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Solar-powered Mobile Robot for Monitoring Gas Distribution Pipe Leak Using IoT Application

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Abstract

The constraints of gas distribution pipe leak monitoring robots in outdoor environments are the limited battery capacity and the method used as a monitoring system to assist the work of gas pipe leak inspection officers, which takes a long time. Therefore, the robot requires independent battery charging and real-time monitoring systems. This study resulted in a solar-powered gas distribution pipe leak monitoring robot that can provide real-time information on the robot's battery capacity and gas odor concentration data along the inspected gas distribution pipe. This robot can directly channel electrical power to the robot's battery using solar energy. This Mobile Robot uses a Photovoltaic (PV) module, Light Detection and Ranging (LiDAR), a Compass, a gas sensor, a voltage sensor, a current sensor, an ATMEGA 2560 Microcontroller, and Node MCU V3 ESP8266. The Internet of Things (IoT) application uses the Blynk application to monitor battery capacity and the concentration value of gas odor detected by the robot. The test results show that by using the PV + battery module, this mobile robot can work for more than 60 minutes compared to using only the battery for around 55 minutes. This work was successfully implemented based on IoT performance using the Blynk Application to monitor battery capacity conditions of voltage and current data and gas concentration data. It is also shown that the average delay time for sending data from voltage, current, and gas sensors to the Blynk application was around 0.226 seconds.

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1. Introduction

A highly sensitive and precise gas odor detection system is essential for monitoring gas distribution pipelines and identifying leaks. Many studies have explored the use of electronic noses in gas odor detection systems in various applications, including portable [1] and mobile [2], with the implementation of active sensing and fast time-scale odor signal processing of odor identity and location [3]. Some applications of electronic noses on mobile robots to track the location of outdoor odor sources using Vision and Olfaction Fusion algorithm [4], Use of robot swarms for odor source localization [5], application of probabilistic algorithms for gas odor detection applications on single and Multi-Robots [6] and Simultaneous mapping and localization method (SLAM) combined with gas distribution mapping (GDM) on mobile robots to plot gas distribution on a map and locate gas sources [7].

As is known, PT. PGN (Perusahaan Gas Negara) serves natural gas customers: households, commercial, and industrial. This service implements a tiered operational distribution system that is implemented through high-pressure distribution pipes, medium-pressure distribution pipes, and low-pressure distribution pipes. Based on the implementation of the operational distribution system, it is a big job to monitor the condition of gas pipe leaks when viewed from the geographical location and coverage. Robots used for outdoor exploration use rechargeable dry batteries [8], such as those used in Lithium-Ion batteries in electric vehicles [9]. However, there are obstacles for robots that are applied in outdoor environments and require long exploration times, namely related to power supply, because dry batteries have limited usage time and power capacity consumed by the robot. Several robotics studies that use solar power for mobile robot power supply include: Liquid Spraying Robots [10], Agriculturally Based Fruit Picking Robot [11], Reconnaissance Robot [12], Fire Fighting Mobile Robot [13], Agriculture Robot [14][15]. When the robot explores, the solar power module must also charge the robot's battery by absorbing sunlight using solar panels. For this reason, power management is needed for the robot to determine the power generated by the solar power module and the power consumption used, so that no power crisis will affect the performance of the mobile robot.

Many studies have been conducted on the application of Internet of Things (IoT) technology for: management and monitoring of air pollution in outdoor environments [16], LPG gas leak detection [17], gas monitoring in poultry farms to improve odor and fly management [18], and for gas leak detection, monitoring and security systems [19]. This makes it easier for operators to monitor the system, but it has not been applied to mobile robots deployed in outdoor environments. Based on several problems described, in carrying out monitoring work on the condition of gas distribution pipes in the external environment, a real-time intelligent system is needed so that it can lighten the work of operators inspecting the condition of gas distribution pipes for leaks.

This study proposes a gas distribution pipe leak monitoring robot using solar power. This robot can channel electrical power directly to the robot's battery using solar power. This four-wheeled robot uses a Photovoltaic (PV) module, Light Detection and Ranging (LiDAR), a compass, a gas sensor, a voltage sensor, a current sensor, a lithium polymer battery, a drive motor, and 4 DC power window motors. The IoT application using Blynk monitors battery capacity conditions and gas odor concentration values detected by the robot. The purpose of this study is to help gas pipe condition inspection officers obtain real-time information about the condition of the robot's battery capacity and the condition of the pipe, whether there is a leak or not, based on voltage, current, and gas concentration data displayed on the Blynk application via Android.

2. Research Methodology

The stages of research carried out are as shown in Figure 1, namely: (1) making robot hardware, assembling supporting electronic components and robot mechanics; (2) making robot software, designing a robot performance control system using the Arduino sketch application and downloading the results to the Arduino Mega2560 module; (3) making a monitoring system using Blynk, creating a battery condition monitoring system in the form of voltage and current data and gas sensor reading results; (4) hardware measurement, taking measurements on each sensor module used; (5) system testing, testing the robot in the external environment using PVC pipes and butane gas in real-time; (6) analysis, producing an analysis of the proof of the research results; (7) conclusion of research results, drawing conclusions and plans for further research.

