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IoT-Based Campus Parking Slot Monitoring System via Ultrasonic Sensors with Real-Time Web Visualization

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Abstract

This research develops a campus parking slot monitoring system based on the Internet of Things (IoT) using the HC-SR04 ultrasonic sensor and the ESP32 DevKitC V4 module. The goal is to overcome parking space limitations by providing real-time information on slot availability thru an OLED display and web interface. The system is designed using a prototype development method consisting of ultrasonic sensors to detect vehicle distance, servo motors to operate automatic gates, and ESP32 as a processor and wireless data transmitter. The data from the sensor readings is processed to determine the status of the parking slots and communicated in real-time to the server. OLED displays real-time status on-site, while the web interface shows the overall parking conditions. The test results show the system is capable of detecting the presence of vehicles with high accuracy and stable data communication without significant delay. This system effectively improves parking space search efficiency and reduces congestion in the campus area. Its implementation supports the smart campus concept thru the digitalization of user-friendly, efficient, and scalable parking facility management, which can be developed into a data analysis-based system for smart parking management in the future.

Keywords: *IoT, ESP32, Monitoring Parking, Sensor Ultrasonic, Smart Campus*

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I. INTRODUCTION

The rapid development of Internet of Things (IoT) technology has brought significant changes to various sectors, including transportation, automation, and smart infrastructure management. IoT technology enables devices to communicate with each other thru a network of connected sensors, providing real-time data for analysis to support efficiency and data-driven decision-making. One rapidly developing implementation is the smart parking system, which plays a crucial role in optimizing land use and reducing user waiting times.

In the context of a modern campus environment, efficient parking management is becoming an essential part of the transformation toward a sustainable smart campus concept. The increasing number of motor vehicles on campus year after year is not matched by an adequate supply of parking space. This imbalance leads to various problems such as local congestion, long waiting times, and a decrease in the efficiency of space utilization. Based on data from the Ministry of Transportation [1], The average ratio of parking space availability to the number of vehicles in the educational area is only 1:5. This means that one parking space must be used by several vehicles on a rotating basis within a single day. Field observations also show that approximately 60-70% of vehicle users' time is spent searching for empty parking spaces, which ultimately increases fuel consumption and carbon emissions in the campus area.

This condition highlights the need for a technology-based system that can automatically monitor parking space availability and present this information to users in real-time. The application of IoT in parking systems has been widely studied in various previous research using diverse types of sensors and microcontrollers [2], showing that integrating ultrasonic sensors with microcontrollers can improve the accuracy of vehicle detection [3], developing a Node MCU-based parking system connected to a web interface to display parking data online [4], using a magnetometer sensor to detect the presence of vehicles [1], while implementing an infrared sensor-based system in commercial areas [5]. designed a vehicle distance detection system using an Arduino Uno-based ultrasonic sensor, which proved that this type of sensor is reliable enough to detect objects [6] Designing an RFID-based parking system integrated with Student ID Cards (KTM) to enhance user security and authentication. Another study by based on monitoring parking, implemented an IoT-based vehicle counting monitoring system in a shopping mall, while successfully achieved 99% accuracy and 98% precision in a JSN-SR04T sensor-based parking system [7].

Although these various studies have made significant contributions to the development of smart parking systems, most of the systems developed are still commercially oriented and use high-cost sensors. Additionally, some systems have not yet integrated historical data analysis and flexible real-time visualization accessible from various devices. Another limitation is the lack of a system specifically designed for a campus scale, considering energy efficiency, ease of maintenance, and low implementation costs. To address this gap, this study proposes the development of an IoT-based campus parking slot monitoring system utilizing the HC-SR04 ultrasonic sensor and the ESP32 Dev KitC V4 module. The ESP32 module was chosen because it supports Wi-Fi connectivity with low power consumption, enabling it to wirelessly transmit sensor reading data to the server. Ultrasonic sensors are used to detect vehicle distance and determine the status of parking slots, while servo motors are used to operate automatic doors. Information on parking space status is displayed via an OLED screen at the parking location as well as a web interface that users can access online. This hardware and software integration is expected to improve the efficiency of parking area management while also making it easier for users to obtain information about parking availability.

