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Autonomous Robot for Gas Pipeline Inspection and Leak Detection

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Abstract: Gas pipeline inspection and monitoring are essential to preventing rupturing with its associated human, economic and environmental costs. Currently, the popular approaches utilized in monitoring gas pipelines are expensive and require sensors attached to the pipeline at different locations. In this work, we propose a microcontroller-based line follower robot for gas pipeline monitoring and leak detection. It uses the sensors, MQ-6 and TGS2611, to detect the presence of natural gases, methane (CH4), propane, carbon monoxide (CO), LPG gases and alcohol. Also, the system has an on-board camera and is configured to wirelessly transmit a real-time video stream as the robot navigates. If the measured gas concentration exceeds the threshold, the system is designed to set off an alarm and signal the operator through SMS, including the measured gas concentration and the GPS location information.

Keywords: Autonomous navigation, Pipeline monitoring, Gas leakage detection, LPG, Geo-location

1. Introduction

Since they present a cost-effective option, gas pipelines are the preferred means of transporting oil and natural gas over long distances. As these pipelines suffer from third party interference and from age-related degradation and corrosion [1], [2] monitoring becomes necessary to prevent gas leakage and also detect leakages on time whenever they occur. Consequently, different systems have been built to improve pipeline failure detection in order to minimize the impact [3], [4]. Early pipeline testing systems were built with a cable network to connect and communicate with sensors located at defined intervals along the pipelines [5]. This approach requires high physical security and is susceptible to network failure [5], [6]. Other monitoring systems include using data management and retrieval system by the computational analysis of the measured pressure, volume and temperature through the deployment of sensors and communication networks [7]. This system however suffers from high cost, long delays, and inflexibility to protocol changes attributes. The mass-volume balance method [8], [9], the negative pressure monitoring method [10], [11], acoustic monitoring method [12], [13] are limited by their dependence on the extent of the leak, leak flow rate and noise [14], [15].

All these leak detection methods can be categorized majorly into exterior, visual, and interior methods [16]. Some of the most recent methods of monitoring pipelines are based on wireless sensor networks (WSN) and Internet of Things (IoT) which may involve the application of machine learning algorithms [17], [18]. Robotic-based technology is an attractive alternative to independent gas leak detection since it eliminates the problem of unsafe plumbing, environmental hazards, and system damage [19]. A number of robotic machine-based techniques have been studied, either in autonomous operation or manually controlled [20]. Integration of Internet of Things (IoT) into robotics makes it more robust adaptable to Artificial Intelligence (AI), enables more multi-parameter monitoring and alarming, and makes it accessible remotely [21]. Due to the small sizes of the sensor nodes, wireless connection compatibility and low cost, system configuration can be easily adjusted to suit different applications and can also be engaged on a large scale [22]. Although such methods have in recent times shown to be effective, manageable and reliable, there are still ongoing efforts toward enhancements and improvements [23], [24].

We present in this paper a system for pipeline monitoring and leak detection with both geo-location data and real-time video coverage for remote pipeline monitoring. It uses a GSM module to enable communication between the robot and the control center and a GPS module to report the location of the gas leak.

2. Related Works

A number of research works have investigated and developed systems for pipeline monitoring and gas leakage detection [25], [26], [27], [28], [29]. These include mainly

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sensor-based monitoring systems and can be classified as either wired or wireless or robot agent-based approaches.

Zhu et al [11], proposed a system utilizing Lead Zirconate Titanate (PZT) sensors. It uses PZT sensors to detect a leakage by determining a variation in the strain due to a negative pressure wave (NPW). However, the accuracy of this method is limited because the energy of a NPW attenuates while propagating along the pipeline, thus limiting the detectable NPW signal to the smallest detectable leakage rate. Moreover, this method assumes a constant NPW velocity for all materials, which isn't practical because the NPW velocity varies with the pipeline materials and the system requires wired connections to link the sensors to the control base, thus increasing the cost and reducing performance and reliability from a possible damage to any of the wires. To mitigate the problem of attenuation in the NPW method, [3] suggested using a localization formula that is dependent only on the sensor spacing and the arrival time of the NPW.

A GSM-Based Alert System for gas leakage detection system that could mainly sense LPG gas was designed [30]. An indicator (LED) was used to communicate with the surroundings and a short message sent to a predefined telephone number to alert a user on the occurrence of a LPG leakage. However, this system is applicable only for restricted areas, detecting occurrence beyond the system's immediate vicinity is not possible.

