System Design for Early Detection of Explosive and Flammable Gas Leaks Using Mobile Robot in Confined Space

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Abstract. The presence of explosive or flammable gases in confined space may contribute towards accidents that threaten the workers safety and industrial progress. Conventionally, the existing instrument for gas detection in confined space is manually carried by humans whereby the workers or competence person itself were exposed directly to the gases. This project is aim to develop a prototype system to detect the presence of gases leak where the robotic system replaces humans to carry gas sensors. Users only need to maneuver the robot using a mobile phone to monitor the specific area that may have an explosive or flammable gas leak which includes Liquefied Petroleum Gas (LPG) and methane gases. The sensors will detect if a change in the gas concentration has exceeded a safety limit and will activate the alarm as an alert signal. The readings of gases as input signals were sent wirelessly to the Personal Computer (PC) as a user device for monitoring purposes. This prototype is successfully developed, tested and calibrated using the samples of LPG gas, methane, smoke and environment temperature. The result proved that the developed system is able to detect an air sample using selected gas sensors and display the data in graph form with live monitoring. This will contribute significantly to acquiring a new and alternative method using the system for detecting the presence of gases in confined space application.

1. Introduction

In Malaysia, every year there will be at least one worker die due to the leakage of gases or involved with explosions in industry especially in confined space. In year 2020, foreign worker was killed by a petrol tank explosion at Perak while the victim was doing pipe-cutting work and he suffered a second degree 80% burn [1]. Flammable and explosive gases are the hazards where the workers are normally exposed while working in confined spaces. The main flammable gas is methane (CH₄) while explosive gas is Liquefied Petroleum Gas (LPG) [2]. As an example, a methane gas is colourless and odourless but it is flammable and able to contribute to serious explosion conditions and is hazardous.

The early detection of gas leakage on the workspaces is very crucial to ensure the normal operation of the entire activity [3]. At present, conventional method for surrounding air testing is done by using direct-reading gas detector that need to be carried manually by the worker towards the location [2]. The main problem is the worker exposed to the gases during the testing activity was carried out. Next, the detector has shown the direct real time measurement where it will also expose workers to the gases. Effective and reasonable leakage detection methods can prevent the harm caused by gas leakage [4]. Therefore, there is a need for a moving detection system that is able to assist and replace the worker for surrounding air testing activity [5,6]. It should be comprises of electronics gas sensors that
capable of recognising presence of gases in air [7,8]. The main aim of this project is to develop a prototype of sensors system for explosive and flammable gases carried by mobile robot. The selection of suitable gas sensors are needed to be identified and the robot should be equipped with an alarming system when hazardous gases are sensed. Next aim is to test and evaluate the developed system capabilities suitable for the application. Lastly, the entire gas readings will be sent wirelessly for user interface to overcome workers from exposure to the hazardous gasses.

2. Methodology

Consist of two main parts which are software and hardware in this developed system. For the software part, the schematics diagram was design and simulated by using Proteus 8 software while SolidWork software was used to design and simulated the mobile robot base. Figure 1 shows the block diagram which is complete as a system that includes input, process and output elements. The input elements consist of power supply, gas sensors, temperature sensor and user device which is smartphone. The process element used a microcontroller Arduino Mega 2560 type as the system brain. For output elements consist of motor drivers, Direct Current (DC) motors as robot actuators, Light Emitted Display (LED), Liquid Crystal Display (LCD) and buzzer for alarming system.