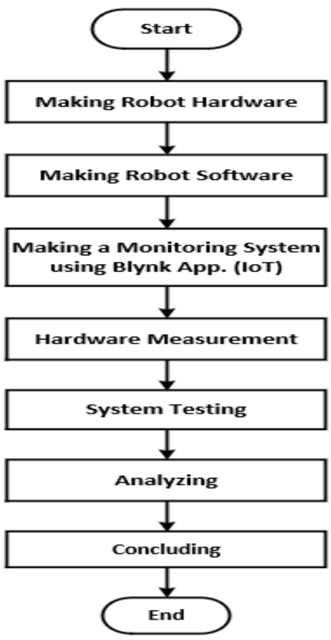


Figure 1. The stages of research

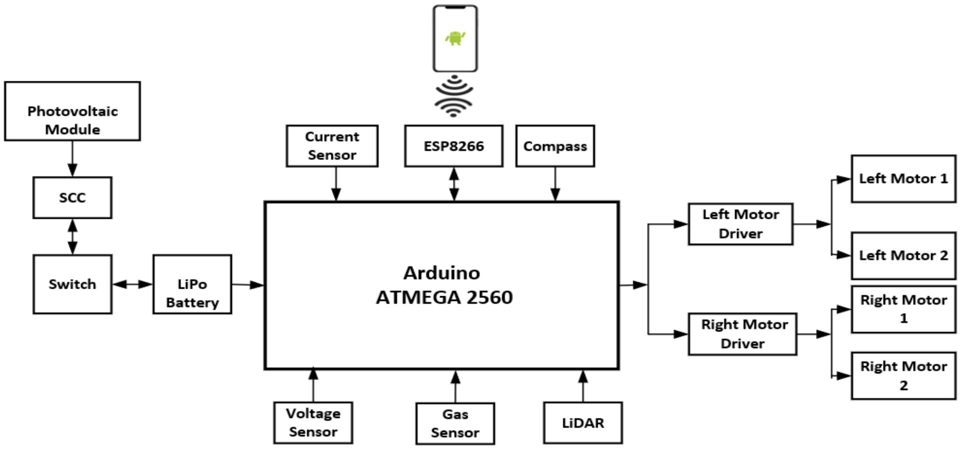


Figure 2. Hardware design

2.1 Hardware Design

The hardware design of the Solar-powered Robot to monitor gas distribution pipe leak conditions based on a Fuzzy Inference System (FIS) and Internet of Things (IoT) consists of a Photovoltaic (PV) Module, Solar Charger Controller (SCC), Lithium-Polymer Battery, Switch, Voltage Sensor, Current Sensor, Arduino ATMEGA 2560, Node MCU V3 ESP8266, LiDAR, Gas Sensor, Compass, Motor Drivers, Left Motors, and Right Motors.

As shown in Figure 2, this Robot uses solar energy as an energy source to supply Energy during the implementation of monitoring gas distribution pipe leaks as an alternative energy if the dry battery type Lithium Polymer (LiPo) used as the robot's energy source experiences a decrease in capacity. When the PV module performs the task of absorbing solar energy, the battery functions to store electrical energy from the conversion of solar energy. The PV module used in this study is Polycrystalline. Its specifications are explained in Table 1.

The PV module is connected to the SCC module to control the battery charging process by controlling the current and voltage generated by the PV Module. If at the time of overcharging from the PV and overuse by the load, this SCC can prevent reverse current to the PV and short circuits on the load. The SCC module used is the MPPT 20A model. The LiDAR sensor used in this study is the YDLIDAR X4 type. This sensor performs a 360° scan to obtain the angular coordinates and distances of objects around the robot. Table 2 describes the specifications of the YDLiDAR X4 sensor.

The HMC5883L Compass Sensor is used for robot navigation. This module is sufficient to detect the Earth's magnetic field. The data generated from the compass is binary data converted from the earth's magnetic field to digital data, for example, north is generated the same as data 0, and south is equal to 7F, and other degree data are linearly. Connection from the module to the microcontroller can be done in 2 ways. One uses PWM (Pulse Width Modulation) data, 1 mS (00) to 36.99 mS (359.90) for high signals (High), in other words, 100µS/0 with + 1 mS offset, low signals (low) around 65 mS between pulses. The second way uses I2C, this method can be used directly, so that the data is read exactly 00 - 3600, equal to 0-255 [20].

Table 1. PV Module Specification

Specifications	Value
Maximum Power	20 W
Operational Voltage	17.2 V
Operational Current	1.18 A
Open Circuit Voltage (V_{oc})	21.6 V
Closed Circuit Current (I_{sc})	1.23 A

Table 2. YDLIDAR X4 Specifications

Specifications	Value
Voltage	5 V
Current	350mA
Sampling frequency	5000 Hz
Range	0.12 – 10 m
Angle Range	0~360°

The INA219 Voltage Sensor and ACS712 Current Sensor measure battery voltage and current and can be sent to an Android via IoT technology using ESP8266 hardware and the Blynk application. The TGS 2600 Gas Sensor is used to detect gas Odor. This sensor has an output in the form of voltage data if it detects gas levels in the air. So that the operator can read the sensor reading data, the reading results are converted by the program to produce a PPM (Parts Per Million) value, so that this data can be sent to Android. The output pin of this gas sensor is connected to Pin A0 on the Arduino ATMEGA 2560. This sensor is supplied with a voltage of 5 volts.