Recently, a number of the reported systems have included the capacity to control gas leakages in addition to reporting the incidence of a leak. A gas detection system was developed using Arduino Uno microcontroller, LED, MQ6 sensor GSM module, and buzzer connected through a valve driver circuit [31]. Upon detection of a gas leakage, the valve is closed, shutting off the gas supply. Also, the LED is turned on and the buzzer is triggered. The administrator is notified through SMS. A sensor network utilizing Bluetooth communication was used by [32] to detect gas leakage. It uses a Bluetooth (HC-05) for communication and send its data to Arduino Uno. The system, upon gas detection, activates an alarm and automatically releases a gas regulator and neutralizes the air with the exhaust fan. However, such systems have a limited coverage area to maintain from the control room to ensure effective communication. An improved monitoring system that uses IOT, it sends the data over to the cloud and also displays them on the LCD was developed [33]. However, it is limited by a lack of system mobility and an absence of visual data feedback which is necessary for an effective monitoring.

A robot which is capable of traversing pipelines back and forth was made [34]. The robot displays its data on an LCD. Gas concentrations above the threshold, the robot stops, triggers the alarm, displaying the gas state on the LCD. While this system solves the problem of mobility, the system data cannot be accessed remotely.

A personal computer-controlled robot was developed [35]. The system's main control unit is a Raspberry PI 3. It uses MQ-2 in sensing the gas concentration. The movement of the robot is controlled from a PC or a mobile phone through the WIFI network. The status of leakage gas can be monitored on a personal computer or Phone with the web-server via WIFI. A problem with this system is that it requires extra manpower to operate it effectively and requires strong internet connections in order to function effectively.

3. System Overview

After a review of the related works, the following are the main objectives that we have set for the proposed system: (1) develop a line follower robot to move along the path drawn close to the pipelines; (2) develop a gas detection circuit to detect the occurrence of a leak in the surroundings; (3) develop a system to communicate sensor data along with the location to the central system; (4) include a surveillance camera system for a real-time video transmission for pipeline monitoring. The system uses two sensors positioned on the robot to monitor the gas concentration of the environment and update the microcontroller. If the gas concentration exceeds the set threshold the system will set off an alarm, send the gas alert SMS along with the leak location to the control room. Wi-Fi, Bluetooth and ZigBee are short range technologies and are unsuitable for long distance applications [36]. As a result, GSM is used to send the data to the control room.

4. System Implementation and Operation

The prototype system comprises of two parts: the gas detection system and a robotic car, on which the camera and other sensors are mounted, for mobility. A block diagram of the system is as shown in Fig. 1. The architecture of the detection circuit consists of the ATMEGA328P microcontroller, and is coupled with a GSM module for communication and a GPS module for geo-location information. The sensor node is an array of MQ-6 sensor and TGS211 sensor and can be customized depending upon the target gases to be sensed. The sensed analog signals are converted to digital through an ADC. ESP32 CAM module is used for video real-time monitoring of the surrounding. The gas detector circuit also has an alarm system to notify people within the surrounding on the event of a gas leak. The robot car is a four-wheel line follower, which trails a pre-defined path and avoids obstacles. It is designed using a PIC16F877A microcontroller and DC motors for its movement. The path to be taken by the robot is drawn using a black line maker. The robot uses Infrared Ray (IR) sensors to find the path and direction and sends the signal to the microcontroller which drives the motor in accordance with the IR sensors' feedback as programmed. The overall algorithm of the system is as shown in Fig. 2.

The sensor node measures the concentrations of gases in the environment using an array of gas sensors. When the sensor values exceed the default threshold value, the

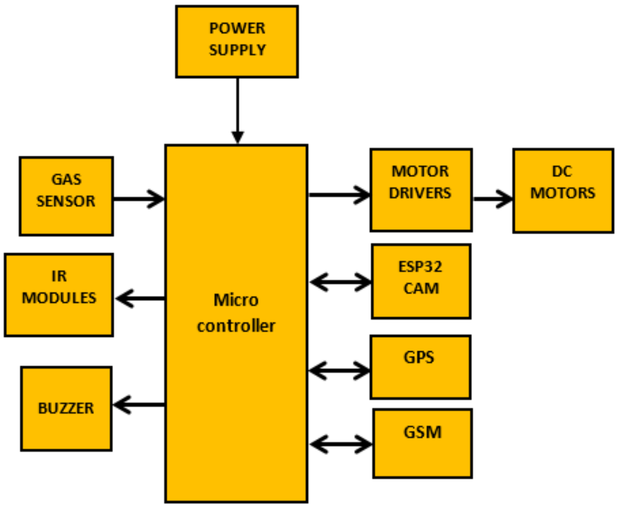

Figure 1. Block diagram of the Gas Pipeline Monitoring and Leakage Detection System