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The ultrasonic sensor is responsible for reading the distance of vehicle objects, the ESP32 microcontroller serves as the data processing center and information transmitted via Wi-Fi, and the server receives and displays the detection results on the web interface. Servo motors are used to automatically move the parking barrier when a space is available, while the OLED screen displays the live parking status on-site. The communication flow between components is designed to be efficient and easy to implement in a campus environment.

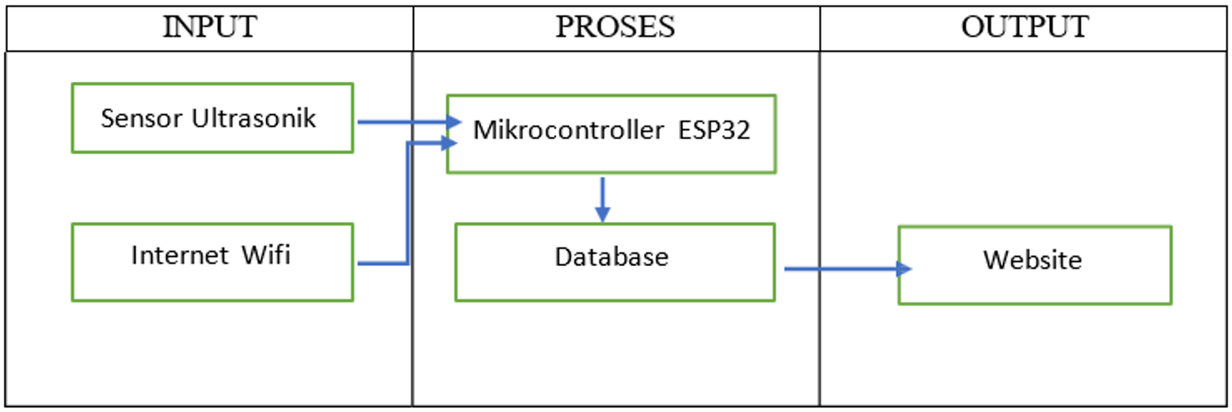

Fig. 1. Diagram System.

Figure 1 shows the system architecture design developed in this study. The data flow begins with the ultrasonic sensor detecting the presence of vehicles, then the measurement results are sent to the ESP32 module for processing and categorization as 'empty' or 'full' slots. This information is transmitted wirelessly to the server and displayed on a web interface in the form of visual indicators, while the on-site OLED directly displays the status. This design supports a power-efficient, scalable system that can provide real-time information updates to users.

This research contributes to the development of a smart campus thru the implementation of an energy-efficient, economical, and easily implementable smart parking system [12]. In addition to focusing on technical innovation, this system also plays a role in supporting the goals of Green Campus and Sustainable Development Goals (SDGs), particularly in the aspect of smart and environmentally friendly transportation [10]. Data from parking monitoring can also be developed into a predictive analysis-based system to map future vehicle occupancy patterns using machine learning [9, 13].

Once the system's architectural design was established, this research was developed based on structured research stages as depicted in the research roadmap [14]. This approach was used to ensure that each research phase not only produced functional output [15], but also had continuity toward the long-term goal of developing an integrated smart parking system within the campus environment [16]. This research map was compiled by referring to the stages in IoT applied research, from problem identification to data integration for predictive analysis.

Figure 2 shows that this study consists of six main stages. The first stage, problem identification and literature review, was conducted to understand the parking lot conditions on campus and review previous research findings as a basis for system development. The second stage, system design and sensor integration, focused on hardware design using the HC-SR04 ultrasonic sensor and the ESP32 DevKitC V4 module, as well as software design for wireless data communication and parking information visualization. The third stage, prototype development, includes component assembly, microcontroller programming, and initial testing of sensor functions and the OLED display. The fourth stage, testing and data analysis, is conducted to measure sensor accuracy, communication stability, and system reliability under real-world conditions.

Next, the fifth stage is the implementation and evaluation of the system in the field, which aims to assess the system's performance in real-world usage scenarios within the campus parking area. The evaluation results are used to determine the efficiency, readability of the display, and response time of the system. The final stage is the development of a data-driven system, where historical parking data recorded on the server can be utilized to identify patterns in parking land use. In this phase, the research is directed toward integrating machine learning systems to build a predictive model capable of estimating parking slot availability based on specific times and days.

