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Design and Construction of a Real-Time Air Quality Monitoring System Using IoT-Based ESP32 to Strengthen Environmental Policies

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Abstract: Air quality monitoring is one of the important steps in maintaining public health and the environment. With the development of Internet of Things (IoT) technology, air quality monitoring can be done in real-time and more efficiently. This study aims to environmental policy and design of an IoT-based air quality monitoring system using the ESP32 microcontroller. This system is designed to measure air quality parameters such as CO, NO2, temperature, and humidity using factory-calibrated sensors (DFRobot) connected to the ESP32 microcontroller. Data obtained from the sensors are processed by the ESP32 and sent to a cloud server via Wi-Fi, allowing real-time monitoring via the ThingSpeak platform which can be monitored via mobile devices or the web. The results of the air quality monitoring system design show that devices using electrochemical CO and NO sensors $_2$and the SHT30 sensor connected to the ESP32 is capable of reading and measuring CO, NOconcentrations., temperature, and humidity with good accuracy with a sample time of ± 20 seconds. In addition, this system can be connected online with the ThingSpeak platform, allowing visualization of measurement data in graphical form in real-time. Thus, the designed system not only functions optimally in detecting air quality parameters, but also supports efficient remote monitoring through Internet of Things (IoT) technology.

Keywords: Air quality monitoring; Electrochemical; Environmental policy; ESP32; IoT

Introduction

Air pollution is a major problem that occurs not only in one country, but all countries around the world according to the World Health Organization (WHO) (Malleswari et al., 2022). Efforts to prevent air pollution can be done by first detecting the parameters of gases such as carbon monoxide (CO), nitrogen dioxide (NO_2) and so on (Hakam et al., 2022). These gases are the cause of air pollution which has a direct impact on human health, including causing dizziness, coughing and lung cancer (Leung et al., 2014; Noorsaman et al., 2023; Sung et al., 2020). In various regions, especially urban areas, increased emissions from motor vehicles and industry have caused a decline in air quality ((Tritamtama et al., 2023). Air pollution has a negative impact on human health, the environment and the city's economy (Kaur et al., 2023).

Accurate and precise air quality measurement and monitoring are very important, especially in the modern era that is increasingly advanced with the use of Internet of Things (IoT) technology connected to sensors in detecting the physical parameters being measured (Ayele et al., 2018). IoT technology is a technology used

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by combining electronic devices and sensors via the internet (Jasim et al., 2021; Pratomo et al., 2023; Wang et al., 2018). IoT technology provides innovative solutions to various challenges and problems in various fields (Sfar et al., 2017). In addition, IoT technology offers great potential to improve environmental monitoring capabilities through automatic and real-time data collection, which can help make faster and data-based decisions (Kumar et al., 2019).

The ESP32 microcontroller is a popular IoT device due to its capabilities in Wi-Fi and Bluetooth connectivity, with resolution levels of up to 12 bits, and low power consumption (Pratama et al., 2023; Singh et al., 2020) and is programmed using the Arduino IDE or open source platformIO (Bhadane et al., 2018).

The use of ESP32 in the design of an air quality monitoring system allows local data processing and sending data to a cloud server for further analysis (Faiazuddin et al., 2020; Hercog et al., 2023). This article will discuss the design of a real-time air quality monitoring system based on ESP32 utilizing IoT technology, and test its effectiveness in monitoring air quality. Many studies have been conducted in the field of air quality monitoring using IoT technology. Several studies have developed monitoring devices using microcontrollers such as Arduino and Raspberry Pi. The advantages of using the ESP32 microcontroller offer advantages in terms of connectivity and lower costs (Hercog et al., 2023).

IoT-based air quality monitoring system designed to measure parameters such as CO, NO2 gas concentration levels and other environmental parameters such as temperature and humidity. The gas sensors used are electrochemical CO sensor model SKU SEN0466 and electrochemical NO2 sensor model SKU SEN0471. Both sensors have been factory calibrated (DFRobot) which provides direct output in ppm (Parts per Million). The electrochemical CO sensor is capable of detecting CO levels in the air ranging from 0 - 1000 ppm and the electrochemical NO2 sensor is capable of detecting between 0-20 ppm (Moskal et al., 2024). The response time (T90) of both gas sensors is ≤ 30 seconds. Temperature and humidity measurements using the analog SHT30 Temperature & Humidity sensor with a fairly high resolution levels produce accurate data.

