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Performance Evaluation of Ultrasonic Obstacle Detection and Real-Time GPS Tracking in an IoT Smart Shoe for Visually Impaired Navigation

Juanda Hakim Lubis[1], *Akhyar Lubis[2], Fajrul Malik Aminullah Napitupulu [3], Nahdah Salsabiil Damanik[4], and Lathifah Tsamratul Ain[5]

[1] Research Scholar, Department of Computer Science, Universitas Pembinaan Masyarakat Indonesia, Medan, Indonesia
[2] Lecturer, Department of Computer Engineering, Universitas Pembangunan Panca Budi, Medan, Indonesia
[3] Lecturer, Department of Computer Science, Institut Modern Arsitektur dan Teknologi, Deli Serdang, Indonesia
[4, 5] Lecturer, Department of Informatics Management, AMIK ITMI, Indonesia

*Correspondence should be addressed to Akhyar Lubis; akhyarlbs@pancabudi.ac.id

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ABSTRACT- This paper outlines how a smart shoe prototype that can help to guide visually impaired people in a safe manner was developed and tested. This system includes an ESP32 microcontroller, an ultrasonic HC-SR04 sensor to detect obstacles, a Neo-6M GPS to track its position in real time and audio-haptic feedback actuators. It also includes an emergency push button to be informed by IoT using Blynk and Twilio. The evaluation of the performance was performed in an indoor and outdoor setting; the parameters of the evaluation were ultrasonic detection accuracy, GPS accuracy, and notification delays. The system achieved a total F1-score of 84.31 in obstacle detection and was more accurate when it was conducted indoors but not when it was conducted outdoors. The GPS module was an average of 5 meters in open field and 10 meters in cities. The delay of the IoT notification was 3.5 seconds in the indoors and 5.2 in the outdoors, which was satisfactory. These findings demonstrate that the suggested prototype of a smart shoe can be a credible means of visually impaired individuals navigating the environment, though further research must work on enhancing the scope of detection, identifying objects on the ground, and GPS precision.

KEYWORDS- Assistive Technology, GPS Tracking, IoT Smart Shoe, Ultrasonic Obstacle Detection

I. INTRODUCTION

According to World Health Organization (WHO), there are over 2.2 billion individuals globally with some type of vision impairment with at least 39 million of these individuals being blind [1]. The Ministry of Health in Indonesia records that the number is approximately 1.5 percent of the entire population or four million people are having vision issues including blindness [2]. These statistics demonstrate the significance of developing assistive technologies that will allow the individuals with the visual impairments to be more self-reliant, safer, and have a better quality of life. White canes and guide dogs have not become irrelevant yet because they cannot see obstacles nor can they provide you with a sense of the position of space. That is the reason why research and innovation in the area of wearable assistive devices based on modern technologies have become more significant.

The technology of digital and sensor-based applications is advancing so fast that it has opened up new possibilities in this area. Ultrasonic obstacle detection and real-time Global Positioning System (GPS) tracking are some of the most promising features that can be used in wearable navigation systems. These technologies provide blind users with real-time data on what is around them and their location and can make them significantly safer and more mobile. Nonetheless, to facilitate the successful implementation, systematic performance tests are necessary because reliability and user confidence is tied to the quality of ultrasonic distance measurements, false alarms, alert latency, GPS accuracies, and system efficiency in general [3], [4]. Nevertheless, in spite of this advancement, there is research gap in the literature. New features of many prototypes are not matched by standard performance measures or detailed tests of the real world performance of integrated systems. The vast majority of research, however, concentrate on the technologies in question or on the theoretical design without fully examining the issues of integration and the overall user experience [5], [6], [7]. Since little research has been done on integration, the visually impaired have difficulty in getting credible mobility solutions that can be applied in diverse environments. Previous studies have often concentrated on the separate elements, including ultrasonic sensor, or GPS module, without looking at how all these interact when brought together as an integrated wearable system [8], [9], [10].