Thru this research map, it can be seen that this research does not stop at the hardware implementation stage, but also emphasizes continuity toward the development of a smart campus system that is intelligent, energy-efficient, and adaptable to future needs. Thus, the results of this research are expected not only to provide a technical solution to the limitations of campus parking space, but also to strengthen the foundation for further research in the fields of intelligent transportation, green mobility, and the digitalization of campus services.

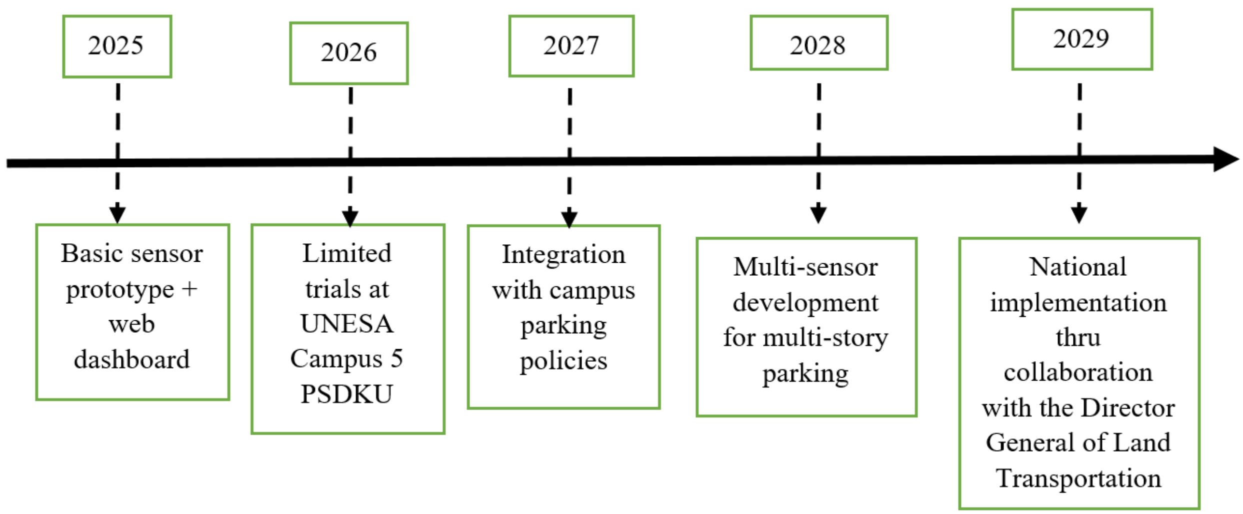

Fig. 2. Research Development Road-Map.

II. RESEARCH METHOD

This research was conducted by referring to the previously designed research development map (Figure 2), where each stage has a logical connection between the system design, implementation, and evaluation processes [17, 15]. Based on the characteristics of the problem and the goals of developing a campus parking monitoring system, this study uses a research and development (R&D) approach [18] with an Internet of Things (IoT)-based prototype model [2] and allows for a continuous system improvement process, from the design stage to performance evaluation [19].

In its implementation, this research approach combines quantitative [7] and qualitative [9] methods to obtain comprehensive results. The quantitative approach is used to objectively measure system performance, including the accuracy of ultrasonic sensor detection [20, 9], system response time [4], and data communication stability on the ESP32 module [12, 17]. The test data was analyzed using simple statistical calculations to determine the system's success rate and reliability. Meanwhile, a qualitative approach was applied to assess user experience thru direct observation and questionnaires [8], in order to determine the level of usability [19] and satisfaction with the system interface.

With this approach, this research emphasizes the importance of the relationship between system functional testing and the real needs of users [11]. Each research stage was conducted step by step and systematically to ensure that the development results could be effectively applied in the campus environment [13, 14]. These stages are briefly explained in the research flowchart in Figure 3, which shows the sequence of processes from design and implementation to a comprehensive system evaluation. The system simulation illustrated in Figure 4 represents the integrated interaction between sensors, microcontrollers, and actuators during operation. The ultrasonic sensor detects vehicle distance and transmits the data to the ESP32 microcontroller, which processes it and triggers the servo motor to lift or lower the parking barrier. This simulation was developed on the Wokwi platform to verify the logic and timing accuracy before physical implementation.