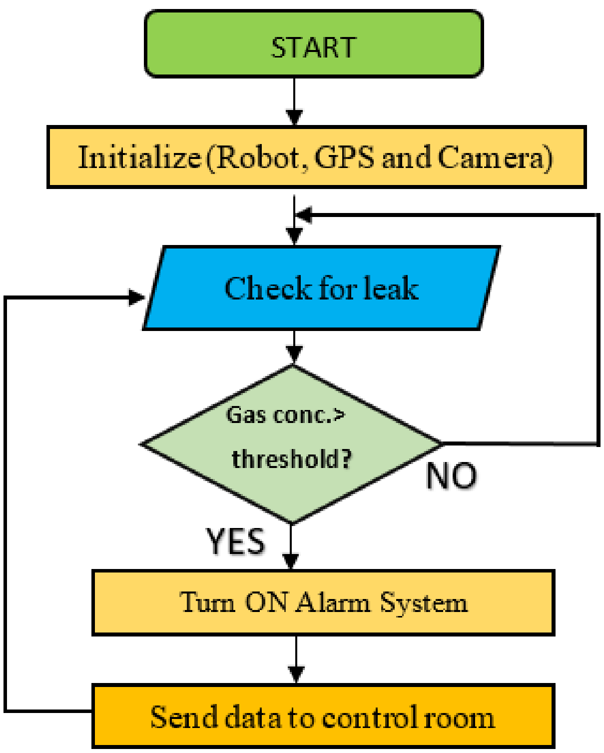

Figure 2. Flow chart of the system algorithm

alarm system is triggered and the control room is also notified. The calibration constants, line equation constants and complex processes were calculated for every family variant using its graph. Using such methods, the real-time software is implemented to calculate the gas concentration in ppm using sensor output voltage. This process is repeated for both sensors. Fig. 3 shows the LPG sensitivity graph of MQ6 sensor using data obtained from the datasheet [37]. The calibration calculation is carried out by reading the analog values from the sensors through an Analog to Digital Conversion (ADC). The gas sensor provides an output voltage which is fed to the microcontroller's ADC input. ADC reads this signal and digitizes it.

The value of the sensor resistance (R_O) measured in clean air is 20kΩ.

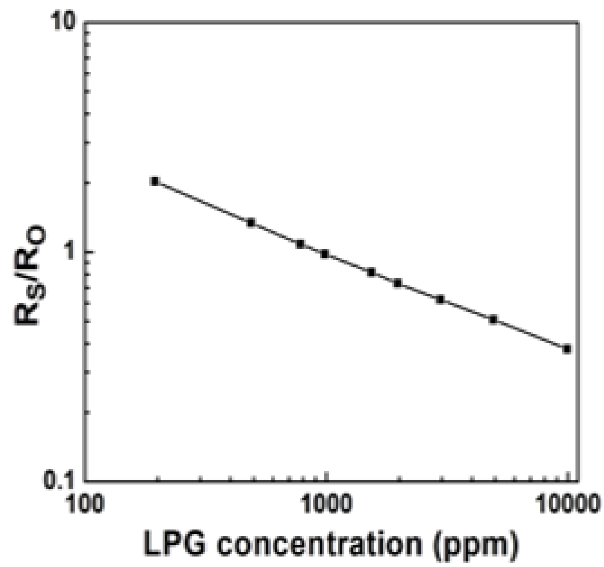

Figure 3. Mq6 sensor sensitivity graph

The relationship between the sensor resistance and the gas concentration for LPG can be expressed as:

$$\frac{R_S}{R_O} = c(PPM)^m \qquad (1)$$

Where 'c' is a constant, (R_S) is the average value of sensor readings in the presence of gas. From the Mq6 sensitivity graph in Fig. 3 and taking two points (x1, y1), (x2, y2) as (1000, 1) and (10000, 0.4) respectively on the LPG curve,

$$\text{Log}_{10}(Y) = m\text{Log}_{10}(X) + \text{Log}_{10}(C) \qquad (2)$$

$$\textit{Where;}\ X = \text{PPM},\ Y = \frac{R_S}{R_O}\ \textit{and}\ c = \textit{intercept} \qquad (3)$$

$$\textit{and}\ m = \frac{d\,[\mathrm{Log}_{10}\,(Y)]}{d\,[\mathrm{Log}_{10}\,(X)]} \qquad (4)$$

Where;

m and c are calculated as -0.4 and +1.19, respectively. (5)

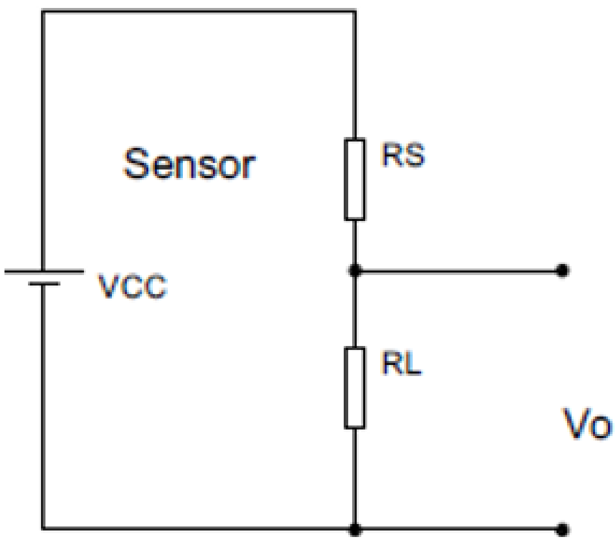

Figure 4. Gas Sensor Connections

In the sensor circuit shown in Fig. 4, (R_S) is the sensor resistance that is series- connected to the load resistance (R_L) and they both form a voltage divider circuit, V_{CC} is the input voltage and V_{OUT} is the output load voltage of the sensor which is read through the analog output and converted to a digital value using (6).

