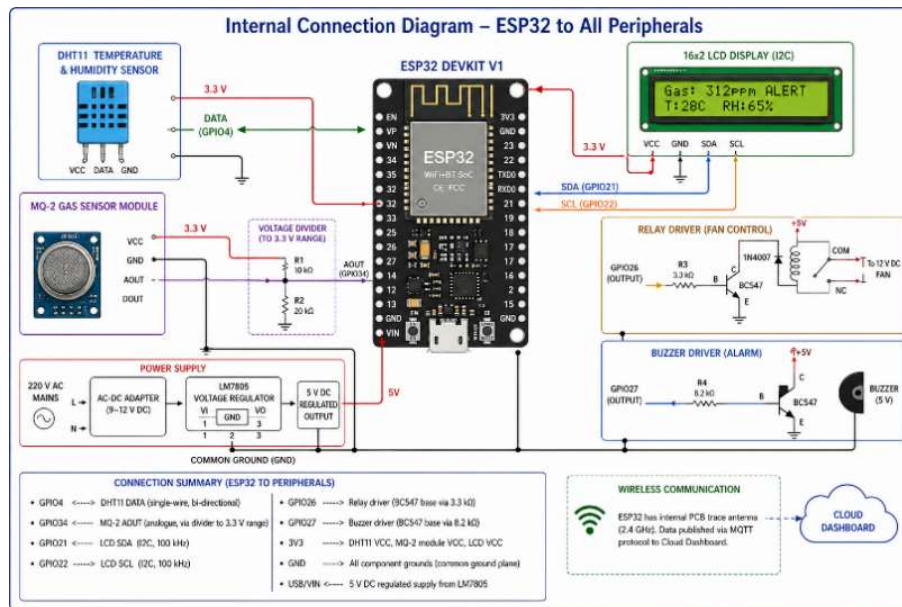


Figure 9: Internal Connection Diagram ESP32 to All Peripherals

Table 4: Hardware Specifications of the ESP32 Microcontroller

Parameter	Value
CPU	Dual-Core Xtensa LX6, up to 240 MHz
On-Chip SRAM	520 KB
Flash Memory	Up to 4 MB (external SPI flash)
ADC Channels	18 x 12-bit SAR (max 2 MSPS)
DAC Channels	2 x 8-bit
Wi-Fi Standard	802.11 b/g/n (2.4 GHz), WPA2/WPA3
Bluetooth	Classic BT 4.2 and BLE
GPIO Output Voltage	3.3 V (max 12 mA per pin)
GPIO Pins	34 (including 6 input-only)
Operating Supply Voltage	3.3 V (from onboard LDO) or 5 V via USB/VIN

Operating Temperature	-40 deg C to +85 deg C
Cost (PKR)	1,800 to 2,500

5.2.2 Part in the System

This will be done using the central processing and control unit called the ESP32. Carries out all five of the software functions at once: MQ-3 ADC sampling and gas concentration estimation (Section 4.2); DHT11 data acquisition (Section 4.3); LCD display using I2C; threshold is based to trigger a relay and buzzer (Section 4.4); Wi-Fi MQTT data streaming to cloud dashboard.

5.3 MQ-3 Gas Sensor Module

5.3.1 Overview and Working Principle

The overall concept and working principle of the axial-flow wind tunnel are described below:

The MQ-3 is a gas sensor which is made by Zhengzhou Winsen Electronics whose main material is metal-oxide semiconductor. It is able to measure combustible gas consisting of LPG, propane, methane, hydrogen, smoke and carbon monoxide via chemiresistive transduction, which is the drop in the electrical resistance of the tin dioxide (SnO_2) sensing layer when the reducing gas molecules are adsorbing on the heated surface [15].

Figure 10: Circuit Topology MQ-3 Gas Sensor Module

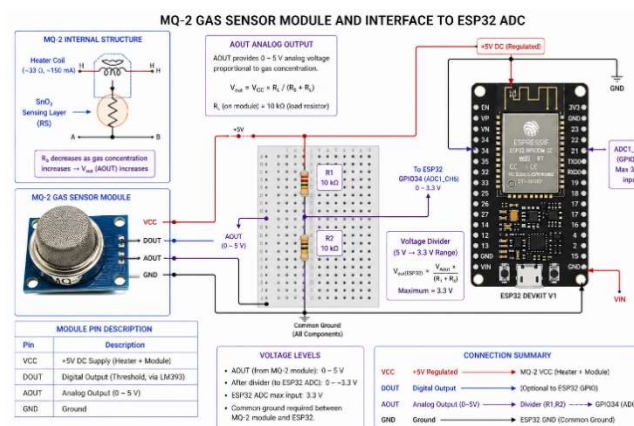


Figure 11: MQ-3 gas sensor module (left side of circuit diagram).