To close this gap, the current paper introduces and demonstrates a prototype of an intelligent shoe with the capabilities of GPS tracking, ultrasonic distance detection, and an emergency notification. This system uses an ESP32 microcontroller with an ultrasonic sensor that is able to identify objects in a 40 centimeter range and gives users real-time audio-haptic feedback. Moreover, the prototype is equipped with an emergency push button sending notifications via various platforms (push messages, SMS and email) via Blynk and Twilio platforms which include embedded GPS coordinates to track the location precisely [5], [11], [12]. The research findings of this study, such as standardized framework of assessing the detection accuracy of obstacles, the notification latency, and the GPS behavior; integration of sensing, processing, and communication subsystem analysis, and identifying limitations and pragmatic challenges in implementing wearable assistive technology are notable.

This work is deliberately reduced to quantification of technical performance parameters directly connected with ultrasonic obstacle detection and GPS tracking but non-technical aspects, like ergonomic comfort, interface usability, and software design are omitted. The given choice permits the study to concentrate on the empirical examination of the main system features, and the user-oriented and ergonomic issues to be addressed in the further research [13]. It is the aim of this study to assist in the enhancement of assistive wearable technologies by demonstrating that IoT-based solutions can help make it scientifically easier to help blind people move around, be safe, and independence.

II. LITERATURE REVIEW

To ensure that assistive technologies are functional and safe, particularly when the devices are designed to address blind individuals, it is significant to be aware of the methods and metrics applied to test the assistive technologies. Researchers have considered employing ultrasonic sensors to locate obstacles, the means of quantifying the performance of assistive systems, the accuracy of consumer-grade GPS devices, and the dependability and speed of the alerts of IoT. These researches indicate the strong and weak aspects of the current approach we have.

A common method of locating obstacles is ultrasonic sensing, which operates based on the time-of-flight principle, i.e. how long it takes emitted ultrasonic waves to strike an object. Research indicates that beam angle is highly crucial with regard to accuracy and range of detection. For distance measurements, narrower beams provide more accurate measurements but less coverage whereas wider beams provide more coverage but less accurate [14]. Some of the things that can cause errors that can lead to performance include surface texture, angle of incidence and environmental conditions such as temperature and background noise just to mention a few. In order to address these issues, scientists have also proposed how to improve things such as by averaging multiple readings or applying filters to smooth outputs, particularly with inexpensive sensors such as the HC-SR04 [15]. These findings demonstrate that in order to be useful in real life, sensors must be purposefully calibrated and their noise minimized.

Determination of evaluation measures is also critical in determining the level of reliability of assistive devices. To compare true positives, false positives people often use such metrics as precision, recall, and the F1-score. Additional measures such as false alarm rates, true positive rates (TPR), and the true negative rates (TNR) provide us with data of the strength of the system [16], [17]. Stability in the design of experiments has also been noted as an important requirement. Indicatively, indoor and outdoor tests must be conducted as the sensor readings are affected by the various surfaces [18]. Systematic procedures and regular maintenance records are also relevant to ensure that the trials can be redone and contrasted [19]. Through these approaches, it is easy to perform in-depth assessments and comparisons, which are mostly lacking in other research.

The other critical field of study concernful of assistive navigation technologies is the precision of consumer grade GPS receivers. The environment is capable of significantly influencing performance, and this is particularly noticeable in cities where satellites are blocked by buildings. This kind of condition undermines the accuracy of satellites because of visibility loss [20]. The positional errors of cheap GPS devices can range between 5 and 10 meters in an outdoor environment with higher errors in harsh environments [18]. People have sought to increase the accuracy of GPS readings by applying validation techniques such as comparing GPS readings with known reference points, or more elaborate techniques such as simultaneous localization and mapping (SLAM) [21]. The outcome of these findings indicates trade-offs between the cheap GPS modules and the level of accuracy which visually impaired users require when they rely on the precise location information.

