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IOT-BASED STANDING WATER MONITORING SYSTEM FOR SUPPORTING PREVENTIVE MAINTENANCE IN AIRPORTS

Rehan Zikri Avian[1], Yayuk Suprihartini[2]
[1]Silampari Airport, Sumatra Selatan, Indonesia
[2]Airport Engineering Technology Study Programme,
Politeknik Penerbangan Palembang, Indonesia
* Correspondence e-mail: rehnzkri27@gmail.com

Abstract

Standing water on airport runways may reduce aircraft braking performance and increase the risk of hydroplaning during takeoff and landing. This study developed an IoT-based standing-water monitoring prototype to support preventive maintenance at Sultan Mahmud Badaruddin II International Airport in Palembang. An R&D method was applied. The system integrated JSN-SR04T ultrasonic sensors, GPS, Raspberry Pi, Arduino, and a camera with U-Net image segmentation, all connected to a web dashboard via HTTP. The dataset consisted of 1,200 runway water images divided into training (70%), validation (20%), and testing (10%) sets. Testing showed that the ultrasonic sensor achieved optimal accuracy at water depths above 2 cm, while the camera detected clear water up to 1.5 m and turbid water up to 2 m. User validation with five expert respondents yielded a feasibility score of 91%, categorized as excellent.

Keywords: *internet of things (iot), runway, standing water, ultrasonic sensor, camera*

Introduction

Air transportation plays a crucial role in supporting mobility and economic development in Indonesia, an archipelagic nation that requires efficient inter-island connectivity (Abad & Momayezi, 2024; Forsyth, 2021). Airports function as vital infrastructure to ensure smooth and safe aviation operations, in accordance with national aviation regulations emphasizing safety as the highest priority (Chang & Kung, 2023; Graham, 2023; Hendra et al., 2023). The runway is recognized as the most critical airside facility that must always remain compliant with safety standards and operational readiness (Riandi et al., 2022). Preventive maintenance is an important program designed to prevent system failures and ensure equipment reliability in runway operations (Kristian et al., 2021).

The presence of standing water on runway surfaces can severely impact aircraft braking efficiency and lead to hydroplaning incidents, creating significant risks during takeoff and landing (Maulana et al., 2022). Hydroplaning occurs when a layer of water causes aircraft tires to lose direct friction with the runway surface, resulting in loss of control (Li, Hu, et al., 2025; Li, Zhou, et al., 2025). According to national regulations, PR 21 Year 2023 about Civil Aviation Safety Regulations, the allowable maximum water depth on a runway is 3 mm to support safe aircraft operations. These challenges indicate the importance of accurate, rapid, and continuous monitoring of runway conditions, especially during wet weather.

At Sultan Mahmud Badaruddin II International Airport, Palembang, heavy rainfall frequently causes standing water to form, especially along the runway edge. Currently, airport inspectors from the Airport Air Side Facilities Department (AASFD) still perform water depth measurement manually using visual checks and simple tools. Manual inspection is considered time-consuming and error-prone, leading to delays in reporting runway conditions to Air Traffic Controllers (ATC). This situation highlights the need for a more reliable system that can support real-time decision-making.

In modern aviation infrastructure, Internet of Things (IoT) technologies have fundamentally transformed operational frameworks by driving advancements in efficiency, security, and real-time environmental monitoring (Amalia et al., 2022; Baláž et al., 2023; Komalasari et al., 2024). To evaluate runway surface conditions from puddle hazards, ultrasonic sensors are widely preferred due to their high accuracy and reliability in measuring physical water depth under fluctuating weather conditions (Hafidh, 2021; Suryan et al., 2023). The operational architecture of these sensor networks generally relies on compact microcomputers, such as the Raspberry Pi, which have proven highly resilient as central controllers for localized environmental data processing (Mathe et al., 2022). To maximize the utility of these parameter measurements, integrating web-based dashboards allows data to be displayed directly to airport operators, thereby accelerating critical maintenance decision-making (Mahrami & Christina, 2021; Nugraha et al., 2023). However, while this telemetry-based approach excels in delivering rapid numerical data, it exhibits a critical limitation as it cannot provide spatial verification regarding the actual spread of standing water across the runway (Leoni et al., 2021; Mahfoud et al., 2024). The visual limitations of physical sensors have driven the parallel development of camera-based detection systems to establish a visual validation layer, confirming water existence through image processing (Hotmartua et al., 2022). This highlights the technological transition toward AI/CNN in airport surveillance. While traditional ultrasonic sensors fall short in complex environments due to inherent limitations, CNNs prove highly effective in addressing challenges that involve image-based data (Maesaroh et al., 2025). More specifically, the U-Net architecture has emerged as a high-performance framework for precise image segmentation, enabling the system to classify and delineate water surfaces based on subtle visual characteristics (Hosseiny, 2021). Collectively, implementing these Artificial Intelligence (AI) mechanisms in airport operations has significantly strengthened safety performance and optimized decision-making efficiency regarding runway inspections and infrastructure maintenance (Biringkanae & Bunahri, 2023; Katnoria et al., 2025).