2.1. Schematic Design for Sensors

The sensor MQ-2 is widely used as a smoke detector which has lower conductivity in clean air. When the target smoke exists, the sensor’s conductivity is high along with the gas concentration (300-10000 ppm) rising. It has good resistor sensitivity $R_s$ (in air)/ $R_s$ (1000 ppm iso-butane) ≥ 5 to smoke in a wide range. It is also mostly being used in industrial smoke detector applications. The sensor MQ-4 has high sensitivity to methane gas that also widely used in gas leakage detecting instruments since it has small sensitivity and has very fast response. It is also able to detect concentration between 200-10000 ppm of methane in natural gas. The sensor MQ-5 has high sensitivity to LPG and is mostly used for detecting gas leakage because it has detecting concentration range between 200-10000 ppm. The LM35 is a basic temperature sensor that gives the reading in Degree Celsius ($^\circ$C) since the output voltage is linearly proportional to temperature. It uses the fact that as temperature increases, the voltage across diode also increases. It has less than 60 Micro Ampere ($\mu$A) current drain and low self-heating, 0.08 $^\circ$C in still air with low impedance output with 0.1 Ohm (\Omega) for 1 milliampere (mA) load.
Figure 2 shows the schematic design for the gas sensors. The 16x2 Liquid Crystal Display (LCD) is used to display the direct gases sensor reading and it is able to display 16 characters in two lines. Once it exceeds the safety limit set in the programming coding, the buzzer will turn “ON” as an alarming signal to the user. The buzzer is an audio signalling device by converting electrical energy into sound energy.

![Figure 2. Schematic design for sensors.](image)

2.2. **Schematic Design for Robot**

The designed circuit for robot movement is shown in Figure 3. Two motor drivers (L298n) are chosen to actuate the DC motors for left side tyres (front and back) and right side tyres (front and back). Although the basic relays circuit are cheapest and simple to design compare to motor driver for motor actuation, but their functionality is limited to the point for modern motor application.

![Figure 3. Schematic design for robot movement.](image)
For interfacing to the Microcontroller Control Unit (MCU), the motor driver enables a direct connection with MCU General-Purpose Input Output (GPIO) and analog-to-digital converter (ADC) pins. For relay, it needed a Darlington-pair of N-doped P-doped N-doped (NPN) Bipolar Junction Transistors (BJTs), two resistors and a protection diode to interface a relay coil directly with an MCU GPIO pin. While the bidirectional motor two dual-packages Single-Pole Double-Throw (SPDT) relay require creating H-Bridge which means for connecting relay to MCU it requires connecting all the discrete components respectively. In the design circuit, the motor driver is directly connected to the digital pins 10-13 of the Arduino Mega 2560 board. The Bluetooth communication module for wirelessly transferring data to PC is connected to the Arduino Tx0 and Rx0 pins.

2.3. Robot Base Design
The design processes that are required are drawing and modifying skills the layout structure of the prototype of robot base. Each part of the robot draws parts by parts and then will be assembled to form a complete robot base. The parts include robot wheels, DC motors, robot base platform and supporters as shown in Figure 4. All dimensions in millimeter (mm) units.

![Figure 4. Isometric view of robot base design.](image)

2.4. Prototype Development
For the hardware part, the robot base was fabricated using Perspex material as the platforms for circuit components placement. The platform fabricated in two levels. The circuit constructions are performed that include robot movement located at the bottom platform, while circuit constructions for power supply, sensors and alarm system located at the top platform. Figure 5 shows the complete hardware prototype development by integrating the mechanical and electronic components.
2.5. System Operation

The system operation is mainly based on the programming sequence. The robot will be moved as in the program coding. Figure 6 shows the robot base flow of the program coding in movement. The character “t” acts as the user input button. When button “1” is pressed, the robot will move forward. If button “2” is pressed, the robot will reverse. If button “3” is pressed, the robot will turn right. If button “4” is pressed, the robot will turn left and if button “5” is pressed the robot will stop moving. The gases and temperature sensors will start monitoring the air environment as the system turns ON and data will be sent wirelessly to the PC for user interface. Buzzer will sound when the gas concentrations exceed the safety limit.

![Figure 5. Prototype hardware development.](image)

![Figure 6. Robot base operation.](image)
3. Experimental Setup
A total of two experiments have been designed to test and evaluate the performance of this developed prototype. The first experiment is to test the capability of the gases sensors when exposed to several gases samples that produce hazardous gases included LPG, methane and even smoke. This testing should be performed at outdoor with an open air environment to prevent unexpected events from happening when involved with flammable or explosive materials. The microcontroller receives input signals from sensors reading, process and send data to the user in terms of ADC value. The data conversion was performed in this part to convert ADC value into part per millions (ppm) as real gases reading value. However, different type gases sensors have their own concentration characteristics that need to refer from technical data (datasheet) provided from sensor manufactures.