The use of cloud computing in an IoT-integrated monitoring system allows data to be accessed in real-time from various devices via the internet (Andriulo et al., 2024; Atlam et al., 2017). A well-designed system can provide accurate data and facilitate monitoring in various locations simultaneously. As a display of measurement results, an open source IoT platform is used, namely ThingSpeak. This platform has provided an API (Application Programming Interface) code that can be used directly to access data on the platform (Ekayana, 2019; Sorongan et al., 2018). The measurement results are shown in this platform in the form of real-time graphs so that the measurement monitoring process can be carried out efficiently and effectively.

Method

The design system is divided into two parts, namely the hardware design system and the software design system. The hardware design system consists of electronics design and mechanical design, while the software design consists of algorithm design created in the Arduino IDE program and development of the ThingSpeak IoT platform.

Electronic and Mechanical Design Systems

The air quality monitoring system is designed using ESP32 as a data processing center. Some of the electronic components used in building this system are ESP32 DevKit V1 as a Microcontroller with Wi-Fi and Bluetooth connectivity capabilities. The normal power consumption required by the ESP32 microcontroller is 5VDC so the LM2596 module is needed. The module is used to convert DC to DC voltage, namely changing the 9VDC voltage from the battery to 5VDC voltage. The physical form of the ES32 DevKit 1 Microcontroller and LM2596 is shown in Figure 1.

Figure 1. ESP32 DevKit V1 and LM2596 microcontroller

Figure 2. CO, NO2, SHT30 and MUX sensors

DFRobot CO and NO2 sensors are sensors that have been calibrated in ppm units. The type of interface communication between the two sensors can be set in the form of I2C or UART. In this design, the communication between the sensor interfaces is set in the form of I2C. In addition to the gas sensor, the SHT30 sensor is also used to detect changes in temperature and humidity in the surrounding environment. In the electronic design, a 16x2 LCD component is also used to display measurement results directly or in situ. Another component is a digital 1 to 8 I2C Multiplexer used as a channel to connect the gas sensor to the ESP32. The physical form of the sensor and digital 1 to 8 I2C MUX is shown in Figure 2. In a mechanical system designed by placing all electronic components into a box-shaped container as protection.

*Cloud Platform*used is ThingSpeak to display data in real-time. Data obtained from the sensor is sent to the ESP32, then sent to the ThingSpeak platform via a Wi-Fi connection to be stored and analyzed in real-time. The process of the tool's working data acquisition system is shown in Figure 3.

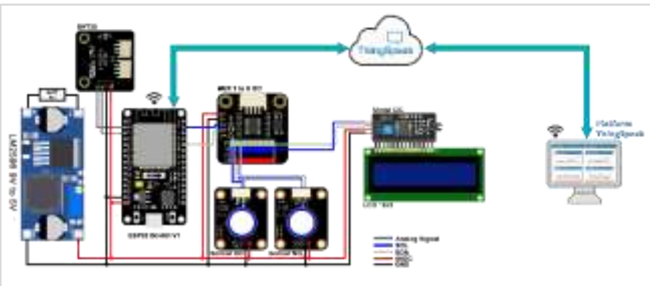

Figure 3. Data acquisition system process

Algorithm Design

The design of the algorithm system is made using the Arduino IDE program. The Arduino IDE program structure consists of the Header section, the initialization section, the setup function section and the loop function section (Cameron, 2021). In the algorithm design, the header section contains the Include Library required for each component. The Include Library contains the default program code to facilitate the process of operating, reading or controlling hardware. The include Library components entered into the Arduino IDE include gas sensor components, multiplexers, 16x2 LCDs, Thingspeak and are diagrammatically shown in Figure 4.