A critical review of these two approaches shows a clear gap in research. Sensor-based IoT systems (de Camargo et al., 2023) provide accurate and direct depth measurements, but they cannot show the shape or visual spread of the puddle. On the other hand, vision-based AI models (Hosseiny, 2021; Hotmartua et al., 2022) excel at mapping the water surface area but fail to provide precise depth data when the water clarity changes. Because of this, integrated systems that combine ultrasonic sensors, GPS mapping, AI image segmentation, and real-time web dashboards for runway inspections are still very rare. Previous studies on integrated mobile runway standing-water monitoring systems with real-time reporting and geospatial mapping capabilities for airport preventive maintenance remain limited. This study directly addresses this problem by developing an integrated mobile monitoring prototype based on a Raspberry Pi. By combining JSN-SR04T ultrasonic sensors, GPS tracking, and U-Net image segmentation, this system successfully delivers both highly accurate depth measurements and real-time visual maps on a single web dashboard for airport preventive maintenance.

This research aims to develop a smart monitoring prototype integrating ultrasonic sensors, camera-based image processing using U-Net, GPS localization, and IoT communication to detect standing water on runways in real time. This system is expected to assist airport authorities in accelerating runway inspection responses and supporting preventive maintenance actions. By combining multiple technological approaches into a unified system, the monitoring process is expected to become more accurate, instant, and proactive.

The scientific urgency of this research lies in ensuring operational safety during wet runway conditions, which directly correlates with aircraft braking performance and accident prevention. The novelty of this study involves integrating multi-sensor data, artificial intelligence segmentation, GPS precision, and web-based decision support for runway management. The practical implication is the enhancement of airport digital transformation toward automated airside infrastructure surveillance under Industry 4.0 aviation systems.

This research contributes to airport engineering knowledge by providing an innovative and deployable prototype that strengthens the accuracy and efficiency of runway condition assessments. Additionally, the developed system demonstrates a technological solution that can be extended to multiple airports across Indonesia to promote safer and more reliable air operations.

Methods

This study adopted a Research and Development (R&D) method based on the model introduced by (Sugiyono, 2022), applying the Level 3 development stage, which focuses on prototype creation and limited testing. This method was selected to enable the development of an initial functional system for monitoring runway standing water and to evaluate its feasibility and performance before wider implementation at airports.

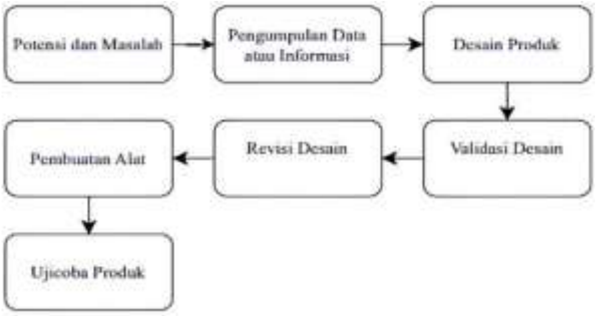

Figure 1. Research Stages

The research began with a needs analysis conducted through direct observation during preventive maintenance activities at Sultan Mahmud Badaruddin II International Airport Palembang. This stage aimed to identify critical challenges in the current inspection process, which still relies heavily on manual visual assessment and is susceptible to human error, especially after rainfall events. In addition, semi-structured interviews were conducted with AASFD supervisors to gain deeper insights into inspection workflows and documentation requirements under SOP 14.09.15/03/04/2023 on runway surface water condition reporting.