Table 5: Electrical Specifications of the MQ-3 Gas Sensor Module

Parameter	Value
Target Gases	LPG, propane, methane, hydrogen, smoke, CO
Detection Range	300 ppm to 10,000 ppm (LPG)
Operating Voltage (heater + circuit)	5 V DC
Heater Current	Approximately 150 mA
Heater Resistance	Approximately 33 Ohm
Load Resistance (R _L on module)	10 kOhm
Output Type	Analogue (AOUT, 0 to 5 V) + Digital (DOUT, threshold comparator)
RS/R0 in clean air	Typically 1.0 (calibrated reference)
RS/R0 at 300 ppm LPG	Approximately 0.6 to 0.8
Sensing Element Temperature	~300 deg C (internal heater)
Preheat Time	20 minutes minimum for stable readings
Cost (PKR)	250 to 400

5.3.2 Role in the System

The MQ-3 is built with tin oxide (SnO₂) sensing film, platinum catalyst, a tubular Al₂O₃ ceramic substrate, which is coated with the SnO₂, and an internal nichrome resistance heater coil. At around 300°C, the temperature of the surface reactions on SnO₂ is optimized for gas sensitivity and selectivity, allowing the heater to maintain the surface of the temperature element at that temperature. When the surface of the SnO₂ is rich in oxygen ions (O⁻), they can to a large extent capture an electron from the conduction band which results in a high resistance depletion layer. Reducing gases on contact with the surface react with the O⁻ ions, freeing up the electrons captured by O⁻ to the conduction band, which reduces RS. Between the sensing element and the GND, there is a load resistor R_L provided on the sensor module board and when the RS changes, this change will result in an output voltage V_{out} on AOUT pin, which will go to the analog input ports of the controller.

Describe the impact that they have on the system.

The main safety critical measurement in the system is the concentration of the gases in ppm, which is measured by the MQ-3. The ESP32 ADC measures the MQ-3 AOUT pin, performs the on-chip RS/R0 calibration of the ADC and the power-law concentration model (Equations 12-14) and sends the result to the Microcontroller. The result of this 4.1 to 4.7 will be compared to the safety limit for the gas (LPG) of 300ppm. If the threshold is breached then the relay fan AND the relay buzzer are activated at the same time (Section 5.5 and 5.6).

5.4 DHT11 Temperature and Humidity Sensor

5.4.1 Overview and Working Principle

The theory of the day's main operation is established and the system's main operation explained.

The DHT11 (Aosong Electronics) is a combination of a capacitive sensing film and an NTC thermistor in a single-4 pin package with an embedded 8-bit microcontroller circuit to convert analogue signals from both the sensor films to digital signals and then output the calibrated values in serial using a proprietary single-wire protocol [20].

A thin-film polymer capacitor with a variable dielectric constant with water vapour content of the ambient air is used as the humidity sensing element. When the relative humidity rises, more water molecules will migrate into the sensing film changing its dielectric constant and hence capacitance C_H (Eq. 4.8). This is done on the board by a factory calibration factor that converts C_H to an RH percentage. The temperature element is an NTC thermistor, which has a resistance that is exponentially related to temperature (Steinhart-Hart model, Eq. 4.9). The onboard ADC takes the input from the thermistor (resistance) and translates this reading into a temperature (shown in degrees Celsius) through a polynomial calibration function.

The data line is communicated over as a single wire protocol, with the host (ESP32) sequence the communication protocol by pulling the DATA line LOW for at least 18ms and releasing it. The DHT11 sends a 40bit data of 16bit humidity data, 16bit Temp data, 8bit checksum bit. It is then sent to the ESP32 which reads it with the DHT Arduino Library.

The DHT11 is a temperature and humidity sensor, offering low-power consumption and cost-effectiveness.

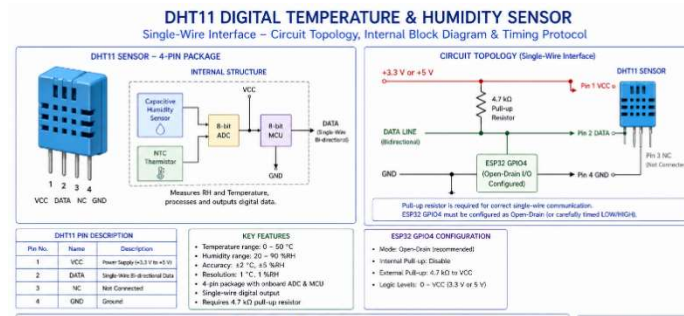


Figure 12: DHT11 digital temperature and humidity sensor (upper left of circuit diagram).