After entering the Include Library from each component, the algorithm work system is built starting with the initialization process until the loop function process is displayed according to the flow diagram in Figure 5. Based on the flow diagram, it can be explained that when the process starts, initialization is needed, namely declaring several variables that are used globally. The main initialization process consists of initializing the ThingSpeak API code, initializing the SSID name and password to connect to the internet signal, initializing the address from digital 1 to 8 I2C MUX, initializing the I2C LCD address and initializing the port on the MUX which is used as a port for the gas sensor and a port for the I2C LCD.

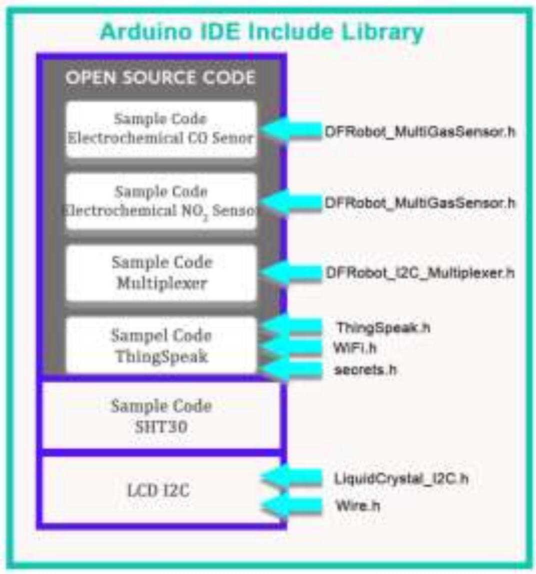

Figure 4. Library component integration diagram in Arduino IDE

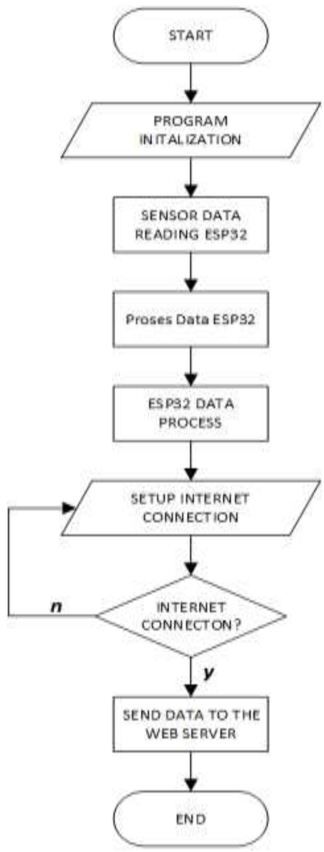

Figure 5. Algorithm systems flowchart

In the function setup section, specific variable initialization is also carried out, including LCD, ThingSpeak, I2C Multiplexer and gas sensor. After the initialization process, the sensor data is sent to the ESP32 microcontroller. The data sent is the SHT30 sensor, CO and NO2 gas sensors and will be displayed on the LCD screen. Furthermore, the ESP32 will perform the connection process with the internet signal. If a connection failure occurs, the connection setup is carried out again. If the connection process is successful, the data is sent to the ThingSpeak cloud and then sent to the ThingSpeak website platform. After the data is successfully received by the Thingspeak platform, the process is complete. Data transmission is carried out repeatedly as long as the internet connection process is properly connected.

Results and Discussion

The results of the design of an IoT-based air quality monitoring system for hardware/electronics are shown in Figure 6. The system consists of ESP32, I2C MUX, LM2596, CO sensor, NO2 sensor, SHT30 sensor and 16x2 I2C LCD components. The device is placed in a black box measuring 15 cm x 9.5 cm x 5 cm. This device is placed in a protective container to maintain the stability of sensor performance in various environmental conditions.

Figure 6. The results of the electronic device design are placed in a box

The tool testing process is carried out in a laboratory, namely by providing exposure to pollution from motor vehicle exhaust fumes. The measurement results show that the electrochemical sensors CO and NO_2able to detect changes in pollutant levels with high accuracy. The results of in situ measurements can be read directly which are shown on the LCD screen as in Figure 7. A study by Moskal et al. (2024) showed that the use of electrochemical sensors in air monitoring systems provides more stable and accurate results compared to conventional semiconductor sensors.