The second experiment is to test the communication performance between the robot movement and the user device which is smartphone. The communication system uses a Bluetooth module (HC05) which shows that the maximum distance ability to communicate is as far as 100 meter tested by the manufacturer. This provided data will be theoretical references to be evaluated while the testing is carrying and to identify is the gas sensors reading are still sending wirelessly when robot reach maximum point of communication.

4. Results and Discussion
4.1 Gas Sensors Performance
Result in graphs form generated from the ThingSpeak application for concentrations of gases and temperature sensors during the first experiment. Figure 7 shows the sensors reading for LPG, methane, smoke and temperature without any sample gas exposure. While Figure 8 shows the sensor's readings when exposed to the samples which are LPG, methane and cigarette smoke at the same temperature environment. The gases sensor reading shows the concentration value changes increasingly while exposed to the gases samples and smoke accordingly compared to the clean air exposure.

![Figure 7. Sensors reading in clean air.](image-url)
Table 1 shows the average concentration in five times repeated exposure of the gases that caused buzzing where three of the gases have exceeded the safety limit that is set in the program coding. For smoke, the safety limit had been set at 100 ppm and the average value indicates at 160.8 ppm. While for methane, the safety limit has been set at 5000 ppm and the average value indicates at 9942.2 ppm. Then the safety limit for LPG gas has been set at 500 ppm, although the value and the average concentrations indicate at 933 ppm.

**Table 1.** The concentration of the gas that caused buzzing.

| Type of Sensor | Testing 1 (ppm) | Testing 2 (ppm) | Testing 3 (ppm) | Testing 4 (ppm) | Testing 5 (ppm) | Average (ppm) |
|---------------|-----------------|-----------------|-----------------|-----------------|----------------|---------------|
| Smoke (MQ-2)  | 117             | 168             | 157             | 242             | 120            | 160.8         |
| Methane (MQ-4)| 16001           | 5216            | 14370           | 6984            | 7140           | 9942.2        |
| LPG (MQ-5)    | 951             | 501             | 755             | 970             | 1488           | 933           |

4.2 Communication Performance

Table 2 shows the distance communication tested between mobile robot and user device in five different points of locations. The mobile robot functions well up to 80 meter only, when the distance reached 90 meter and above the Bluetooth communication has lost the connection for robot movement. However, the sensors reading are still sending wirelessly to the PC through the ThingSpeak application when the robot location is more than 100 meter.
Table 2. The communication connectivity performance.

| Type of Sensor       | Distance | 20 meter | 40 meter | 60 meter | 80 meter | 100 meter |
|----------------------|----------|----------|----------|----------|----------|-----------|
| Robot Movement (HC05)| ✓        | ✓        | ✓        | ✓        | ✓        | X         |
| Smoke (MQ-2)         | ✓        | ✓        | ✓        | ✓        | ✓        | ✓         |
| Methane (MQ-4)       | ✓        | ✓        | ✓        | ✓        | ✓        | ✓         |
| LPG (MQ-5)           | ✓        | ✓        | ✓        | ✓        | ✓        | ✓         |
| Temperature (LM35)   | ✓        | ✓        | ✓        | ✓        | ✓        | ✓         |

5. Conclusion
In conclusion, methane and LPG are main gases that exist in the surrounding air especially in confined space and the suitable gases sensor selection has been identified which is MQ-4 for methane and MQ-5 for LPG gases. Since these are flammable and explosive gases, then the smoke may produce and presence if small fire or spark occurs and MQ-2 is the best sensor selection to detecting. Also, concluded that the prototype system was successfully being designed and developed to replace workers from exposed to hazardous gases during confined space air testing. The system is capable of detecting, wirelessly sending the gas readings and able to display in live for user monitoring purposes from far. This technology is suited for the early detection of gases leaks during air testing carried out in a confined space before other routine work is carried out inside it in order to prevent worse accident from happening and negatively impact to the industry progress.

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