Important is the latency and reliability of IoT-based alert systems embedded in assistive devices, as well. Communication at the right time is highly significant in ensuring that people remain safe, particularly during crisis. Different latencies can be experienced in cloud-based platform due to network congestion and processing times [22]. Latency variability is dangerous in real-time applications in which delays might make it less safe [23]. In order to deal with these issues, some empirical standards of tolerable alert latency have been proposed, especially to SMS and push notifications that are widely utilized in assistive devices [24]. Dependable notification systems with minimal or no delay are thus required to verify that these systems are prepared to be utilized in the daily life.

Overall, the literature indicates that important advancements have been made in the fields of ultrasonic sensing, indicators of evaluation, accuracy of GPS, and reliability of IoT alerts. However, there is still a significant gap in the research: few studies provide a consistent framework and combine these elements to make them a unified wearable system and evaluate them in detail in a real-life setting. Most studies do not fully test the combination of individual technologies: e.g., how effective is obstacle detection with GPS tracking and what does this mean to the user experience. This loophole highlights the necessity of smart wearables, like smart shoes, that are built to integrate ultrasonic wearable detection, GPS location tracking, and IoT notifications. The current research aims to address this gap by providing an organized performance evaluation that would study these three fundamental elements in combination, therefore, improving the development of assistive navigation technologies in visually impaired individuals.

Table 1: Comparative Summary of Prior Studies

Researcher	Focused/Method	Censor/Component	Limitation
Axsom et al. [14]	Ultrasonic location mapping	Ultrasonic Sensor (ToF)	Not yet tested on wearable applications for the visually impaired
Breed & Severns [15]	Consumer GPS evaluation	GPS receiver	Multipath interference and environmental conditions
Carbonneau & Dietrich [16]	System performance evaluation with precision-recall	Experiment protocol	Not specific for the visually impaired
Li et al. [17]	GPS/INS/UWB integration	GPS/INS/UWB with 2 phase filter	Higher costs, system complexity
Davidson et al. [20]	Evaluation of smartphone-based GPS devices	GPS smartphone	Only tested under limited conditions
Harvey et al. [19]	Position measurement experiment	Cheap UAV + GPS	Not discussing wearable systems
Müllenheim et al. [25]	Cheap GPS for outdoor activities	GPS receiver	Not ideal in densely built-up areas
Waters et al. [18]	Test protocol validation	Experiment protocol	Not specific to blind navigation systems
Lucas et al. [22]	Evaluation of IoT cloud latency	Cloud computing	There is no standard for real-time assistive technology
Paziewski et al. [23]	Evaluation of multi-GNSS	GNSS high-rate RTK & PPP	Requires expensive equipment
Pratt & Avelar [24]	IoT notification latency analysis	GPS & barometer	Not yet tested on assistive IoT devices

III. METHODOLOGY

In this research, the applied research design was used to create and test a prototype of a smart shoe with the implementation of Internet of Things (IoT), ultrasonic sensors, and GPS. The methodology consists of 3 key phases: system design, prototype implementation and experimental evaluation.

During the system design, the smart shoe was designed around the ESP32 microcontroller as the key component with an ultrasonic HC-SR04 sensor to detect obstacles, a Neo-6M GPS to track the position, and actuators added including a buzzer and vibration motor to generate audio-haptic feedback. It was also installed with an emergency push button that sends cloud-based notifications via the Blynk and Twilio platform that relay real-time GPS positions to the caregivers or family members.

The prototype implementation entailed the solder up of the hardware on a printed circuit board (PCB) and embedding it into a pair of shoes to represent real world conditions. The ultrasonic sensor was placed at the frontal part of the shoe near the toe to sense obstacles in front of the shoe with a threshold of 40 cm, and the GPS module was set to give constant coordinate readings. The firmware was created in the Arduino IDE, including sensor initializing, distance calculation according to the time-of-flight principle and GPS interpretation, activation of the actuators. Upon button activation, the system sent an emergency message with GPS location information via SMS, push notification or email.