$$V_{out} = \frac{\text{Analog Value x 1023}}{5} \qquad (6)$$

Applying voltage divider rule to the circuit in Fig. 4 and dividing by (R_O):

$$\frac{Rs}{Ro} = \frac{(Vc - Vout)}{Vout}\,\frac{R_L}{Ro} \qquad (7)$$

From (2),

$$ppm = 10^{\left[\frac{\log\left(\frac{Rs}{R_O}\right) - \mathrm{Log}\ (C)}{m}\right]} \qquad (8)$$

substituting (7), into (8),

$$ppm = 10^{\left[\frac{\log\left(\frac{R_L - (Vc-1}{R_O V_{out}}\right) - \mathrm{Log}\ \ (C)}{m}\right]} \qquad (9)$$

Where, R_L, V_C, and Vout are constants, m and c calculated already. The gas concentration in parts per million (ppm) is obtained from (9). The software is implemented by applying these equations. The value of the load resistance used is 47kΩ.

5. Car Robot System Locomotion

The robot is placed on a path such that the line (black), intended to be drawn beside the pipeline, lies in-between the left and right wheel with one sensor each put at both sides. The system is configured to move in the forward direction if the left and right IR sensor detect any colour other than black. If the left IR sensor senses the line, the robot turns leftward. However, a detection by the right IR sensor would make the robot turn rightward. The flow chat in Fig. 5 shows the algorithm. A line is drawn across the initial line at the terminal point so that as soon as both sensors detect the line, the robot stops.

The rated speed, current and voltage of the dc motor are 1000RPM, 0.3A and 6V respectively. The speed is controlled by feeding a PWM from the PIC microcontroller to the enable pin of the L293D IC which changes the voltage across the motor. The speed and the direction are controlled from the code command.

The wheel diameter is 68 mm (approximately 214 mm circumference) and it has a center hole of 5.3 x 3.66 mm. As the motor speed is measured in rotations per minute, to cover a longer distance in the same time, one with a higher circumference and a higher motor effort is used [38]. The rubber wheels have a higher traction which enables it go through bends better without skidding off the lane. The wheels weigh 3.2 grams each and this reduces the weight of the robot and improves its traction.

The whole system is attached to the bottom of the enclosure. Metal studs of 7mm length provide the necessary spacing between the wheel and the enclosure. The wires from the motors are taken out through the pipe extender and passed to the circuit.

6. System Hardware and Software

Fig. 6 shows the layout diagram of the gas detection system using the MQ-6 and TGS2611 respectively. It includes a buzzer to create the alarm system. The system uses a GSM module to enable remote communication with the control room while the GPS module acquires the leakage location. The microprocessor frequency is set to operate at an optimal value of 16MHz. The microcontroller used in the design of the car robot is the PIC16f877a. The system (shown in Fig. 7) performed optimally at a clock frequency of 16MHz. The DC motors are driven through L293D IC (because the microcontroller cannot power the 6V motors directly). The