This research was conducted in a structured and chronological manner, as represented by the research flowchart:

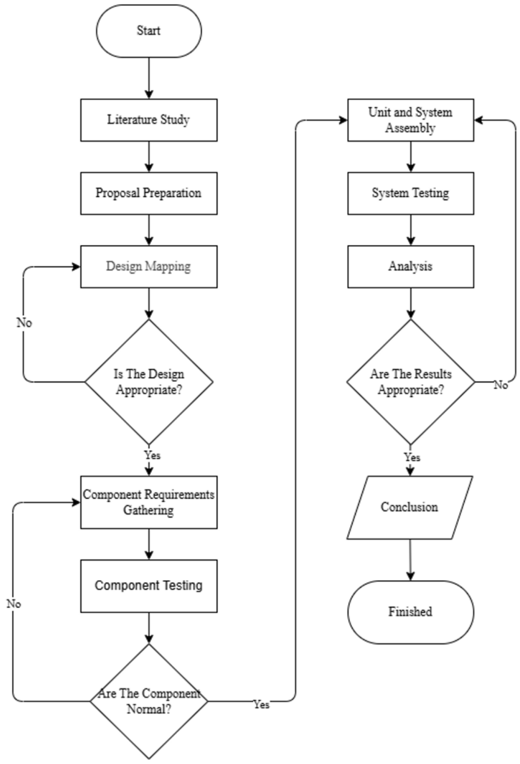

Fig. 3. Research Flow Diagram.

1. Literature Study and Needs Analysis: this stage aims to collect theoretical references from journals, books, and previous studies, while simultaneously observing real parking conditions on campus to identify problems and system requirements.
2. System Design: System design can be followed up by engendering two groups of hardware and software division systems. Feast, a mixing design consisting of conceptual or embryonic planning and progressing to architecture. Compare, analyze four states, plan disposal protocol planning, and the result is an octopus in various statements and precedents.
3. System implementation and component testing: implementation is made from evidence, considerations, and has testing. Meanwhile, this component testing is carried out in several aspects, namely: hardware prototype assembly, individual component and component interaction testing, namely: ultrasonic sensor, ESP32 microcontroller, and website backend server, and system testing.
4. System Testing and Evaluation: After the prototype is integrated, thorough system testing is conducted in a simulated environment that resembles real-world conditions. The measured variables include sensor accuracy, system response time, and the effectiveness of the user interface. The evaluation also involved distributing questionnaires to users to measure satisfaction levels and ease of use.

To ensure the developed system meets the expected performance standards, several success indicators were established, including:

1. Sensor direction accuracy must be at least 90%
2. The system's response time from detection to status update on the web interface must be no more than 5 seconds.
3. Data connection between devices must be stable with packet loss below 2%
4. User satisfaction level must be at least 80% based on trial results and questionnaires.

These four indicators are used as the basis for evaluation to assess system performance from both technical and functional perspectives. The main components of the system consist of an HC-SR04 ultrasonic sensor, an ESP32 microcontroller, an LED indicator module, and a Wi-Fi network connection for data communication. System architecture.

The architecture shows the data flow from the sensor to the microcontroller, then to the server via a Wi-Fi network, and finally visualized in a real-time web interface. A three-layer model (physical-network-application layer) was implemented to ensure the reliability of communication between components. The system design consists of three main parts: input, process (control), and output, which are equipped with hardware and software. For the input hardware, the HC-SR04 ultrasonic sensor is used to detect the presence of vehicles in each parking slot, and at the entrance and exit gates. During processing, the ESP32 microcontroller serves as the main processing unit, handling data from the sensors and providing Wi-Fi connectivity for IoT-based communication. For the output, the SG90 servo motor acts as an actuator to automatically open and close the parking barrier. As a local interface, the OLED display serves to show parking status information, and the web interface acts as a real-time visualization medium for users.

As for the software, the Arduino IDE is used to program the firmware on the ESP32 microcontroller, and Python with the Flask framework is used to build the backend and API (Application Programming Interface) that manages data communication between the hardware and the database. HTML, CSS, and JavaScript are used to develop the user interface (frontend) of the website, which displays real-time visualizations of parking slots. Wokwi, as a simulation platform, is used to test electronic circuits and program code before physical implementation.