The testing was carried out in the indoor and outdoor environment to observe the effectiveness of the system in various environments. We measured three things: (1) Obstacle Detection Accuracy, which entailed the placing of obstacles at distances less than and more than the 40 cm mark and recording the results in a confusion matrix of True Positives (TP), False Positives (FP), False Negatives (FN), and True Negatives (TN); (2) GPS Accuracy, which involved the comparison between the logged coordinates and the predetermined reference points in the open fields and urban areas; and (3) IoT Alert Latency, which involved the duration of time it took to press

System performance was quantified using precision, recall, and F1-score, defined as:

$$Precision = \frac{TP}{TP + FP}$$

$$Recall = \frac{TP}{TP + FN}$$

$$F1 = 2. \frac{Precision. Recall}{Precision + Recall}$$

These measurements were computed independently of the indoor and outdoor experiment, and summed up to come up with total performance. Also average GPS error (in meters) and average latency of IoT notification (in seconds) were reported as complementary indicators. This research was focused on technical reviews of obstacle detection, GPS tracking, and IoT alerts only but not on the ergonomic comfort, battery life, and user interface ergonomics.

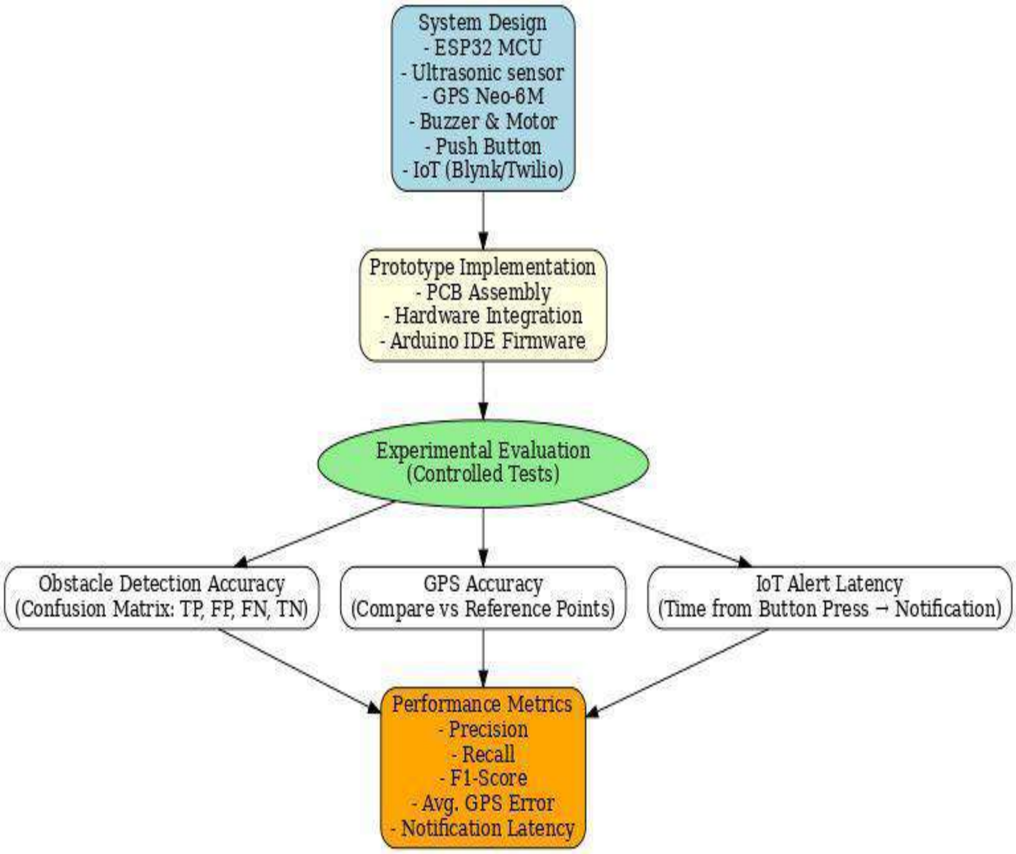

Figure 1: Research Methodology Flowchart

IV. RESULT AND DISCUSSION

The prototype of the smart shoe is based on ESP32, ultrasonic HC-SR04, GPS Neo-6M, and audio-haptic actuators successfully implemented. Real time distance sensing, location acquisition with GPS and notification of the emergency by Blynk and Twilio were possible with hardware integration and software development with Arduino IDE. The hardware interfaces, including ultrasonic and GPS interfaces, push