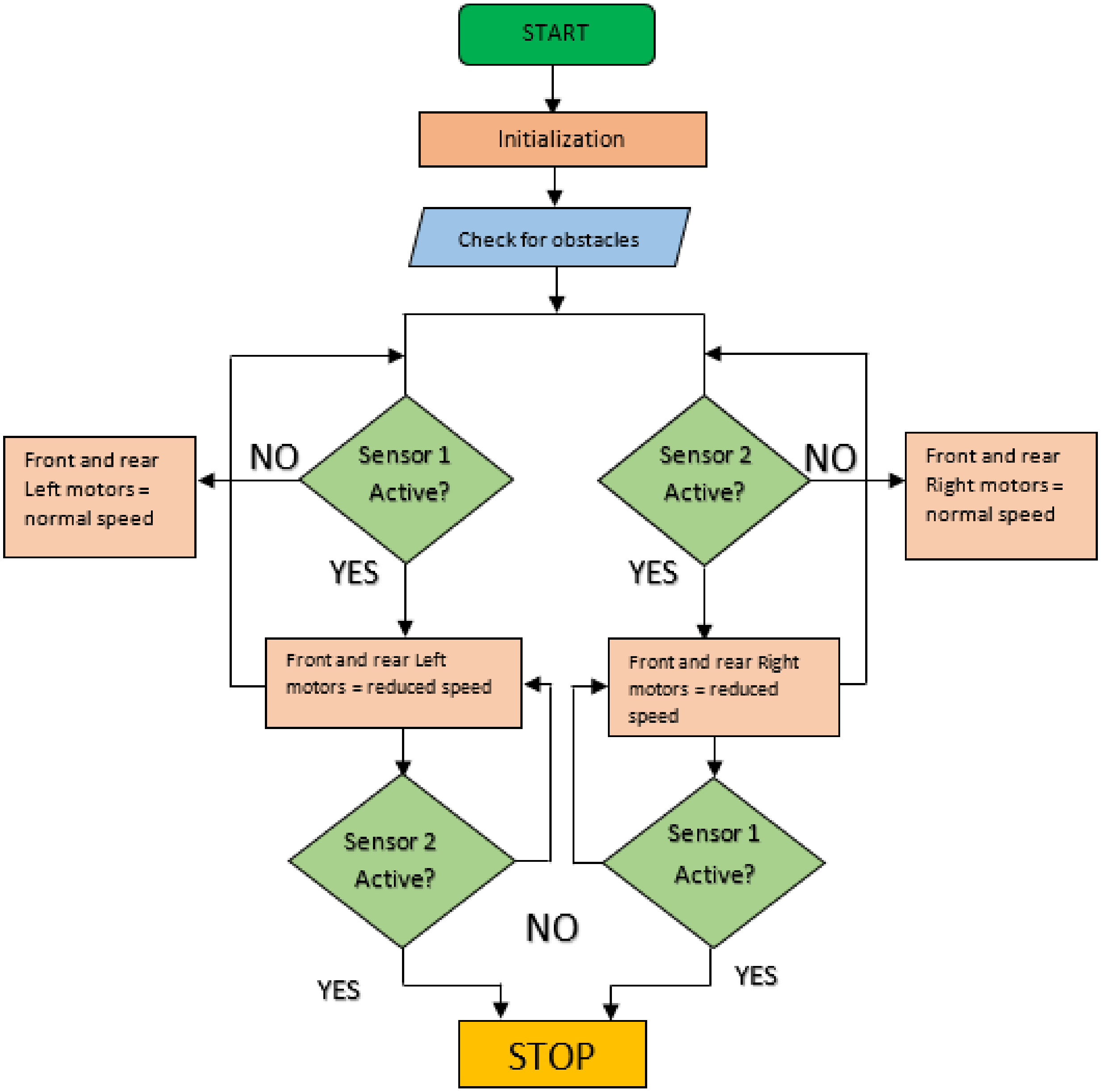

Figure 5. Flowchart of the line follower locomotion

robot has two IR sensors attached to it in order to sense the path to follow. The microcontroller receives signals from the sensors and controls the robot accordingly to ensure that the robot moves on its track.

7. Results and Conclusion

The sensors were preheated for over 24 hours before carrying out the calibration to make the readings more accurate. The practical testing of the prototype system (shown in Fig. 8) was done using butane based lighter, which forms an ingredient of our gas system. When the lighter is turned off, the gas sensors do not detect the gas. The buzzer is triggered as soon as the lighter is turned on and a message containing the location is sent. The test results confirm the effective operation of the prototype by detecting low and high gas leakage levels and alerting the users by issuing appropriate audio and radio warning signals. Fig. 9 shows a message sent to the control room when the robot detects gas leakage.

The system test was also carried out outside. At 0m, a LPG gas concentration level reading of 490 PPM was recorded. From the graph in Fig. 10, it is observed that the farther away the gas leakage detection system is from the LPG gas cylinder, the lower the detected gas concentration level and vice versa. This experiment was performed in