Based on the findings, the prototype design was carried out, including mechanical modeling in SketchUp; embedded system development, including an ultrasonic sensor for water depth measurement; a camera module with dataset-based image analysis to identify water coverage; a GPS module for positioning; and IoT-based communication to support real-time reporting. The hardware specifications utilized in this prototype include a JSN-SR04T waterproof ultrasonic sensor. The JSN-SR04T is suitable for water-related applications, such as river level monitoring. The accuracy and consistency of this sensor's readings are designed for industrial purposes with a high level of reading stability. This guarantees precise and consistent distance measurement results. Furthermore, the JSN-SR04T features a wide measurement range, with a detection reach between 25 cm and 450 cm, making it flexible for various distance measurement needs (Wibowo & Setyaningsih, 2025). Visual data was captured using a 2 MP USB webcam module connected to a Raspberry Pi 4 Model B (4GB RAM) as the central processing unit, while an Arduino Uno served as the secondary microcontroller for initial sensor signal conditioning. It determines the location coordinates using a Neo-6M GPS module operating with a position accuracy of 2.5 m CEP (Hadmadi et al., 2026). The utilization of the Neo-6M GPS module in an IoT framework aligns with modern connected vehicle networks that require seamless, real-time geographical data collection and cloud-based synchronization for localized monitoring (Moumen et al., 2023). The system architecture establishes a sequential data flow where the JSN-SR04T sensor and Neo-6M GPS module continuously feed depth and coordinate metrics to the microcontrollers. Telemetry data and physical images from the webcam are packed into JSON payloads by the Raspberry Pi. This data is transmitted via HTTP POST communication over a local cellular gateway to an external web server hosting the real-time monitoring web dashboard. The initial design was evaluated through Focus Group Discussion (FGD) sessions with experts in airport engineering technology and airside operations to assess conformity with operational standards and expected performance requirements, and to gather valuable feedback for designing an effective tool that meets operational needs (Khoirudin, 2024).

Following expert feedback, necessary design revisions were completed and a fully functional prototype was produced. Limited testing was conducted in campus and airport environments to evaluate system performance in terms of sensor accuracy, camera detection capability, GPS coordinate precision, battery endurance, and system responsiveness. User acceptance testing was also performed to assess practicality and ease of use for technicians responsible for runway inspections. User acceptance testing involved five expert respondents from airport operations and aviation academia.

Quantitative data analysis was performed using a five-point Likert scale consisting of four evaluation aspects: usability, effectiveness, efficiency, and user satisfaction (Amalia et al., 2020). The scoring results were calculated into percentage values using the following formula by (Abdullah et al., 2021).

$$Validation\ Score = \frac{Total\ Score}{Maximum\ Possible\ Score} x100\%$$

Table 1. Product Classification

Percentage	Category
84.01% – 100%	Excellent
68.01% – 84.00%	Good
52.01% – 68.00%	Fair
36.01% – 52.00%	Poor
20.00% – 36.00%	Very Poor

Furthermore, qualitative feedback from experts and users was analyzed to support product improvement recommendations in future development stages.

Results and Discussions

The IoT-based system integrates ultrasonic sensors, a GPS module, a camera, and a web interface to support preventive maintenance inspections. During operation, these three core components run simultaneously. As the inspection vehicle moves along the runway, the sensors continuously measure water depth, the camera captures real-time images, and the GPS records the geolocation of each event. The Raspberry Pi processes this aggregated data and transmits it automatically to the monitoring website. If the water level exceeds the safety threshold, the system triggers an alert and flags the specific runway segment as potentially unsafe. This mechanism provides operators with both numerical and visual evidence to streamline decision-making for Runway Condition Assessments (RCA).