button, buzzer and vibration motor, worked as expected during initial testing. The research (e.g., ultrasonic testing, GPS interface, buzzer and motor integration and final prototype assembly) has figures 1 to 4 that demonstrate successful implementation of each subsystem.

Figure 2: Blynk interface

Figure 3: GPS Tracking

Figure 4: Prototype Shoe

A. *Obstacle Detection Performance*

Obstacle detection system was tested at detection threshold of 40 cm and 50 trials were taken in the indoor and outdoor conditions. The outcomes were entered into a confusion table indicating True Positives (TP), False Positives (FP), False Negatives (FN) and True Negatives (TN). These numbers were used to compute the performance metrics, which are shown in Table 2.

Table 2: Confusion Matrix and Performance Metrics of Obstacle Detection

Scenario	TP	FP	FN	TN	Precision (%)	Recall (%)	F1-Score (%)
Indoor (n=50)	23	3	2	22	88.46	92	90.20
Outdoor (n=50)	20	6	5	19	76.92	80	78.43
Total (n=100)	**43**	**9**	**7**	**41**	**82.69**	**86**	**84.31**

The findings reveal that the performance was higher inside since the conditions were more stable. It performed worse outside due to noise, reflections on surfaces and environmental changes. The system was quite effective in terms of being sensitive and reliable, evidenced by the overall F1-score of 84.31%.

Figure 5 compares performance among precision, recall, and F1-score of indoor and outdoor testing to further demonstrate the differences in the performance.

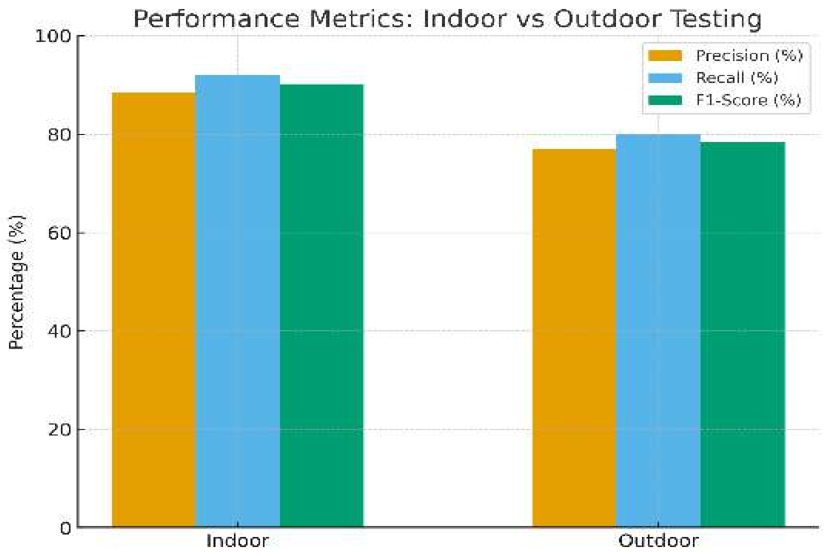

Figure 5: Performance Metrics: Indoor vs Outdoor Testing

In the Figure 5, it is clear that even at indoor tests the same performed better than outdoor tests on all the metrics. It demonstrates the influence of environmental factors on the level of effectiveness of ultrasonic sensing.