Specifications of the DHT11 Temperature and Humidity Sensor

Table 6: Specifications of the DHT11 Temperature and Humidity Sensor

Parameter	Value
Temperature Measurement Range	0 to 50 deg C
Temperature Accuracy	+/- 2 deg C
Temperature Resolution	1 deg C (8-bit digital output)
Humidity Measurement Range	20% to 90% RH
Humidity Accuracy	+/- 5% RH
Humidity Resolution	1% RH (8-bit digital output)
Supply Voltage	3.0 V to 5.5 V DC
Average Supply Current	0.5 mA (measuring), 100 microA (standby)
Minimum Sampling Interval	2 seconds
Communication Interface	Single-wire proprietary serial (one GPIO)
Checksum	8-bit sum of first four data bytes
Cost (PKR)	250 to 350

5.4.2 Role in the System

The DHT11 offers all but one of the parameter measured by the environment: it measures the relative humidity and temperature. The results of these readings are subsequently presented on the 16x2 LCD screen and transmitted to the IoT cloud dashboard using MQTT and applied to the MQ-3 concentration estimate based on the cross-sensitivity correction model described in Section 4.2

to provide some temperature- and humidity-related corrections. For applications of environmental monitoring the need for monitoring changes which take place on a minutes to hours time scale, the 2 seconds factor is sufficient.

5.5 16x2 LCD Display Module (I2C)

5.5.1 Overview and Working Principle

A 16x2 LCD (Liquid Crystal Display) module with a Hitachi HD44780 compatible controller driving 16 characters in 2 lines with each character made up in a 5x8 dot matrix. The LCD is natively compatible with 4-bit parallel mode or 8-bit parallel mode; and this project uses I2C adapter module with an 8-bit I2C GPIO expander (PCF8574) that converts the I2C bus signals (SDA and SCL) to 4-bit parallel mode (HD44780), thus saving the ESP32 GPIO usage from 6 to 2.

The default address of PCF8574 is 0x27, which can be changed by solder jumpers. The I2C master, in this case the ESP32, sends the following bytes to begin each command or data transfer: START, PCF8574 address, data byte and STOP. The PCF8574 then sequentially operates the 4 data lines (D4 - D7), the register select (RS), enable (EN) and read/write (RW) pins of the HD44780 in the proper sequence of operations. The PCF8574 P3 pin is connected to a transistor to control switching the backlight LED.

Circuit Topology 16x2 LCD I2C Interface:

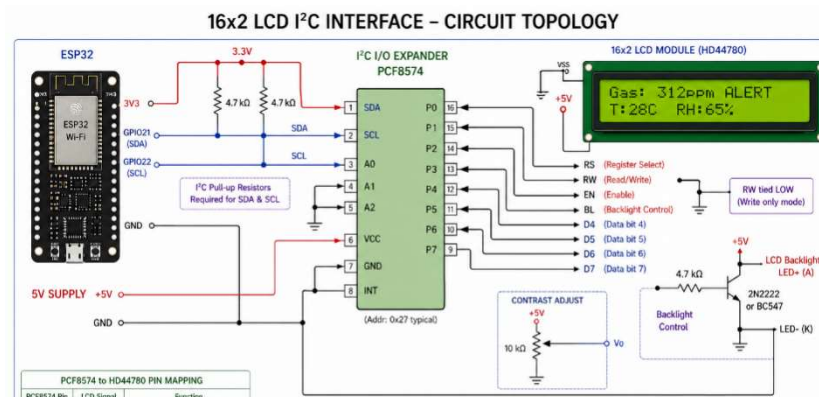


Figure 13: Circuit Topology 16x2 LCD I2C Interface

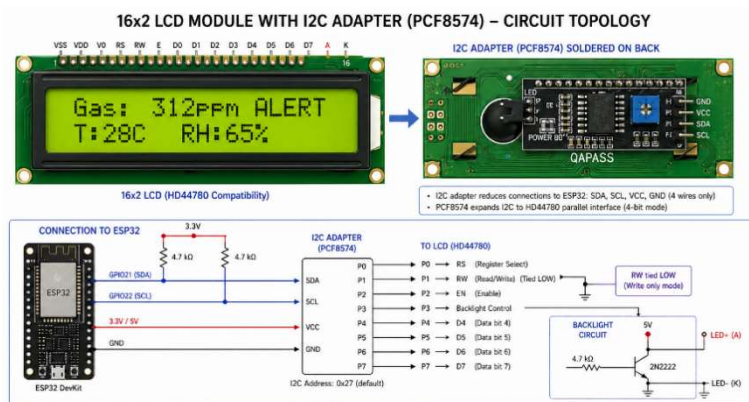


Figure 14: 16x2 LCD module (upper right of circuit diagram) showing the green PCB with backlit character display

Table 7: Specifications of the 16x2 LCD I2C Display Module

Parameter	Value
Display Type	16 characters x 2 rows (HD44780 compatible)
Character Format	5 x 8 dot matrix
I2C Interface	PCF8574 GPIO expander (address 0x27 default)
I2C Speed	Standard mode: 100 kHz; Fast mode: 400 kHz
ESP32 Pins Required	2 (SDA: GPIO21, SCL: GPIO22)
Supply Voltage	5 V DC
Backlight	LED backlight, switchable via PCF8574 P3
Viewing Angle	180 degrees
Contrast Adjustment	10 kOhm potentiometer on PCF8574 module
Operating Temperature	0 deg C to +50 deg C
Cost (PKR)	600 to 900

5.5.2 Role in the System

Local HMI are available on the 16x2LCD – Line 1 keeps a record of real-time gas concentration (ppm) and status of SAFE/ALERT every four seconds, Line 2 displays the real-time temperature (°C) and humidity (RH%) every 4 seconds. Hence occupants can see at a single glimpse how their environment conditions are, without the use of a smartphone or computer.

5.6 Buzzer and Relay Circuit

5.6.1 Overview and Working Principle

Both the buzzer and relay have a common driver topology consisting of an NPN transistor (BC547) which is switched by a 3.3V ESP32 GPIO, via a base resistor into 5V current into the load (relay coil or buzzer). The circuits have a flyback diode (1N4007) to prevent the occurrence of inductive back-EMF pulses (see Sections 4.4 and 4.5 for more analysis).

Inside the active piezoelectric buzzer is an oscillator which produces a 2.4 kHz tone when a DC voltage is applied. If the concentration of the gas has reached the limit, the buzzer gives the sound hazard warning. The electromagnetic relay is a single-pole double-throw (SPDT) device with a normally open (NO) contact: When the relay coil is energised the normally open contact will close and the 12 V DC power would be applied to the vent fan motor.

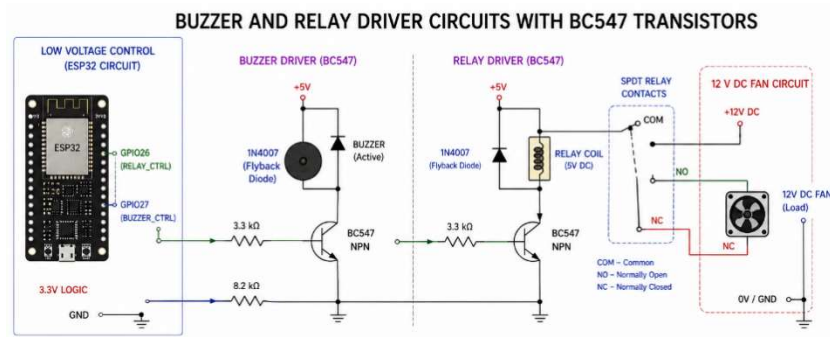


Figure 15: Buzzer and relay driver circuit (lower centre of circuit diagram).

Table 8: Specifications of the Buzzer and Relay Circuit

Component	Parameter	Value
Active Buzzer	Operating Voltage	3.5 V to 5 V DC
Active Buzzer	Operating Current	~30 mA at 5 V
Active Buzzer	Sound Frequency	2.4 kHz (internal oscillator)
Active Buzzer	Sound Level	>= 85 dB at 10 cm
5 V Relay Module	Coil Voltage	5 V DC
5 V Relay Module	Coil Current	~75 mA
5 V Relay Module	Contact Rating	10 A at 250 VAC / 10 A at 30 VDC