Data collection was carried out using several methods to ensure the completeness and validity of the information:

1. Literature Study: A literature study was conducted by reviewing various scientific sources such as journals, books, research reports, and other policy documents relevant to the chosen theme. This stage plays an important role in building
2. Observation: Directly observing and understanding the flow, density, and problems of the campus parking area is important for information gathering.
3. Experiment: Conducting functional testing on the prototype to quantitatively measure performance metrics. Sensor accuracy testing is conducted to compare sensor readings with standard measuring instruments (meters).
4. Questionnaire: The survey questionnaire was distributed to potential users to gather qualitative information regarding perceived ease of use and satisfaction with the system interface.

Data analysis combines quantitative descriptive methods. The sensor test results were analyzed to determine the accuracy and precision levels using the percentage error formula. System functionality testing as a whole is performed using the black box testing method, where the system is tested based on the given inputs and the resulting outputs without considering the internal structure of the code.

After the hardware and software system design is complete, a testing phase is conducted to ensure the system functions according to the design. This testing is conducted in stages, starting with single sensor testing, data communication testing between the microcontroller and the server, and finally, visual data display testing on the web interface.

The ultrasonic sensor was tested by placing objects at various actual distances (10-300 cm) to compare with the sensor's readings. The measurement data is used to calculate the accuracy level using Equation 1.

$$\text{Accuracy} = \left(1 - \frac{|\text{Actual Value} - \text{Sensor Value}|}{\text{Actual Value}}\right) \times 100\% \tag{1}$$

Meanwhile, the average error rate is calculated using Equation 2.

$$E = \frac{\sum |\text{Actual Data} - \text{Sensor Data}|}{N} \tag{2}$$

Which N is the number of observations.

The system's response time testing was conducted by recording the time difference between the sensor condition change and the latest status appearing on the web display. Additionally, a connection stability test was also conducted between the ESP32 device and the server to ensure data could be sent without packet loss.

Finally, the last stage is usability testing, which is conducted by asking at least 10 respondents (students and parking attendants) to try the system, then assess its ease of use and interface clarity thru a simple questionnaire. The results of each testing stage are used as the basis for analyzing system performance in the Results and Discussion section.

III. Results and Discussion

The research results are divided into three parts based on integrated system functionality testing, testing the accuracy of the main input component, namely the ultrasonic sensor, and analyzing data visualization and response time on the web interface.

A. System Functionality Testing System

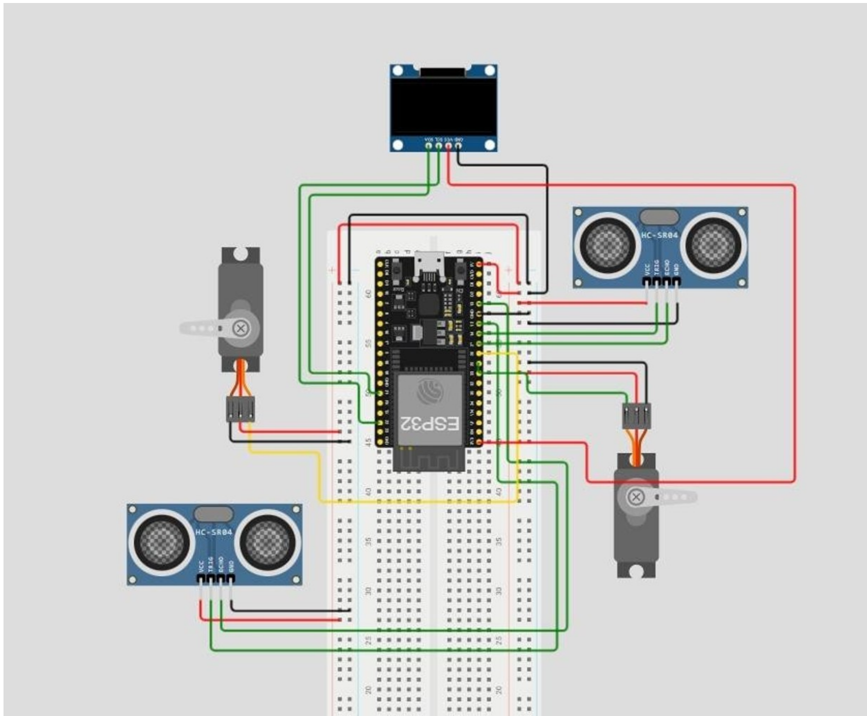

Fig. 4. System Simulation.