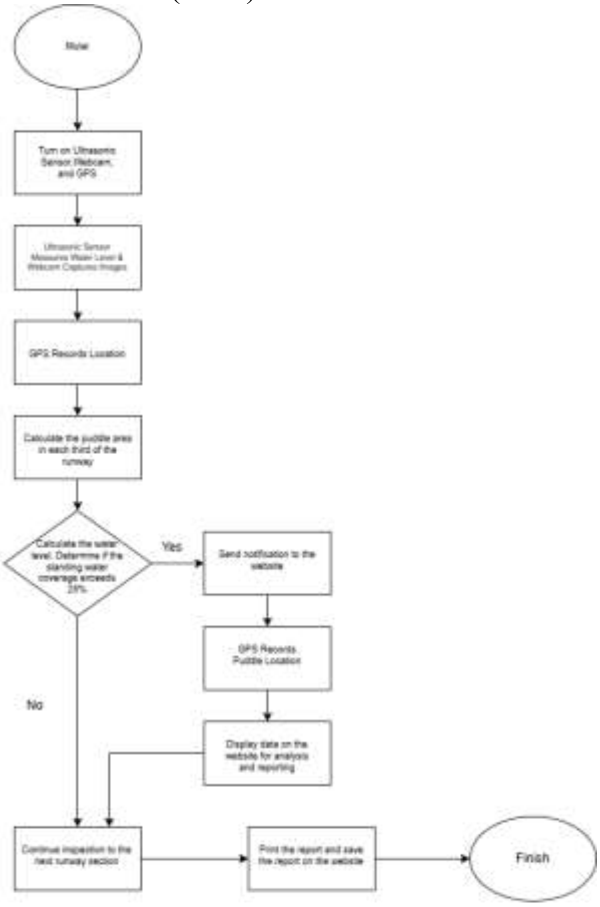

Figure 2. Flowchart System

This design specifically aims to overcome the gaps in previous research by creating a mobile system (mounted on an inspection vehicle) capable of dynamic geospatial mapping. The initial design was validated through a FGD involving experts from AASFD and Airport Quality. This validation yielded several important revision recommendations, such as optimizing the camera's direction and lighting and adding a protective casing to improve the tool's durability and aesthetics. The final product design after revisions, which includes the protective casing and component placement, is shown in Figure 3.

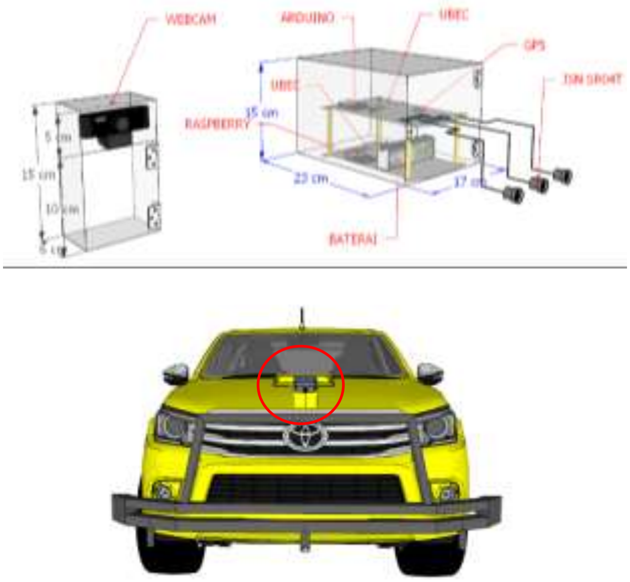

Figure 3. Design IoT Standing Water Monitoring System

Functional testing of the prototype was performed on several core components. First, the AI image segmentation framework utilizes a customized U-Net architecture. The experimental dataset comprises 1,200 high-resolution runway surface images captured directly under varying daytime lighting and precipitation conditions at the airport. Data preprocessing involved resizing images to 256x256 pixels and applying data augmentation techniques, including horizontal flipping and brightness adjustments, to enhance model generalization. To ensure the integrity of the model and prevent data leakage, the complete dataset was partitioned into a 700 image training set, alongside separate validation and testing sets.

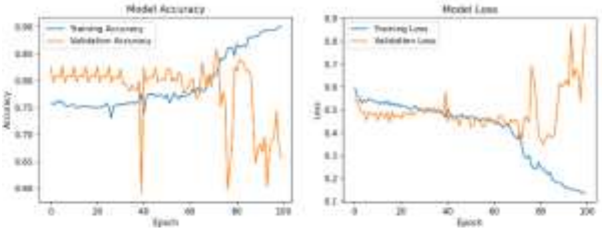

Figure 4. Result Validation Dataset

Physical camera testing also demonstrated adequate visual detection capabilities, where the system could detect clear water puddles up to a distance of 1.5 meters and turbid water puddles up to 2 meters.