Node MCU V3 ESP8266 is an Internet of Things platform module. This study uses it as a WIFI module to connect directly to WIFI and create a TCP/IP connection [21]. The BTN7960 motor driver module is an H-bridge module based on two BTN7960 Half-Bridge ICs combined into one. The driving motor uses a 12-Volt DC Power Window Motor. This type of DC motor has a large torque but is needed for low speeds, because this robot monitors gas leaks.

The Arduino ATMEGA 2560 microcontroller functions to process input data and produce the desired output [22]. It has 54 digital input/output pins, where 15 pins can be used as PWM output, 16 pins as Analog input, and 4 pins as Universal Asynchronous Receiver Transmitter (UART), a 16 MHz crystal oscillator, USB connection, power jack, ICSP header, and reset button. ATMEGA 2560 itself has 11 ports and has a total of 100 pins. The chip has Serial Data (SDA) and Serial Clock (SCL) pins, 4 serial communications, and a change interrupt pin, which is very possible if used for control system needs that use many sensors and serial communication lines.

2.2 Software Design

The working system of the Solar-Powered Robot for Monitoring Gas Distribution Pipe Leaks Based on the Fuzzy Inference System (FIS) and Internet of Things (IoT) is described through a flowchart as shown in Figure 3. Figure 3(a) is a flowchart of the main program.

The next subprogram is a program that sends battery capacity and gas concentration data to Android. This subprogram is shown in Figure 3(b). This subprogram is used to display battery voltage, battery current data, and gas concentration data to determine whether the gas distribution pipe is leaking or in normal condition. The Blynk application installed on Android will display battery voltage, battery current, and gas concentration sensor reading data if the WIFI pairing configuration from the ESP8266 component to the Android portable hotspot is connected. The display of the Blynk application used on Android is shown in Figure 4.

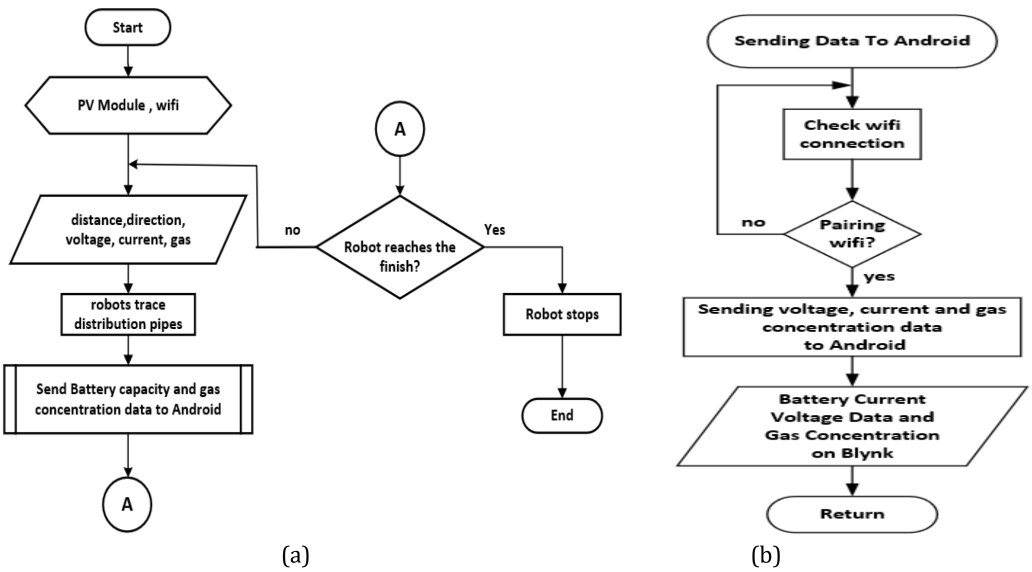


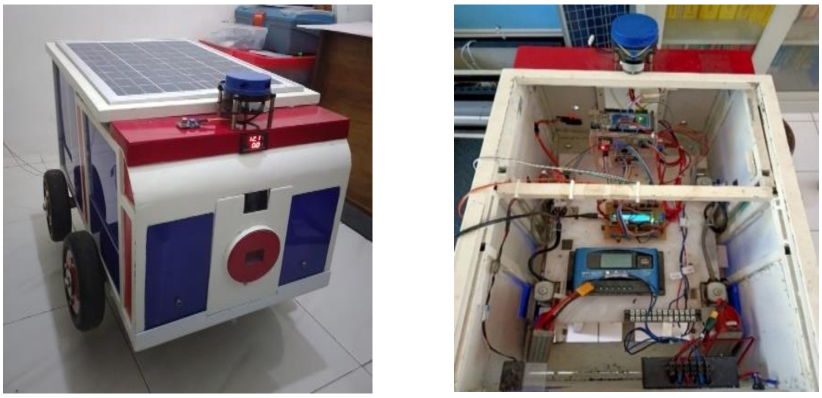
Figure 3. Flowchart of the system; (a) Main program; (b) Subprogram for sending data to android

Figure 4. Initial design of the IoT display in the Blynk application

3. Results and Discussions

3.1. Hardware Design Result

Figure 5 shows the results of the hardware design of the Solar-powered mobile robot that monitors gas distribution pipe leaks using the Internet of Things (IoT) application. Figure 5(a) shows the result of the mechanical hardware design, and Figure 5(b) shows the electrical installation hardware design result. This smart robot weighs 26 kg and uses a Lithium Polymer battery with a capacity of 2600 mAh.