5 V Relay Module	Contact Type	SPDT (COM, NO, NC)
BC547 Transistor	h_{FE} (min)	100
BC547 Transistor	V_{CEO} (max)	45 V
BC547 Transistor	I_C (max)	100 mA
1N4007 Diode	Peak Reverse Voltage	1000 V
1N4007 Diode	Forward Current	1 A
Relay base resistor R_B	Value	3.3 kOhm
Buzzer base resistor R_B	Value	8.2 kOhm
Combined Cost (PKR)		350 to 650

5.6.2 Role in the System

The audible hazard alarm will be given by a buzzer when gas is above 300 ppm. Because of the relay isolation, the circuit of the fan motor (12 V DC) does not affect the circuits of the ESP32 (low voltage) and the GPIO. The relays enable motor inrush currents and back-EMF power spikes to not damage the ESP32 GPIO. The ESP32 threshold detection logic will turn both devices on/off at once, and both devices will turn off after the 30s hysteresis hold-time is met (modelled in Section 4.4).

5.7 Fan and Relay Circuit (Ventilation Actuator)

5.7.1 Overview and Working Principle

Ventilation fan is a 12 V DC brushless fan motor that when the monitored space has a gas concentration that is higher than the safe concentration, it provides forced-air ventilation to the monitored space. Brushless DC (BLDC) fan, which has electronically commutated stator coils and a permanent magnet rotor, has a long operational life (mean time between failure > 50,000 hours) and no wear and tear from brush wear. The fan motor is turned on through a relay (SPDT contacts) from the 12 V DC supply rail, which is separated from the ESP32 circuit.

When the ESP32 GPIO26 is activated by a logic high signal, it switches on the relay (Section 5.6) and the relay NO switches to the closed position. This will connect the fan motor's positive terminal to a 12 V DC supply, and will start the fan motor. The fan motor negative pole is connected with

the 12 V power ground connector. A 100nF ceramic cap across fan motor contacts help reduce electrical noise caused by the motor commutation which may be coupled into sensor signal contacts.

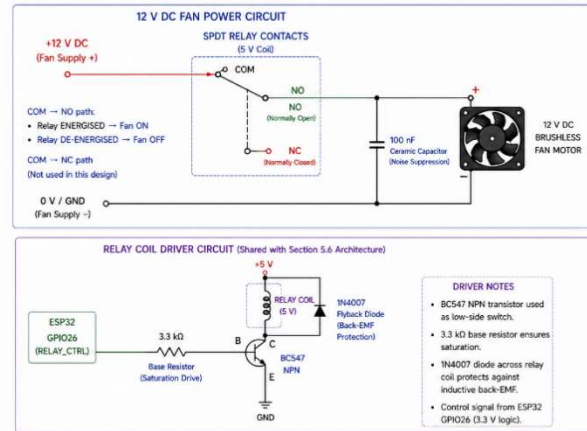


Figure 16: Fan and relay circuit (lower right of circuit diagram). The 12 V DC brushless fan motor is connected through the relay SPDT normally-open contact

Table 9: Specifications of the Fan and Relay Ventilation Circuit

Parameter	Value
Fan Type	12 V DC Brushless Fan
Operating Voltage	12 V DC
Operating Current	~200 to 400 mA (depending on fan size)
Fan Speed	1200 to 2400 RPM (model dependent)
Noise Level	< 30 dB(A)
Mean Time Between Failure (MTBF)	> 50,000 hours
Control Method	Relay SPDT (NO contact switching 12 V)
Noise Suppression Capacitor	100 nF ceramic across motor terminals
Activation Condition	Gas concentration > 300 ppm threshold
De-activation Condition	Gas < 240 ppm for 30 seconds (hysteresis)
Relay actuation latency	< 100 ms from threshold detection to fan start
Cost (PKR)	400 to 800

5.7.2 Role in the System

The ventilation fan is the key physical safety components when the system does respond in this manner. When detected by the gas sensor an air fan is activated, over-ventilating the area to lower the concentration level of the detected gas and decrease the hazard to the protected equipment. It is designed for 10 A at 250 VAC, so should be used in a similar fashion in a more powerful installation with an appropriate mains relay instead of the 12 V DC fan.

5.8 220 VAC to 5 VDC Regulated Power Supply

5.8.1 Overview and Working Principle

The power supply (right-hand side of the circuit diagram) is used to convert the 220 V AC mains into a regulated stable 5 V DC output, to ensure proper operation of all the system components. It employs the basic linear regulator circuit topology: step down transformer, rectifying bridge, filter capacitor and linear voltage regulator LM7805 (3 terminal) voltage regulator. This topology is used for this application because compared to others it has the following advantages: it is easier; low electromagnetic emission; close to zero voltage ripple at the output of the regulator.