Figure 7. In situ measurement results of CO and NO2 gases

In addition, temperature and humidity measurements using the SHT30 sensor show stable values with minimal deviation. This sensor has a high resolution levels and can provide more accurate results compared to previous generation temperature and humidity sensors (Hercog et al., 2023). The results of in situ temperature and humidity measurements are displayed on the LCD screen in Figure 8.

Figure 8. Results of in situ temperature and humidity measurements

Data obtained from sensors are sent to the ThingSpeak platform in real-time via a Wi-Fi connection.

This allows users to monitor air quality conditions remotely. A study by Atlam et al. (2017) stated that the integration of monitoring systems with cloud computing increases the efficiency of data processing and enables big data-based analysis to support decision-making in environmental policy.

Another advantage of this system is the relatively fast sample time, which is around 20 seconds. This response time is better than some conventional monitoring systems that take longer to obtain valid data. Research by Budianto et al. (2024) also found that IoT-based systems are able to provide high-efficiency air quality measurements, so they can be used in various environmental monitoring scenarios. The display of measurement results on the ThingSpeak platform is shown in Figure 9.

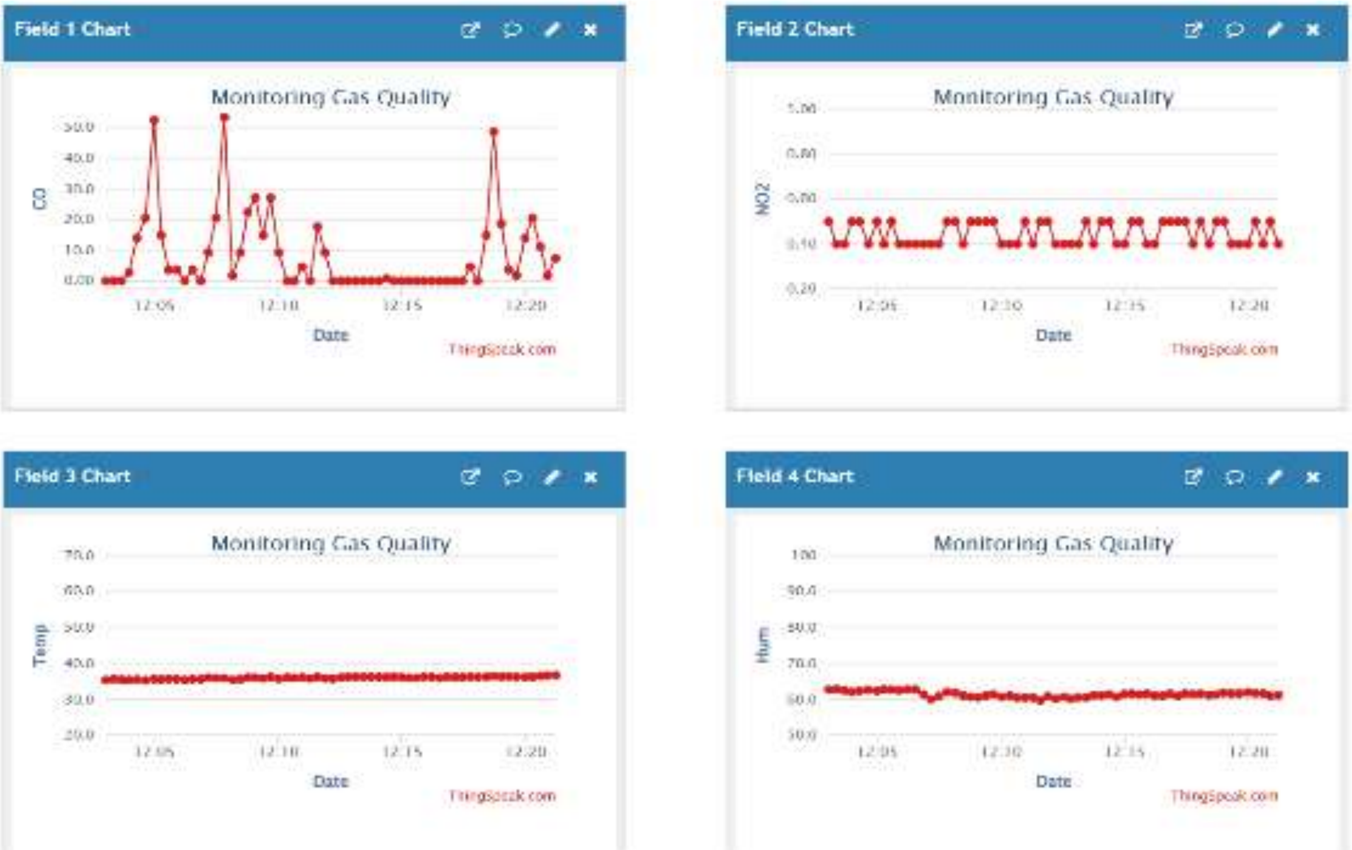

Figure 9. Display of air pollution measurement results on the TingSpeak platform