(a) (b)

Figure 5. Robot design result; (a) mechanical; (b) electrical installation

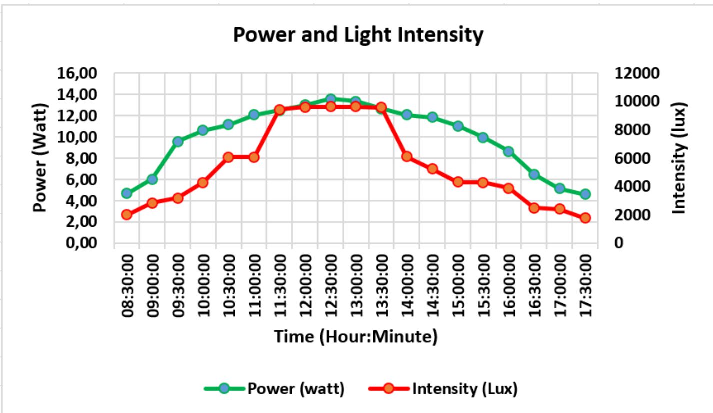


Figure 6. Results of power measurements against light intensity

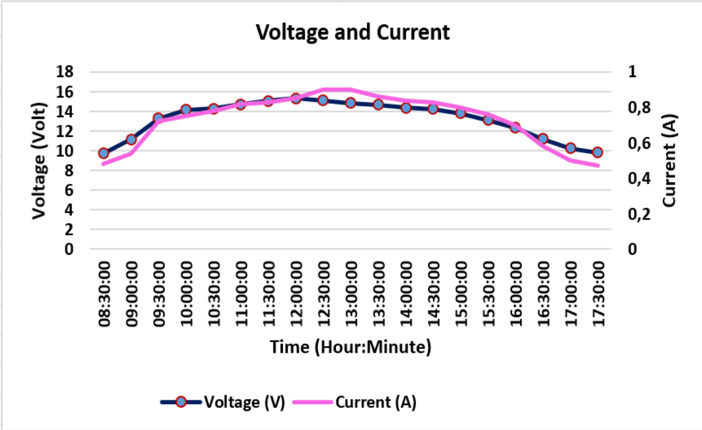


Figure 7. Results of measuring voltage against current

The Photovoltaic (PV) module is positioned as installed on the Robot with a slope of about 0º. The results of testing this PV module show that the PV can produce current from 08:00 to 17:30 WIB. The power generated depends on the light intensity. Figure 6 and Figure 7 show that the maximum current obtained is 0.9 A from 12:00 to 13:30 WIB with an average light intensity of 9620 lux. The voltage produced by this PV module is 15.30 Volts. Thus, the maximum power potential of this PV module is 13.59 Watts.

3.2. Battery Test Result

Several experiments have been carried out on the PV module to determine how much maximum current can be supplied to charge the Robot's battery. In this Robot battery test, two tests were carried out, including to find out how long the PV module requires when charging the current from the battery, and how long the battery runs out when the robot works in the field using the help of the PV module and without the PV module. Previously, direct measurements were made on the total current of the robot load. The total current measurement data is presented in Table 4.

Table 4 explains that the average total current required by the Robot when operating is 3600mA, so the power supply from the battery and PV module must meet the total current. Both combinations of power supplies enable the current Robot to work longer. Testing charging when not operating and discharging the battery when operating can be presented in Table 5 and Table 6.

From the results of battery power measurements, when a robot is operating without using a PV module, the Robot can be operated for 55 minutes. When assisted by a PV module, the Robot can last 125 minutes during the day, when the PV module produces the maximum current to charge the battery. This can be proven by the ability of the PV module to charge the battery for 75 minutes without operating. While at 09.00 and 15.00 the robot only lasted less than 30 minutes, this is because at that time the PV module was not optimal in supplying power to the battery and the load on the Robot increased with the presence of the PV module and SCC on the battery so that the power in the battery runs out quickly compared to without installing the PV and SCC modules.

Table 4. Data of current measurement on the robot.

Equipment Operations	Average Current Usage (mA)
Electronic equipment on: (ATMega2560, ESP8266, and sensors)	800
4 Motor on	2800
All loads	3600

Table 5. Battery charging duration measurement

Time (Hour)	Lux Average	Duration (minute)
09:00	5430	150
12:00	9566	75
15:00	3805	180

Table 6. Battery discharging duration measurement

Mode	Time (Hour)	Lux average	Duration (minute)
Battery	-	-	55
	09:00	5430	25
PV+ Battery	12:00	9566	125
	15:00	3805	30