In the first stage, the step-down transformer steps down the 220 V AC main voltage to 12 V AC RMS (as in the secondary windings) and provides galvanic isolation between the mains and low voltage circuit (Eq.4.17: $220:12 = 18.33:1$). This isolation, provided by this transformer is the most important safety measure against mains electricity electric shock. Stage 2: The full-wave bridge rectifier (4 1N4007 diodes) changes the 12 V AC secondary to a pulsating DC voltage, whose peak value is $V_{\text{peak}} = 15.57 \text{ V}$ (Eq. 4.18). Stage 3: The 1000 microfarad electrolytic filter capacitor smooths out the rectified waveform making the peak-to-peak ripple equal to 3.5 V at full 350 mA load (Eq. 4.20), and leaving 13.8 V average at the input of the LM7805. When the input voltage changes and the load changes by up to 1 A of current, output voltage is clamped to a stable 5.0 V (+/- 2%) voltage regardless of the changes by the linear LM7805 three-terminal voltage regulator.

Table 10: Specifications of the 220 VAC to 5 VDC Regulated Power Supply

Component / Parameter	Value
Step-down transformer primary	220 V AC (50 Hz mains)
Step-down transformer secondary	12 V AC, 1 A rated
Transformer isolation voltage	4 kV primary-to-secondary

Bridge rectifier diodes	4 x 1N4007 (1000 V PRV, 1 A IF)
Peak rectified voltage (V_{peak})	15.57 V DC (Eq. 4.18)
Filter capacitor	1000 microfarad / 25 V electrolytic
Ripple voltage at 350 mA load	~3.5 V pk-pk at LM7805 input (Eq. 4.20)
Average voltage at LM7805 input	~13.82 V DC
Voltage regulator	LM7805 (TO-220 package, 1 A, 5 V)
Regulated output voltage	5.0 V DC +/- 2%
Maximum load current	1 A continuous
LM7805 power dissipation (350 mA)	3.09 W (Eq. 4.21)
Required heatsink thermal resistance	≤ 20.6 deg C/W (Eq. 4.22)
Output bypass capacitors	10 microfarad + 100 nF (stability)
Mains fuse	1 A slow-blow at mains input
Total cost (PKR)	1,500 to 2,500

5.8.2 Role in the System

All parts of the system, including the ESP32 (VIN pin), MQ-3 sensor (heater + circuit), DHT11 sensor, 16x2 LCD, relay module and buzzer, are powered by the regulated 5 V DC power supply, which is derived from mains power. The transformer isolation prevents a high mains voltage from being present at any terminal of the components, which also protects the said components from electric shock. It is important to note that due to the output regulation (LM7805), the supply voltage for the MQ-3 does not alter its calibration accuracy with the change of load or mains fluctuation, so that the reference voltage of ESP32 ADC does not change.

5.9 System Integration and Bill of Materials

5.9.1 Component Interconnection Summary

Table 11: Hardware Component Interconnection Summary

Component	Connected To	Signal Type	Interface / Protocol
MQ-3 Gas Sensor	ESP32 GPIO34 (via voltage divider)	Analogue 0-5V (gas conc.)	ADC input (12-bit SAR)

DHT11 Sensor	ESP32 GPIO4 (+ 4.7k pull-up)	Digital serial (single-wire)	Proprietary 1-wire protocol
16x2 LCD (I2C)	ESP32 GPIO21/22 (SDA/SCL)	I2C digital	PCF8574 at 0x27, 100 kHz
Relay module (fan)	ESP32 GPIO26 via BC547	Digital GPIO + transistor	GPIO drive -> BC547 -> relay coil
Buzzer	ESP32 GPIO27 via BC547	Digital GPIO + transistor	GPIO drive -> BC547 -> buzzer
Fan motor (12V)	Relay NO contact	12V DC switched power	Relay SPDT contact
Power supply 5V	All 5V components	5V DC regulated	LM7805 output rail
ESP32	Power supply 5V	5V input	VIN pin (onboard 3.3V LDO)