Table 2. Clear and Turbid Water Visual Test

Clear Water Visual Test

Water Type	Distance (m)	Detection
Clear	0.5	Detected
Clear	1.0	Detected
Clear	1.5	Detected
Clear	2.0	Not detected
Clear	2.5	Not detected

Turbid Water Visual Test

Water Type	Distance (m)	Detection
Turbid	0.5	Detected
Turbid	1.0	Detected
Turbid	1.5	Detected
Turbid	2.0	Detected
Turbid	2.5	Not detected

Second, accuracy testing of the JSN-SR04T ultrasonic sensor was conducted to measure water depth, which is a critical parameter. Three sensors were tested at various water heights and compared with manual measurements taken with a ruler. The test results in Table 3 and Figure 5 show that Sensor 3 (center) had the most stable and accurate performance, achieving 100% accuracy at depths of 2 cm and 3 cm. This high accuracy is crucial for providing quantitative data that is far superior to manual visual estimates. However, this result reveals a critical limitation compared with aviation safety regulations that require standing water monitoring at a depth of approximately 3 mm. The prototype therefore still faces challenges in detecting shallow water accumulation within the regulatory threshold.

Table 3. Ultrasonic Sensor Accuracy Results

Water Depth (cm)	**Sensor 1 Accuracy**	**Sensor 2 Accuracy**	**Sensor 3 Accuracy**
1	70	70	80
1.5	66	66	80
2	100	90	100
2.5	92	88	96
3	96	96	100

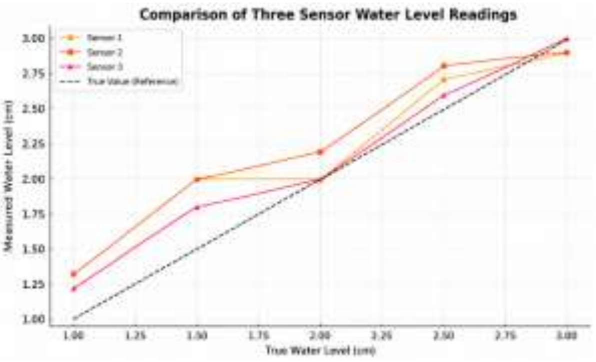

Figure 5. Graph of Water Level

Third, GPS module testing was conducted in three different locations to validate the geospatial mapping capability. The results showed very high precision, with a very small average error rate, specifically below 0.00150% compared to Google Maps coordinates. This capability directly addresses one of the main gaps in previous research—the lack of precise location mapping—and constitutes the core novelty of this system.

Table 4. GPS Coordinate Accuracy Test

Location	**Error Latitude (%)**	**Error Longitude (%)**
Behind TRBU	0.00034–0.00137	0.00008–0.00016
In front of Main Building	0.00034–0.00103	0.00001–0.00002
Behind AASFD office	0.00000–0.00138	0.00011–0.00016

Fourth, the endurance test of the 2,200 mAh Li-Po battery demonstrated that the prototype could operate stably in active monitoring and data transmission modes for 30 minutes while retaining remaining power. This duration is considered sufficient, given that the current average time for a single manual inspection cycle also ranges around 30 minutes.

Table 5. Battery Endurance Test

Time (min)	**Voltage (V)**	**Current (A)**	**Power (W)**
0	10.94	3.1	33.91
5	10.90	3.1	33.79
15	10.78	3.1	33.42
30	10.63	3.1	32.95

The final stage was the user acceptance test to evaluate the prototype's feasibility, functionality, and alignment with end-user needs. The test involved five expert respondents from airport operations and academia, who assessed four aspects: usability, effectiveness, efficiency, and user satisfaction. Although the number of respondents was limited and cannot fully represent broader operational users, the evaluation was intended as preliminary feasibility testing during the prototype development stage.