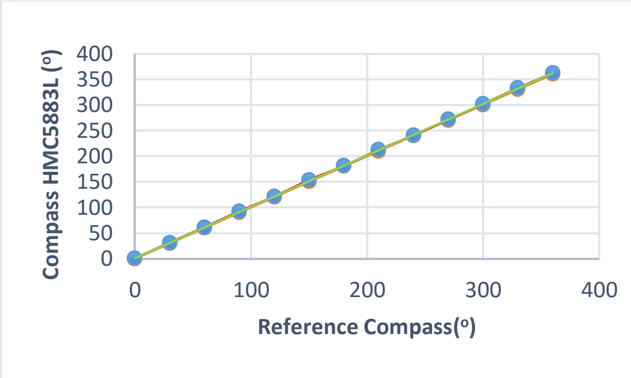


Figure 8. Graph of the test results of the HMC5883L compass sensor against the reference compass

3.3 Compass Test Result

The HMC5883L compass sensor test was carried out by comparing the sensor reading results with the reference compass sensor. In this test, the reference compass sensor was used, namely the compass sensor on the REALME 3. The reading of each sensor was installed with a heading angle of 0° and rotated clockwise. The results of the compass sensor test can be seen in Figure 8.

From Figure 8, it can be explained that the compass angle is read between 0 < angle < 360. The measurement of the reference compass with the measurement results of the HMC5883L compass has a small percentage of error. The compass reading is close to linear, as evidenced by the measurement results and the results of the linear equation with x values and constants less than 5.

3.4 LiDAR Test Result

This test measures the minimum to maximum range of LiDAR to the object. The test is done by measuring the distance of the target object in LiDAR. Table 7 shows the data on the results of reading the minimum distance of the object that can be read by the LiDAR sensor, with a test distance range of 0 - 0.24 meters, with an average error of 0.83%. Referring to the data in Table 7, the results show that the minimum distance LiDAR can measure the distance to an object is 0.12 meters.

Table 8 shows the data for the maximum distance reading of Lidar with a test distance range of 0.5 - 12 meters and an average reading error of 0.93%. In the data in Table 8, it is known that Lidar has a maximum range of 10.5 meters. It can be concluded that the further the distance of the object, the higher the average reading error will be.

Table 7. Minimum distance testing data of LiDAR.

Distance (Meter)	Read Distance (Meter)	Error (%)
0 – 0.11	0	-
0.12	0.121	0.83
0.16	0.161	0.83
0.2	0.201	0.83
0.24	0.241	0.83
Average		0.83

Table 8. Maximum distance testing data of LiDAR.

Distance (Meter)	Read Distance (Meter)	Error (%)
0.5	0.505	1
1.5	1.495	0.33
2.5	2.509	0.36

3.5	3.517	0.48
4.5	4.531	0.68
5.5	5.525	0.45
6.5	6.561	0.93
7.5	7.606	1.41
8.5	8.6	1.17
9.5	9.679	1.88
10.5	10.662	1.54
11.5	0	-
12.5	0	-
Average		0.93

3.5 Gas Sensor Result

The test was conducted using butane gas. It was conducted indoors and outdoors, as shown in Figure 9. This test shows the sensor's response to changes in gas concentration in the air and environmental conditions. Figure 10 shows the results of the indoor gas sensor test, while the outdoor gas sensor test is shown in Figure 11.

From this test, it can be concluded that the detection of gas concentration in the air has a response according to the wind speed around it. Where in Figure 10 the gas concentration data tends to be high when tested indoors, while when tested outdoors as shown in Figure 11 it is known that the gas sensor response is greatly influenced by the wind speed around it so that when the wind is strong the gas concentration decreases and even reaches a value of 0ppm.

3.6 Voltage Sensor Test Result

The voltage sensor connected to the battery has an output of 15.89 volts, and the voltage sensor connected to the load has an output of 12.7 volts. The voltage sensor output is also affected by the condition of each component connected to the sensor, so the measurement results are constantly changing. The results of the voltage sensor measurements can be seen in Table 9.

(a) (b)

Figure 9. Gas sensor testing; (a) inside the lab room; (b) outside the lab room

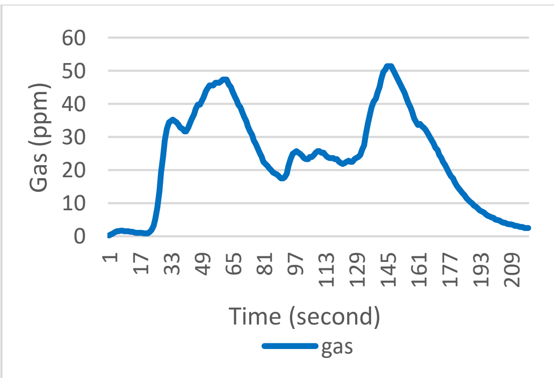


Figure 10. Indoor gas sensor test graph

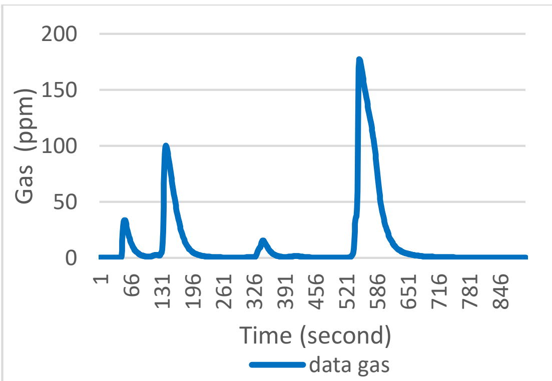


Figure 11. Outdoor gas sensor test graph

Table 9. Data of the voltage sensor test.