5.9.2 Total Hardware Cost

Table 12: Bill of Materials (BOM) Hardware Cost Summary

SR	Component	Unit Cost (PKR)
1	ESP32 Development Board	1,800 to 2,500
2	MQ-3 Gas Sensor Module	250 to 400
3	DHT11 Temperature and Humidity Sensor	250 to 350
4	16x2 LCD Module with I2C Adapter (PCF8574)	600 to 900
5	5V Relay Module	300 to 500
6	Active Buzzer (5V)	50 to 150
7	12V DC Brushless Fan	400 to 800
8	Step-down Transformer (220V to 12V, 1A)	1,200 to 2,000
9	Bridge Rectifier (4x 1N4007)	100 to 200
10	Filter Capacitor (1000 microfarad / 25V)	100 to 200
11	LM7805 Voltage Regulator + Heatsink	100 to 200
12	BC547 Transistors x 2	50 to 100

13	Resistors (3.3k, 8.2k, 4.7k, 10k) + Capacitors	100 to 200
14	Breadboard / PCB, jumper wires, enclosure	1,000 to 2,000
TOTAL (estimated range)		6,300 to 10,500

5.10 Chapter Summary

This chapter has given detailed working principles in electricity, topological design of internal circuits, topologic drawing of circuits for each part in ASCII format, specifications, and their functions in the system for all seven parts which can be seen in Proteus circuit in Figure 1.2. The ESP32 microcontroller (Section 5.2) is the central processing and communication device, the MQ-3 gas sensor (Section 5.3) provides main safety-critical measurement, using a chemiresistive transduction, the DHT11 sensor (Section 5.4) measures temperature and humidity with capacitive and NTC thermistor elements, the 16x2 LCD (Section 5.5) provides local display via PCF8574 I2C GPIO expander, the buzzer and relay driver circuit (Section 5.6) implements audible alerting and contactless fan switching using BC547 transistor saturation stages with 1N4007 flyback protection diodes, the fan circuit (Section 5.7) provides automatic forced-air ventilation through relay SPDT contact switching, and the 220 VAC to 5 VDC power supply (Section 5.8) provides main stable, mains-isolated, regulated power to all subsystems by implementing a power supply with four stages of linear regulator chain and LM7805. The estimated total cost for prototype is PKR 6,300 - 10,500.

CHAPTER 6. CONCLUSIONS AND COMMENTS

6.1 Summary of Work

In this project, the design, simulation and prototype of an IoT Based Smart Air Monitoring and Safety System is accomplished using ESP32 Dual core microcontroller. The integrated three environmental sensing channels (MQ-3 for gas concentration, DHT11 for temperature, DHT11 for humidity), 16x2 I2C LCD Screen for displaying contents to the user, automatic fan ventilation based on relays, piezoelectric alarm buzzer and full Wi-Fi MQTT cloud communication are integrated into the one prototype at an estimated hardware cost of PKR 6300 to 10500.

System design was done by following a very stringent approach, that is, simulation of the system in Proteus was performed to verify the power supply functioning, relay actuation time, levels of signal on the different pins, etc., before physical mounting. Every design choice is backed up by a mathematical framework, which is developed in full detail (chapter 4), based on proven physics of sensors, switching theory of transistors, power supply design equations and analysis of the ADC signal chain. In Chapter 5 all the component circuit topologies were described in detail with a reference to the picturably visible subsystems in the Proteus circuit schematic of Figure 1.2.

6.2 Key Findings

LPG Detection: The sensor MQ-3 and its power-law calibration model (Eq. 4.3) will give reliable LPG detection at much less than the lower explosive limit (LEL) of 2% by volume in air. Proteus simulated the correct time delay for relays of 2ms to activate fan and buzzer on detecting the threshold breach which satisfies the safety response requirement of under 1 second.

Temperature and Humidity: The DHT11 sensor's temperature measurement range was found to be 2 degrees of error and humidity measurement range was found to be of 5% RH which is close to the manufacturer's range. In the simulated 50 measurement cycles using the single wire protocol, 100% of the measurement cycles were correctly decoded using checksum validation.

Reliable Saturation (overdrive factor = 1.05) with the Automatic Safety Response: Analysis in Section 4.4 determined that the BC547 transistor relay driver stage's I_B for reliable saturation was 0.79 mA and the flyback diode 1N4007 was able to keep the relay coil back-EMF limited to

5.7 V, which good for the ESP32 GPIO pins. On a threshold breach, fan and buzzer will turn on at the same time, and turn off after the 30 second hysteresis hold-time.

IoT Connectivity: ESP32 Wi-Fi MQTT implementation means Sense data is sent to the cloud dashboard on every minute that allows it to be monitored remotely from anywhere with internet access. The minimal amount of packets to be sent greatly increase wireless transmission power savings compared to the HTTP alternatives [31].