Table 6. User Satisfaction Result

Respondent	Usability (1-5)	Effectiveness (1-5)	Efficiency (1-5)	Satisfaction (1-5)
User 1	5	4	5	5
User 2	4	4	5	5
User 3	4	5	5	5
User 4	5	4	5	5
User 5	5	4	5	5

The quantitative analysis was performed using the feasibility percentage formula adapted from (Abdullah et al., 2021). Based on the data from the questionnaires (Table 6), a total score of 91 was obtained out of a maximum ideal score of 100. The calculation is as follows:

$$Validation\ Score = \frac{91}{100} x 100\% = 91\%$$

In results, the 91% satisfaction score indicates the prototype successfully addresses the core problem of manual inspection inefficiency. Building upon these results, a deeper analysis was conducted to compare the system's performance with previous research and expert findings to evaluate its alignment with theoretical principles and operational standards. Consistent with (Wibowo & Setyaningsih, 2025), the ultrasonic reflection achieved greater stability over wider reflective surfaces. In practical applications like water level monitoring, this characteristic complements the capabilities of the JSN-SR04T sensor. With its wide measurement range spanning from 25 cm to 450 cm and its specialized design for water-related environments, the sensor effectively leverages this reflective stability to deliver highly precise and consistent data across varying distances. However, fluctuations in shallow water levels encountered in this study indicated that installation height still influenced the sensor reading response. Although the ultrasonic sensor demonstrated improved accuracy at water depths above 2 cm, its performance decreased at depths below 1 cm. This limitation is important because aviation regulations specify a critical standing-water threshold of 3 mm for runway safety assessment.

The camera was able to detect clear water up to 1.5 meters and turbid water up to 2 meters, supporting the findings of (Hotmartua et al., 2022) that visual monitoring is important for identifying water conditions that cannot be measured by sensors alone. This detection range was considered adequate for low-speed runway inspection vehicles during preventive maintenance activities. However, further testing under nighttime conditions, heavy rainfall, and higher vehicle speeds is still necessary to evaluate the system's performance in real airport operations.

The deep-learning segmentation accuracy (validation accuracy 78–83%) in this research also aligned with the findings of (Hosseiny, 2021), who demonstrated that U-Net has high robustness in water region identification, although model performance may decline due to dataset limitations. The GPS testing revealed very low measurement error (<0.00150%), confirming the claim made by (Waluyo et al., 2018) that high-precision IoT location tracking is essential for effective monitoring in transportation infrastructure areas. This directly contributes to the improvement of runway safety monitoring as recommended by ICAO through accurate condition reporting to support RCA.

The 91% user satisfaction rating categorized as "Very Satisfied" also strengthens the statement of (Abdullah et al., 2021), who noted that ease of use and functionality significantly affect user acceptance of digital inspection systems. Although the prototype performed well, respondents recommended enhancements in lighting performance and stability during higher-speed operation, which aligns with the limitations reported in previous sensor-based system studies (Hotmartua et al., 2022).

Overall, the comparison with earlier expert studies confirmed that the system developed in this research had achieved functional readiness and demonstrated potential operational benefits. Nevertheless, improvements related to illumination support, casing protection, and high-mobility testing are required to ensure the system's reliability in a fully implemented airport environment.

Conclusion

This research successfully developed an IoT-based standing water monitoring system that integrates Internet of Things (IoT), Artificial Intelligence (AI), and multi-sensor technology to support airport preventive maintenance. The system combines a JSN-SR04T ultrasonic sensor for measuring water depth, a U-Net-based camera for visual detection, a GPS module for location tracking, and a web-based dashboard for monitoring. The results showed that the prototype worked effectively in improving runway inspection efficiency. The ultrasonic sensor achieved 100% accuracy at water depths of 2–3 cm, the GPS module produced very small location errors (<0.00150%), and the AI model showed good performance in detecting standing water. Furthermore, the system's viability was validated by end-users, achieving a 91% user satisfaction rating, which is categorized as "Very Satisfied". This prototype is therefore considered a feasible solution that can enhance preventive maintenance effectiveness and significantly support flight safety. Scientifically, this study contributes to the development of integrated airport monitoring systems combining IoT and AI technologies for runway safety monitoring. Practically, the prototype supports faster runway inspection reporting and digital maintenance management. Future development should focus on the recommendations gathered during testing. Future research should focus on implementing higher-resolution water sensors capable of detecting standing water below 3 mm, expanding AI datasets under various weather conditions, integrating infrared or low-light cameras for nighttime operation, and conducting long-term operational testing in active airport environments.

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