Functionality testing uses the black-box testing method to see if each main function works according to the design objectives. Based on the tests conducted, the entire system workflow from vehicle detection to data visualization runs successfully. The functionality testing performed revealed the following key findings:

1. Parking Gate Detection and Control: Ultrasonic sensors installed at the entrance and exit gates of the parking area successfully detected vehicles at the expected distance (less than 20 cm). This detection automatically activates the servo motor to open the parking barrier and close it again after a program time. This functionality aligns with the design in other studies that also implement automatic parking barriers using Arduino and ultrasonic sensors.
2. Slot Availability Detection: Ultrasonic sensors in each parking slot automatically and accurately detect parked vehicles. When a vehicle occupies a slot, the system automatically updates the slot's status from 'Available' to 'Occupied'.
3. Data Transmission and Updates: Data from all sensors is processed by the ESP32 microcontroller and then transmitted via Wi-Fi to the database server. The web platform receives this data and updates it in real-time whenever the parking slot status changes. This architecture has proven effective, as demonstrated in other IoT-based smart parking systems that utilize ESP modules for internet connectivity.

B. Web Interface Visualization and Response Time Data

Visualization based on integrated research on the web interface is created to provide clear and concise information to users.

Figure 5 is the main dashboard view where users can easily see the parking status with information on the number of occupied and empty slots, the total number of parking spaces, and real-time occupancy.

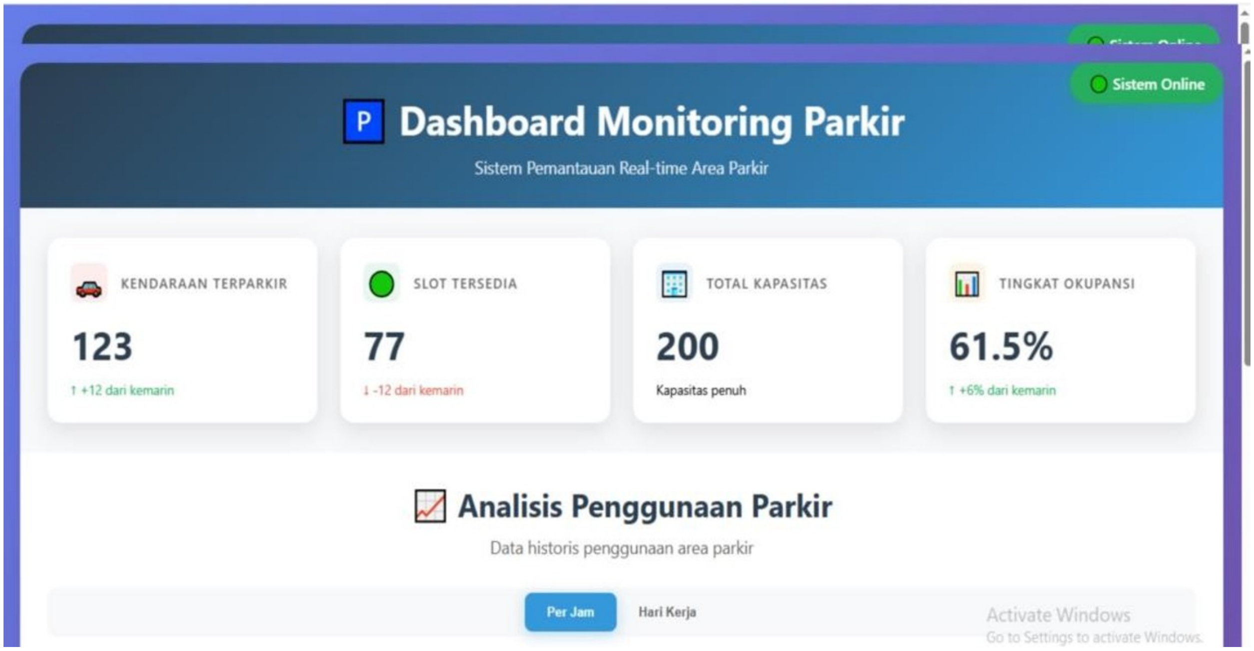

Fig. 5. Web Display of Parking Space Availability.