Component	Input (Volt)	Output (Volt)
Battery Voltage Sensor	4.96	15.89
Load Voltage Sensor	4.96	12.7

Table 10. Data of the current sensor test.

Component	Input (Volt)	Output (Ampere)
ACS712 Battery to Load Current Sensor	4.97	0.94

3.7 Current Sensor Result

In the ACS712 current sensor, the battery to the load gets a current sensor input voltage of 4.97 VDC with an output current of 0.94A. The measurement results of the ACS712 current sensor can be seen in Table 10.

3.8 Blynk Test Result

Test results of sending voltage, current, and gas concentration sensor reading data to Android based on IoT technology using the Blynk application are shown in Figure 12, namely, the Blynk display in the form of voltage, current, and gas concentration sensor data when the robot is on standby but not yet running and butane gas has not been detected.

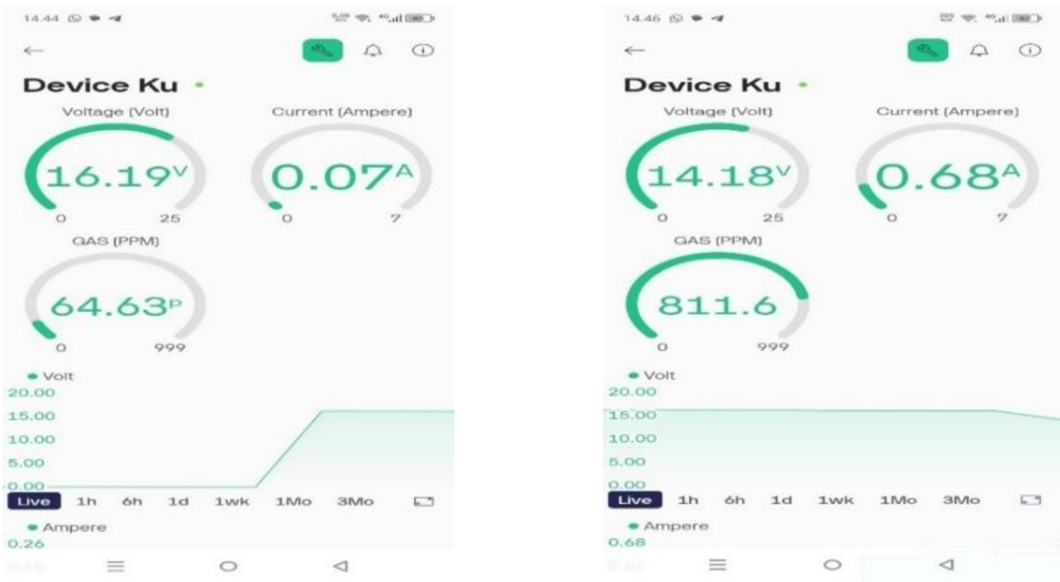
Based on the outcomes of five tests conducted for real-time monitoring of voltage, current, and gas concentration displayed in a Serial Monitor using the Blynk Application, as indicated in Table 11, it can be noted that the average transmission delay for data from the voltage, current, and gas sensors in the Blynk application is approximately 0.226 seconds.

Figure 12. Blynk display shows the robot is on standby and has not detected the smell of butane gas

Table 11. Data of delay time for delivery of voltage, current, and gas concentration.

Testing To-	Time in Blynk (seconds)
1	0.21
2	0.24
3	0.23
4	0.23
5	0.22
Delay Average (seconds)	0.226

Figure 13. Overall system testing in the outdoor environment



(a) (b)

Figure 14. Blynk displays when the robot is activated and given the smell of Butane gas; (a) sensor reading data at minute 3; (b) sensor reading data at minute 3.15

3.9 Overall System Testing Result

The testing of a solar-powered robot monitoring the condition of gas distribution pipe leaks using the Blynk application was carried out in the motorbike parking lot of the Universitas Bhayangkara Surabaya campus in Surabaya. The test medium was a 4.5” PVC pipe with a length of 18 meters, a U model, and Butane gas as a source of gas odor, as shown in Figure 13. The results of reading gas concentration data by the robot can be directly viewed using the Blynk application, as shown in Figure 14, so when the robot is run in the field and given a gas Odor, gas concentration information can be obtained, which is always up to date automatically. Likewise, to update the robot’s battery capacity data while operating.

While the robot is in motion, information is gathered from the voltage, current, and gas sensors, as illustrated in Figure 14(a). This figure presents the data on Blynk at the 3rd minute, where the battery voltage is recorded at 16.19 volts and the current at 0.07A. In contrast, Figure 14(b) displays the data at the 3.15th minute, revealing a battery voltage of 14.18 volts and a current of 0.68A.

Figure 15 displays the results from the examination of gas concentration levels in the outdoor environment, as shown in Figure 14. At 3 minutes and 15 seconds, the robot detected a notable gas odor measuring 64.63 ppm. At 3 minutes and 15 seconds, the highest gas concentration recorded was 811.61 ppm, indicating a leak in the gas distribution pipe. At 3 minutes and 17 seconds, the gas concentration level started to drop to a value of 0.04 ppm, as the gas odor was not identified until the robot completed its task.