The graph displayed on the ThingSpeak platform shows changes in CO and NO levels.$_{2}$when the device is exposed to pollution, while the temperature and humidity are relatively stable. This is in line with the research of Pratomo et al. (2023) which emphasizes that the IoT-based monitoring system is able to record fluctuations in environmental parameters accurately and can be used as a basis for formulating data-based environmental policies.

Figure 10 shows that the air condition is not polluted by vehicle gas, where the CO and NO2 graphs are relatively constant. The measured air temperature and humidity also show a relatively constant graph. Thus, the designed system not only provides accurate air quality monitoring, but also supports evidence-based policy making in air pollution mitigation efforts in various regions.

The study of aspects of environmental pollution, especially air, is inseparable from the policies made by relevant stakeholders. In accordance with Policy Implementation Theory (Najam, 2010), in terms of Policy/Law Characteristics Variables, there are already Regional Regulations (*Perda*) that regulate zoning. The initial literature review that has been carried out, in Maluku Province there is Local Regulation Number 16 of 2013 concerning the Regional Spatial Plan of Maluku Province in 2013-2033, and Local Regulation number 15 of 2014 concerning Environmental Protection and Management. Then the Regional Spatial Plan in Central Maluku Regency is also regulated by Regional Regulation Number 1 of 2012 which is valid from 2011 to 2031.