This system also presents historical parking usage graphs in Figure 6, which can be analyzed to support campus parking management decision-making, including specific hours that are often chaotic with only about 15% vacancy. Usability testing was conducted on at least 10 respondents consisting of students and parking attendants. The questionnaire covered aspects of ease of use, clarity of the interface display, and system response speed. The results of the questionnaire showed that the average user satisfaction level reached 87%. The highest-rated aspect was ease of navigation at 90%, followed by visual clarity of the display at 88%, while information update speed received 85%. The majority of respondents rated the system as easy to use and informative, although improvements to the display were suggested for optimal performance on mobile devices.

Based on these results, the system is deemed suitable for campus-wide implementation with minor adjustments to the interface.

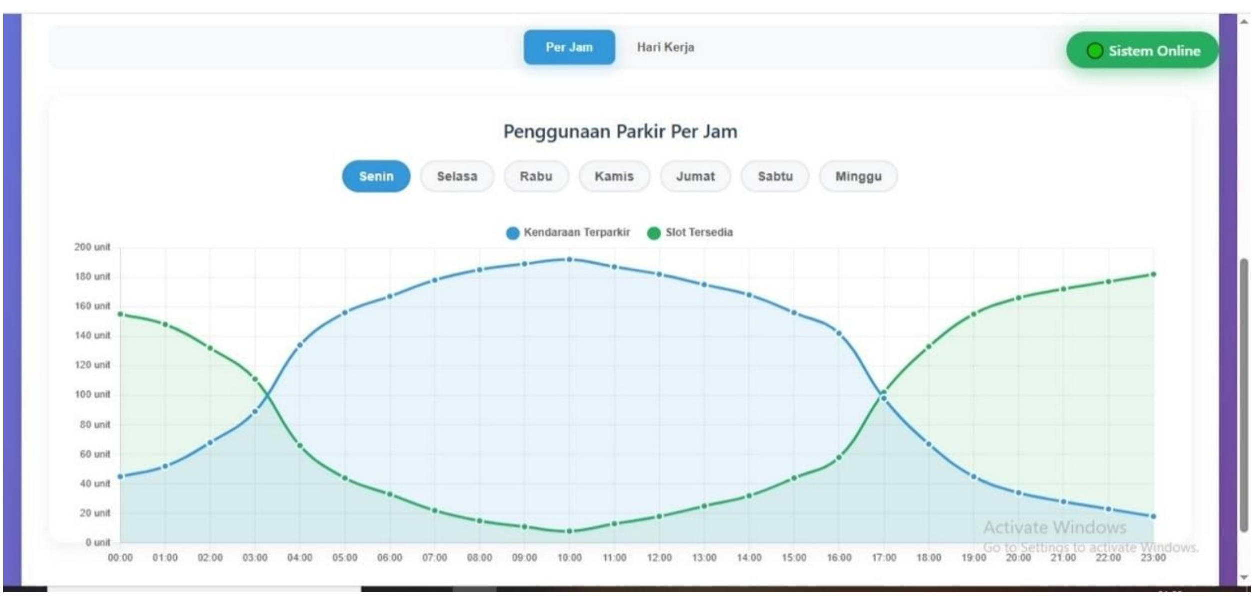

Fig. 6. Parking Usage Graph.

Based on performance measured by the system's response time from change detection to the user receiving information on the web interface, the average response time required never exceeded 5 seconds. This fast response time performance is crucial to ensure users always receive relevant and accurate information.

TABLE I. RESULT OF ULTRASONIC SENSOR ACCURACY TESTING.