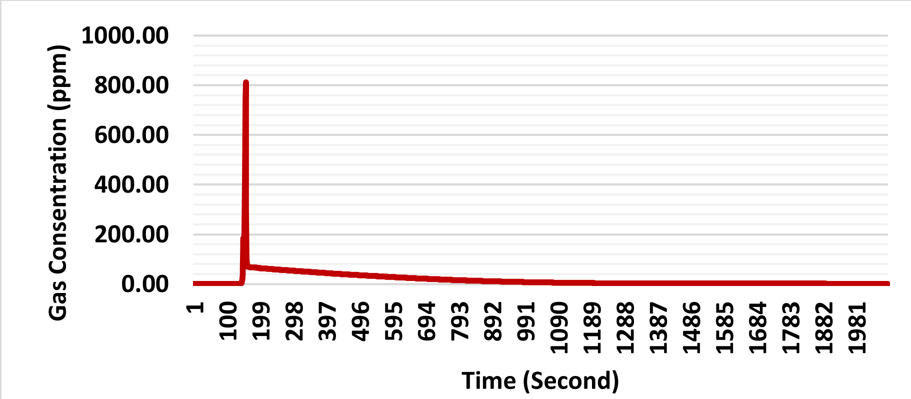


Figure 15. Graph of gas concentration reading results in the outdoor environment

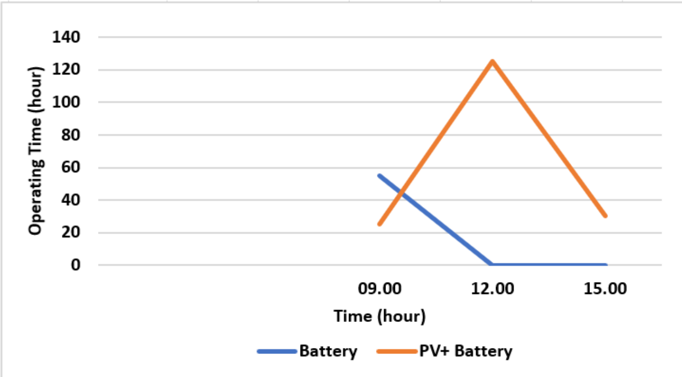


Figure 16. Comparison of the robot's operating time when using only batteries and using batteries and PV modules

3.10 Discussions

Based on the results of hardware creation, software, hardware measurements, and overall system testing, it can be analyzed that using PV modules greatly helps robots overcome battery power crisis conditions. This proves that the robot can work longer than if it only uses batteries, as shown in Figure 16.

The use of IoT technology for monitoring battery conditions in the form of battery voltage and current data and gas odor concentration information greatly assists the work of gas distribution pipe leak monitoring operators as shown in Figure 14 (b) there is information about gas distribution pipe leaks, namely a gas odor of 811.6 PPM was detected. However, the robot cannot yet provide information on the location of the leaking distribution pipe.

4. Conclusion

Based on the design and testing results of this solar-powered gas distribution pipe leak monitoring robot, it is known that the PV module can produce a maximum average light intensity of 9600 lux; the maximum power produced is 13.4 Watts at 11:30 - 13:30. Gas Sensor can detect the level of gas odor concentration with a distance of 30 cm at a response time interval of 30 seconds in clean air indoors, while in an outdoor environment at a time interval of 40 seconds. The robot can work longer, when using PV module and battery resources, namely for 125 minutes at 12.00 with an average sunlight intensity of 9566 lux, compared to only using batteries for around 55 minutes. By utilizing the application of IoT technology, operators can monitor battery capacity remotely in the form of voltage and current data and gas odor concentration, so that it can be known whether the distribution pipe is in good condition or there is a leak based on the gas odor concentration data sent to the Blynk application, where the sensor data information sent by the microcontroller wirelessly to Android has a delivery delay of 0.226 seconds.

Future work that will be conducted is to develop a solar-powered mobile robot monitoring system using GPS, IoT, and website-based technology. So that it can monitor in real-time the location of the robot and the distribution pipe that is leaking.

Acknowledgment

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References

[1] P. Borowik, L. Adamowicz, R. Tarakowski, K. Siwek, and T. Grzywacz, "Odor detection using an e-nose with a reduced sensor array," *Sensors (Switzerland)*, vol. 20, no. 12, pp. 1–20, 2020, doi: 10.3390/s20123542.

[2] J. Burgués, M. D. Esclapez, S. Doñate, and S. Marco, "RHINOS: A lightweight portable electronic nose for real-time odor quantification in wastewater treatment plants," *iScience*, vol. 24, no. 12, 2021, doi: 10.1016/j.isci.2021.103371.

[3] J. Crimaldi *et al.*, "Active sensing in a dynamic olfactory world," *Journal of Computational Neuroscience*, vol. 50, no. 1, pp. 1–6, 2022, doi: 10.1007/s10827-021-00798-1.

[4] S. Hassan, L. Wang, and K. R. Mahmud, "Robotic Odor Source Localization via Vision and Olfaction Fusion Navigation Algorithm," *Sensors*, vol. 24, no. 7, pp. 1–19, 2024, doi: 10.3390/s24072309.

[5] J. Wang, Y. Lin, R. Liu, and J. Fu, "Odor source localization of multi-robots with swarm intelligence algorithms: A review," *Frontiers in Neurorobotics*, vol. 16, 2022, doi: 10.3389/fnbot.2022.949888.