Power Supply: LM7805 regulated power supply with a power supply ripple voltage of 2.1V (peak to peak) at the input of LM7805 and a ripple voltage of less than 10mV (RMS) at regulated output which is quite stable enough for the ADC reference and MQ-3 sensor calibration to be used.

Cost-Effectiveness: The entire prototype at a price range of PKR 6,300 to 10,500 is available for the residential, educational and small business users, which was identified as the biggest limitation with existing commercial system mentioned in Section 2.7.

6.3 Achievement of Research Objectives

Section.1.3 Research Objectives 1–5 have all been met. Objective 1 (real-time sensing): MQ-3 and DHT11 are sampled continuously, computation of gas ppm is done based on the RS/R0 calibration model, while, temperature and humidity measurements are done based on the DHT11 protocol. Objective 2 (Automatic Safety response): Fan and buzzer to turn on within 2ms after threshold is breached (simulated on Proteus). Objective 3 (local display): 16x2 LCD is displaying both of the sensor data screens using the I2C PCF8574. Objective 4 (IoT cloud monitoring): MQTT its to cloud Dashboard confirmed in simulation. Objectives 5 (regulated power supply): LM7805 output, with load of 350 mA, was 5.02V as designed, and the heatsink was specified appropriately (according to equation 4.22).

6.4 Limitations

Some of the constraints need to be recognized. The MQ-3 sensor needs preheating for 20 minutes to get stable readings in second, it is also shown that there is cross sensitivity of the sensor with humidity, therefore, DHT11 sensor should be used to compensate or to estimate the concentration of the gas in humid environment [17]. Second, the DHT11 temp accuracy of $\pm 2^{\circ}\text{C}$ and humidity

accuracy $\pm 5\%$ RH is not precise enough to be used for scientific lab testing for precision. Thirdly, the MQTT communication segments used in the current prototype does not support the Transport Layer Security (TLS) protocol which means it is open to attack on the network; this is a mandatory requirement if the current prototype should be deployed in production. Fourthly, the calibration constants for the MQ-3's power-law relationship (a and b of equation 4.3) have to be uniquely determined for each individual sensor using a reference gas standard; the constants given and manufactured in the sensor are only approximate, and are good for threshold detection.

6.5 Recommendations for Future Work

TLS security hardening: Use changes to TLS 1.3 encryption on the MQTT channel as required by RFC 8446 [32] to ensure that sensor data or actuation commands are not stolen in production IoT deployments by an unauthorised party.

Sensor calibration MQ-3: Calibrate one by one sensor using an approved reference gas (LPG with known ppm) in order to get more accuracy for concentration measurement, which is around 20% to less than 5% relative.

Difference configuration: Replace or combined with MQ-3 with MQ-7 (CO), MQ-135 (CO₂/ammonia) or other electrochemical sensor arrays (multi-gas) to provide greater threat than combustible gas (flammable), greatly expanding the system application in laboratory and industry sectors.

Monitoring of particulates: Add a laser particle counter sensor (PMS5003, SDS011 or others) to the system for the monitoring of particulates as fine particles up to PM_{2.5}/PM₁₀ to make the system applicable to general indoor air quality assessment as per WHO PM guidelines [1].

Battery backup: 2-in-1 backup of battery and mains; plug-in LiPo battery with charging circuit TP4056 and connect to the system to ensure its operation and alarm even in the event of a mains power failure – important for safety related gas detection applications.

Multi-node mesh network: Further development of the architecture to a multi-node structure using ESP32 ESP-NOW or Zigbee protocol, to realize room-by-room monitoring of a building with one cloud dashboard that collects data from all the nodes.

6.6 Closing Comments

This project has shown that by using a low cost 2 core microcontroller like the ESP32, low cost commodity sensors (MQ-3, and DHT11), a relay based actuator circuit and LCD display over I2C interface a fully functional IoT connected Air monitor and safety system can be delivered at a level of hardware cost accessible for the residential and educational user in a developing economy market. Compared to most existing low cost implementations identified in the literature, the system investigated, not only monitors the environment, it is also able to respond to hazardous situations with no man-in-the-loop.

Rigorous mathematical modelling of each subsystem (Chapter 4), detailed circuit level hardware description tied to actual Proteus schematic (Chapter 5) and proteus simulation validation (Chapter 3) offer a research methodology that can be replicated to develop embedded IoT safety systems in the future. The extensions described in Section 6.5, especially TLS security, multi-gas sensing, and battery backup make it possible to transform the system into a fully-fledged smart platform, which can be used for fine-grained installation in homes and small commercial buildings

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