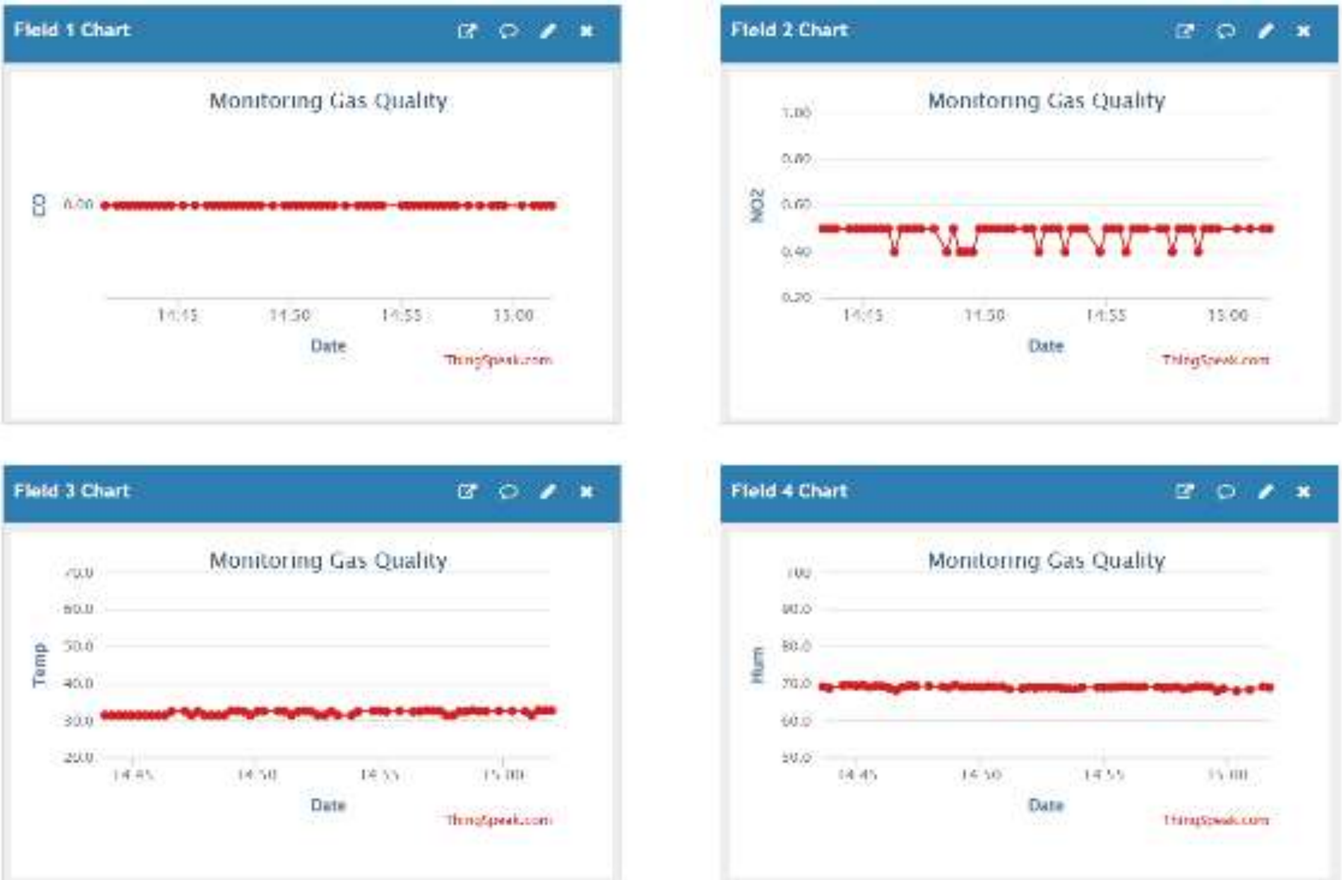

Figure 10. Viewing polluted air measurement results on the ThingSpeak platform

In Ambon City, there is already a local regulation No. 24/2012 on the 2011-2031 Ambon City Spatial Plan. However, there are findings related to land conversion in the last 20 years, resulting in a decrease in the amount of mangrove forest by 10 hectares. The management plan and conservation plan for mangrove forested beaches in the RTRW regulation are directed at mangrove forested beaches in the areas of Waiheru, Negeri Lama, Passo, Lateri, Laha, Tawiri, Rutong and Leahari. Observations show that many mangrove forests have been converted into businesses and settlements.

Conclusion

The design of a real-time air quality monitoring system using ESP32 based on IoT has been successfully developed to support environmental policies. This system is able to detect and measure the concentration of CO, NO_2, temperature, and humidity with high accuracy using electrochemical sensors and SHT30, with a sample time of around 20 seconds. Integration with the ThingSpeak platform allows real-time data monitoring in the form of graphical visualization, thus supporting efficient remote monitoring. With this capability, the designed system contributes to the provision of accurate and up-to-date environmental data to strengthen data-based policy making in air pollution mitigation efforts.

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Author Contributions
Conceptualization, YTEA and RMK; methodology, RMK and FM; validation, YTEA and RMK; formal analysis, FM; investigation, YTEA and RMK; resources, RMK and FM; data curation, FM and RMK: writing-original draft preparation, FM and RMK; writing-review and editing, FM and YTEA: visualization, and FM All authors have read and approved the published version of the manuscript.

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Conflict of Interest
All authors declare that there is no conflict of interest in and during the writing of this article.

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