[6] A. Francis, S. Li, C. Griffiths, and J. Sienz, "Gas source localization and mapping with mobile robots: A review," *Journal of Field Robotics*, vol. 39, no. 8, pp. 1341–1373, 2022, doi: 10.1002/rob.22109.

[7] W. A. S. Norzam *et al.*, "Mobile Robot Gas Source Localization Using SLAM-GDM with a Graphene-Based Gas Sensor," *Electronics (Switzerland)*, vol. 12, no. 1, pp. 1–17, 2023, doi: 10.3390/electronics12010171.

[8] D. McNulty, A. Hennessy, M. Li, E. Armstrong, and K. M. Ryan, "A review of Li-ion batteries for autonomous mobile robots: Perspectives and outlook for the future," *Journal of Power Sources*, vol. 545, pp. 1–22, 2022, doi: 10.1016/j.jpowsour.2022.231943.

[9] A. Rastegarpanah *et al.*, "Towards robotizing the processes of testing lithium-ion batteries," *Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering*, vol. 235, no. 8, pp. 1309–1325, 2021, doi: 10.1177/0959651821998599.

[10] N. Evalina, F. Irsan Pasaribu, and A. Azis Hutasuhut, "The Use of Solar Power in Liquid Spraying Robots," *Engineering and Applied Technology*, vol. 1, no. 2, pp. 131–135, 2023.

[11] I. Miah, S. Sultan, J. Wangchuk, and S. R, "Development of Solar Power Agriculturally Based Fruit Picking Robot," *ESP Journal of Engineering & Technology Advancements*, vol. 2, no. 4, pp. 54–59, 2023, doi: 10.56472/25832646/jeta-v3i1p109.

[12] C. C. Alpe, H. Pandey, and S. Kolte, "Solar-powered Reconnaissance Robot," *International Journal of Novel Research and Development (IJNRD)*, vol. 7, no. 5, pp. 326–334, 2022.

[13] N. Duc-Nam, V. Le-Huy, L. Trong-An, N. Dinh-Trung, and N. H. Viet-Anh, "Design and Implementation of a Solar-Powered Mobile Robot for Transportation Application," *Universal Journal of Mechanical Engineering*, vol. 12, no. 2, pp. 17–24, 2024, doi: 10.13189/ujme.2024.120201.

[14] N. Nireekshana, M. A. Goud, R. B. Shankar, and G. N. Sai Chandra, "Solar Powered Multipurpose Agriculture Robot," *International Journal of Innovative Science and Research Technology*, vol. 8, no. 5, p. 299, 2023.

[15] A. Ghobadpour, A. Cardenas, G. Monsalve, and H. Mousazadeh, "Optimal Design of Energy Sources for a Photovoltaic/Fuel Cell Extended-Range Agricultural Mobile Robot," *Robotics*, vol. 12, no. 1, pp. 1–22, 2023, doi: 10.3390/robotics12010013.

[16] S. M. Popescu *et al.*, "Artificial intelligence and IoT driven technologies for environmental pollution monitoring and management," *Frontiers in Environmental Science*, vol. 12, pp. 1–19, 2024, doi: 10.3389/fenvs.2024.1336088.

[17] F. Prasetia and B. Soewito, "Iot system for leak detection and monitoring of liquefied petroleum gas," *Journal of Theoretical and Applied Information Technology*, vol. 98, no. 15, pp. 3000–3010, 2020.

[18] D. Jeevitha, K. Aarthi, T. Yashika, T. Pasavakeerthi, and P. C. S. M. E, "Iot-based Gas Monitoring in Poultry Farms: Enhancing Odor and Flies Management," *International Research Journal of Modernization in Engineering Technology and Science*, vol. 6, no. 5, p. 927, 2024, doi: 10.56726/IRJMETS55439.

[19] M. P. Kalpana*, M. S. Kumar, M. S. Vignesh, and V. R, "Gas Leak Detection, Monitoring and Safety

System using IOT," *International Journal of Recent Technology and Engineering (IJRTE)*, vol. 8, no. 6, pp. 4785–4787, 2020, doi: 10.35940/ijrte.f9041.038620.

[20] D. A. P. Wardhana, D. C. Happyanto, E. Purwanto, G. E. A. Akbar, and K. T. Putra, "AutoDock-IPS: An Automated Docking for Mobile Robot Based on Indoor Positioning System," *Journal of Electrical Technology UMY*, vol. 5, no. 1, pp. 32–39, 2021, doi: 10.18196/jet.v5i1.12310.

[21] H. S. Nugroho and T. Sutikno, "Fire Extinguisher Wheel Robot Based on Arduino Mega 2560 R3 with Android Smartphone Control," *Buletin Ilmiah Sarjana Teknik Elektro*, vol. 3, no. 1, pp. 31–40, 2021, doi: 10.12928/biste.v3i1.1760.

[22] Saut Situmorang, "Application of Roboduino ATMega 2560 in the Making of the Fire Extinguisher Beetle Robot," *Journal of Science Technology (JoSTec)*, vol. 2, no. 1, pp. 54–59, 2020, doi: 10.55299/jostec.v2i1.53.