Actual Distance (cm)	Sensor Testing (cm)	Difference (cm)	Accuracy (%)
50	50.45	0.45	99.10
100	99.82	0.18	99.82
150	149.21	0.79	99.47
200	198.65	1.35	99.33
Average Accuracy			**99.43**

The measurement data presented in Table I were obtained from experimental testing by placing a vehicle model at various distances from the ultrasonic sensor (50-200 cm). Each reading was compared with the actual measured distance using a standard ruler to calculate the sensor's accuracy. Based on the table, the test results show that the difference between the sensor measurement values and the actual distance is relatively small across the entire test distance range. The highest accuracy value was achieved at a distance of 100 cm, reaching 99.82%, while the lowest value remained within the range of 99.10% at a distance of 50 cm. The overall average accuracy reached 99.43%, indicating that the ultrasonic sensor is capable of stable and highly precise operation. This high accuracy value indicates that an ultrasonic sensor-based detection system can be relied upon to detect the presence of vehicles in parking slots without significant deviation from the actual distance. An accuracy value above 99% also indicates that the sensor calibration process is running optimally, and there is no significant influence from environmental factors such as temperature, humidity, or reflections from objects around the testing area.

With these results, the ultrasonic sensor used can be categorized as having very good performance and is suitable for use as a main component in an Internet of Things (IoT)-based parking monitoring system.

C. Discussion

From the test results above, it can be concluded that the successfully developed system prototype can prove the initial hypothesis that an effective and accurate IoT-based parking slot monitoring system exists. The smoothness of the main system and its normal operation, as indicated by the extremely high accuracy of the sensors and their response time, prove that this system is indeed suitable as a prototype that can be implemented on campus. The 99.43% accuracy rate of this parking system is even very consistent, perhaps, with previous research findings. Auliya et al. [20] found that the average error percentage of the JSN-SR04T sensor measurement was only 0.65%, comparable to its accuracy value of 99.35%. Meanwhile, Tatang Adi Julianto's research on the HC-SR04 sensor in an automatic lighting system achieved an accuracy of 99.26%. Furthermore, in slightly different applications such as monitoring sea tides and using other ultrasonic sensors, accuracies of up to 99.554% were obtained. This consistency in results strengthens the argument that low-cost ultrasonic sensors are a mature and reliable technology for object detection in various IoT applications.

In this topic, another approach that has proven effective is a system architecture that integrates sensors, the ESP32 microcontroller, and a web platform. As Hidayat did, Yusuf [10] recorded their success using a similar architecture in the implementation of their smart parking system. From this, it can be concluded that this research is strongly built on a solid technological foundation. Beside real-time monitoring, this allows for historical data processing, which is the foundation for more efficient parking management in the future. There is a key competitive advantage, which is its ability to be implemented on campus as a low-cost solution. By utilizing widely available components and open-source web platforms, this system offers a more affordable alternative to complex commercial parking systems, while still addressing the main issues of reducing parking search time and improving land use efficiency.

IV. CONCLUSION

Based on the entire research and testing process that has been carried out, it can be concluded that this project has successfully achieved its objectives. A functional IoT-based smart parking system prototype has been successfully realized. The initial assumption that such a system could be built effectively and accurately also proved to be true. This success is evident from the test results, where all components - from the sensor that detects vehicles, the data processing brain which is the ESP32 microcontroller, to the motor that drives the parking barrier can work together harmoniously and integrated.

Furthermore, when the accuracy of the ultrasonic sensor was tested, the results showed a very high level of precision, with a detection success rate exceeding 99%. These findings are highly consistent with what has been reported by similar studies, further reinforcing the reliability of this sensor technology. This developed system is capable of sending real-time parking availability status information from devices in the field directly to a webpage. This is a direct solution to a common problem: people wasting time just driving around looking for an empty parking space. Thus, this research confirms that an accurate and responsive intelligent parking system can be built using relatively affordable IoT technology.

Looking ahead, there is a great deal of room for development to make this system more sophisticated and beneficial. For future research, this system can be developed by adding a vehicle license plate recognition feature using a camera module like the ESP32-CAM. With this feature, the system can not only detect the presence of a car but also automatically record its license plate number, which is very useful for improving security and paving the way for a fully automated payment system. Beside proving the technical feasibility of the system, this research also contributes to the development of an efficient, environmentally friendly, and user-adaptive smart campus infrastructure.

This system can serve as the foundation for future data-driven advanced development for predictive parking management. Finally, the historical data on parking usage patterns continuously collected by this system has immense value. This data can be further processed. By applying predictive analytics, future systems can provide estimates or forecasts about when parking areas are likely to be full. This kind of predictive information can help users, both students and staff, plan their arrival times better, as well as assist management in making more strategic parking management policies.

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