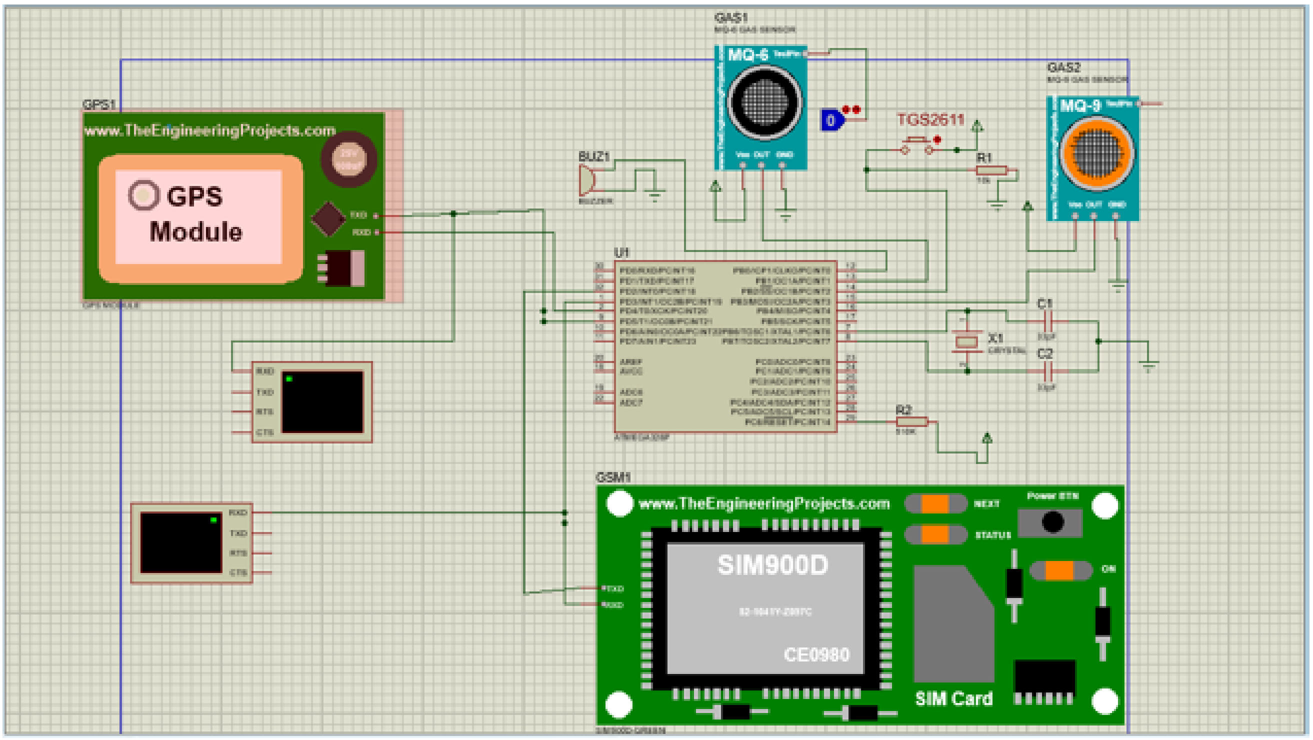

Figure 6. Wiring diagram of the Gas Leakage System

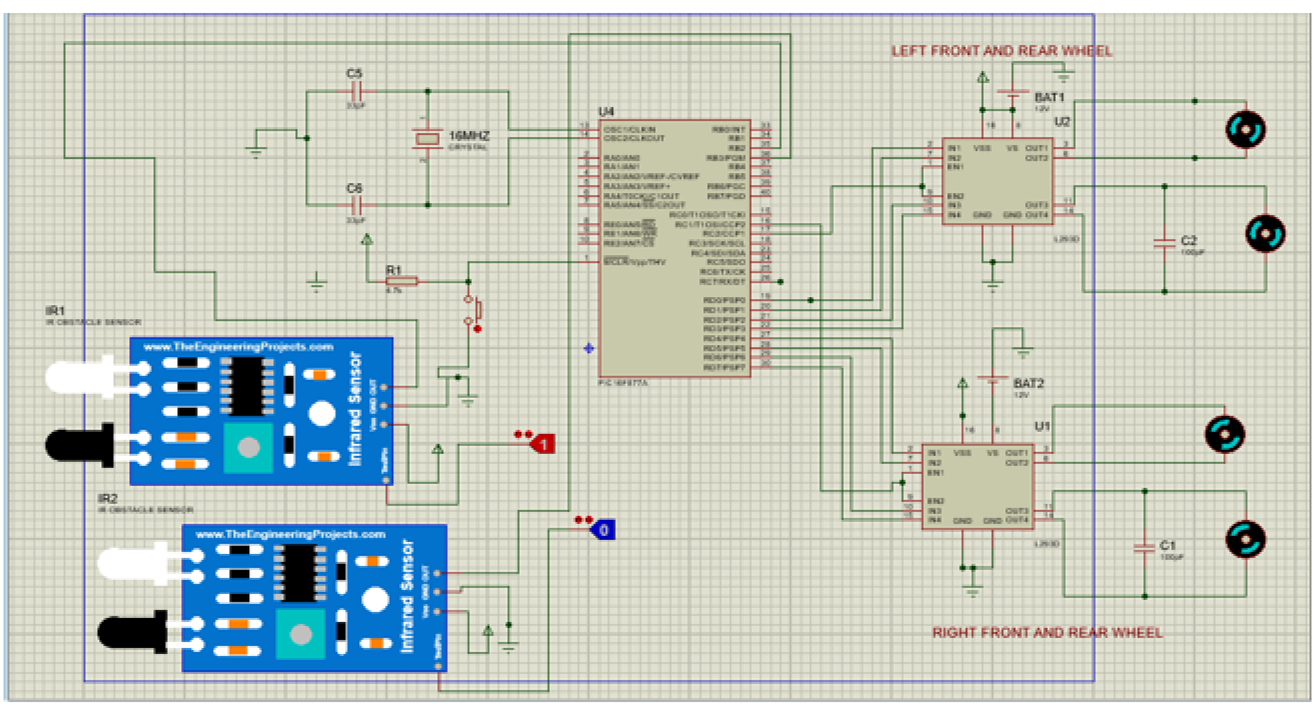

Figure 7. Wiring diagram of the Line Follower Robot

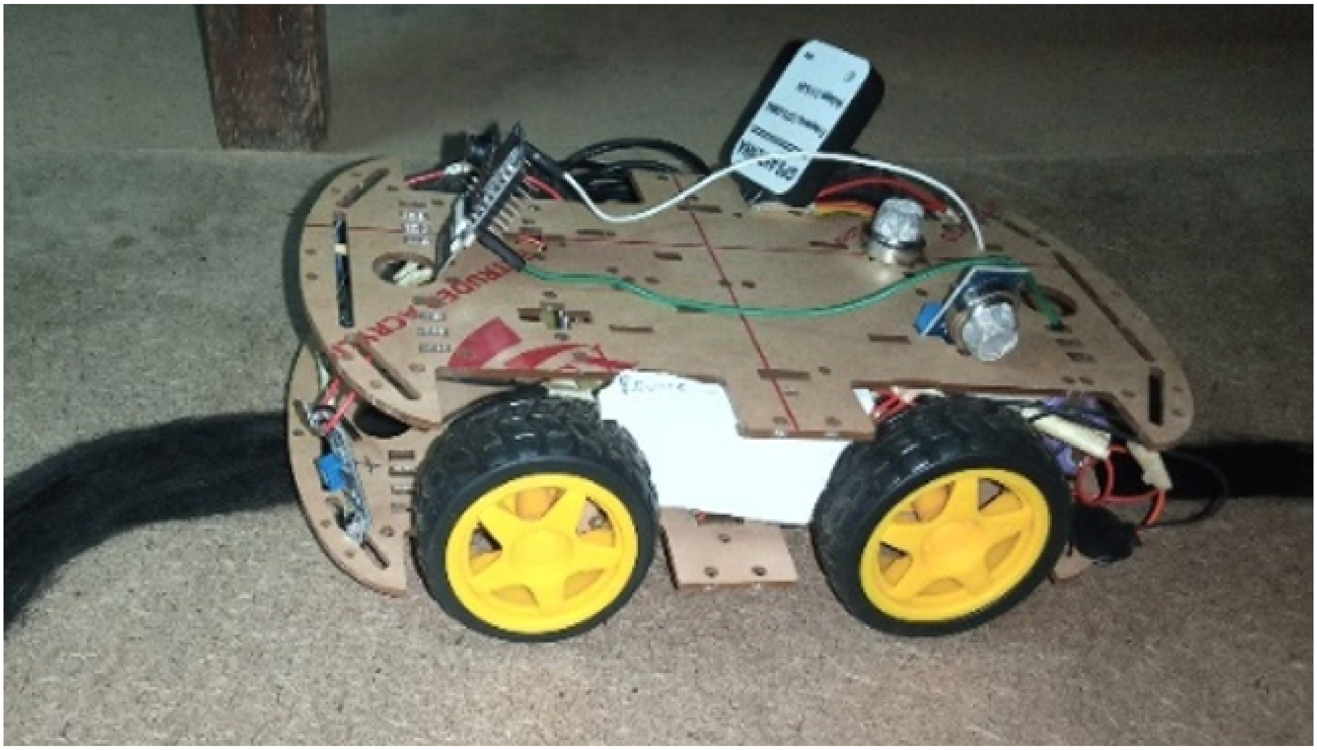

Figure 8. Image of the developed gas detector robot

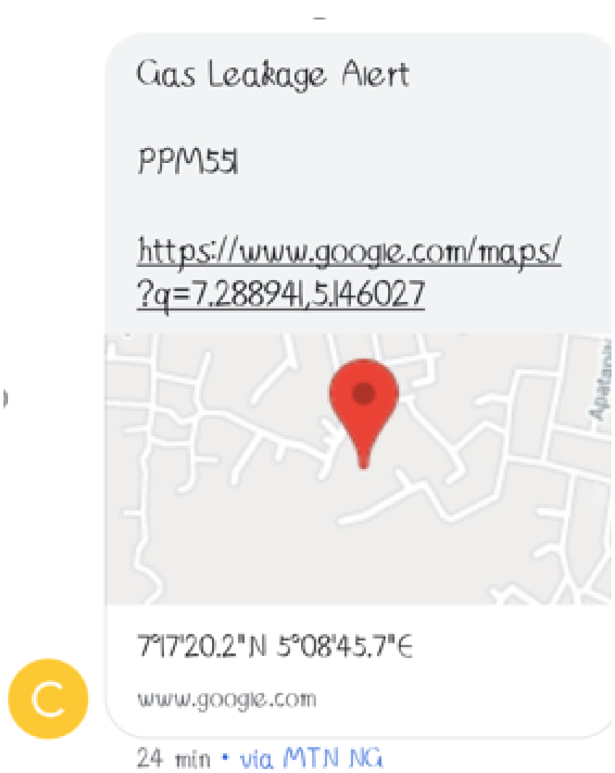

Figure 9. Message sent by the robot to the control manager upon gas leak

the open space and is affected by environmental parameters such as wind speed and direction.

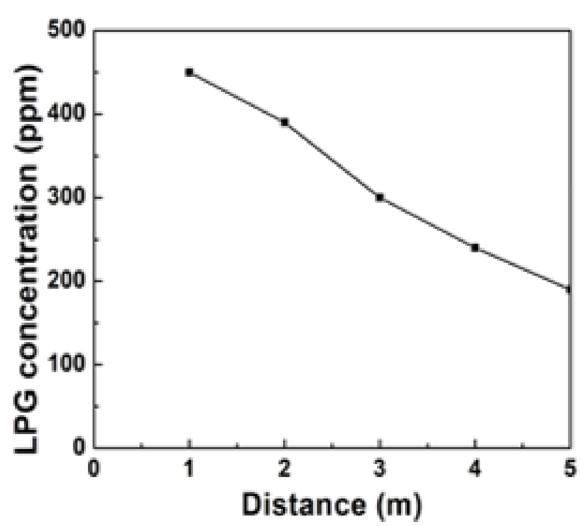

Figure 10. Gas concentration level variation as a function of the distance from LPG containers

In our previous work, a similar system was tested indoors and the gas detection time was found to vary as a function of distance from the gas source as given in (10) [28].

$$T_c = 5\,(D_{LC} - 1) \tag{10}$$

Where; T_C is the time taken to rise above the threshold gas concentration level and D_{LC} is the distance from the gas source.

A screenshot of the real-time video stream interface of the system is shown in Fig. 11. It was designed using ESP32 CAM. The code was written in C and programmed using an FTDI programmer. The output can be received on either a laptop or mobile phone with hotspot feature. This simultaneously takes the live feed and also stores the video in a memory card stick.

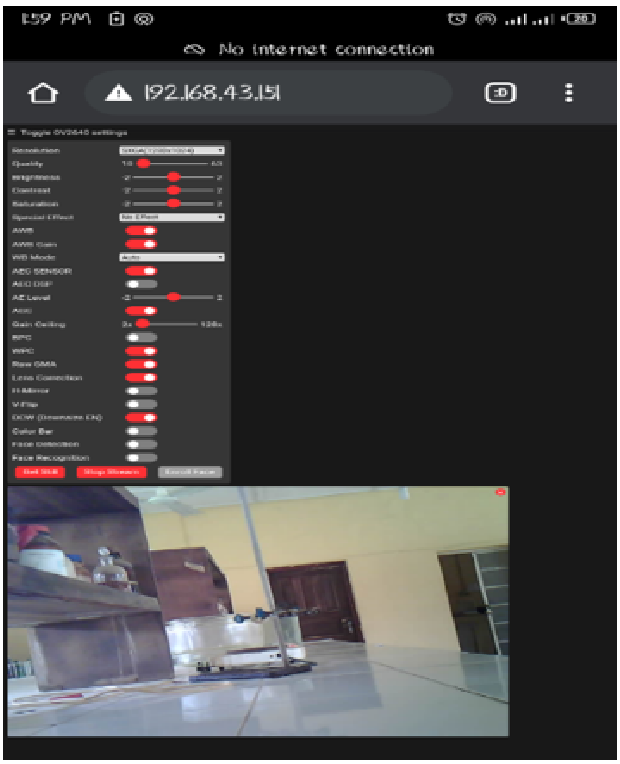

Figure 11. The Camera output interface showing the parameter settings.

8. Conclusions and Future Scope

In this work, we have developed an autonomous robot for gas pipeline inspection and leak detection. It uses an IR sensor-based line follower robot to navigate along a specified path. The gas detection system uses MQ6 and TGS2611 sensors to detect and measure the gas concentration, setting off an alarm and sending a text message if the gas concentration is above the prescribed limits. Also, the developed system is capable of video surveillance, a necessary tool for monitoring the state of health of the pipeline. This system provides real time inspection of gas pipeline and has a quick response rate, thus making the diffusion of critical situations faster than the manual methods. The work could be extended by using UAVs thus increasing its capacity for wide area surveillance of pipelines and over water bodies. Also, integration with IoT could prove useful in locations that have a good data network connection.

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