B. GPS Accuracy

We tested the GPS module (Neo-6M) by comparing the coordinates it recorded to known reference points. When the conditions were open fields, the average positional error was about 5 meters. When the conditions were urban, where there could be multipath interference, the error grew to about 10 meters. This result is in line with what other studies have found: consumer-grade GPS modules are accurate to within 5 to 10 meters, but they don't work as well in urban canyons.

These results show that GPS can be useful for locating emergency notifications, but its limitations need to be taken into account when used in densely populated areas.

C. IoT Alert Latency

The emergency push button successfully triggered notifications via Blynk and Twilio. In indoor Wi-Fi settings, the average time between pressing a button and getting a notification was 3.5 seconds. In outdoor mobile data settings, it was 5.2 seconds. These delays are fine for emergency communication, but they show how much we depend on the quality and connectivity of the network. Consistency of delivery was confirmed, with no failures observed across multiple test cycles, validating system reliability.

The comparison between GPS error and IoT latency across indoor and outdoor environments are shown in Figure 6.

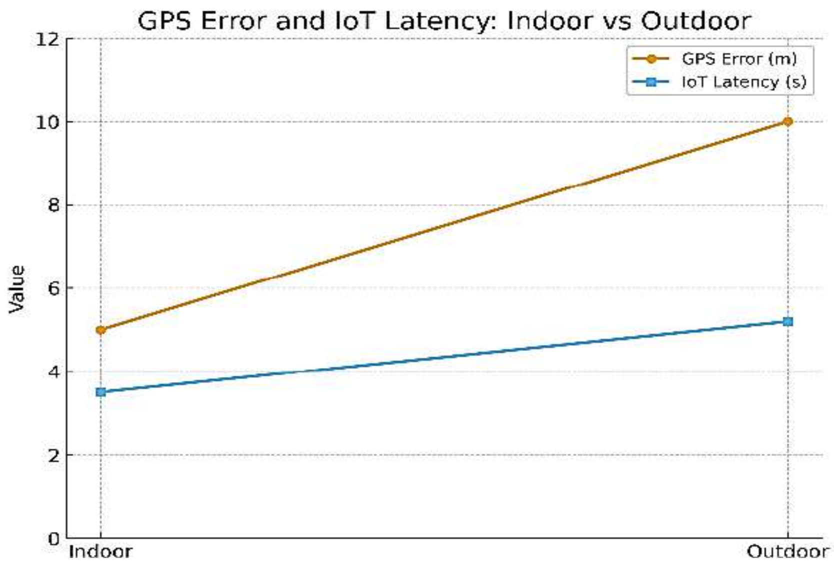

Figure 6: GPS Error and latency of IoT: Indoor and Outdoor

The diagram illustrates that not only GPS error was greater but also the IoT latency was greater in the open spaces than in the indoor testing. This is the way multipath on and fluctuation of mobile data networks in open air environments combine.

D. Discussion

The findings indicate that the smart shoe prototype will be able to identify obstacles, monitor your position, and alert about the emergencies in good time. The F1-score of obstacle detection was extremely high particularly when it was indoors. Results of the GPS were consistent with what one would expect with a consumer-level device. IoT latency remained within a reasonable level, and it is possible to optimize it, reducing delays.

Still, some limits were found. The ultrasonic sensor was not able to view the hazards on the ground, such as potholes or elevation changes, making it less effective in places with a high concentration of various kinds of landscapes. The fact that the maximum detection distance was 40 cm complicated the quick reaction of the users to the problems that were coming their way fast. GPS can be not so effective in big towns and you can have difficulties in sharing your position.

It could also be enhanced in the future by adding multi-sensor fusion (e.g., infrared, LiDAR or camera fusion), expanded obstacle detection range and support of multi-GNSS to render localization more effective. These advancements would make smart shoe technology more stable and helpful to assist people with vision issues with movement.

V. CONCLUSION

This study has developed and experimented on a prototype smart shoe that utilises ultrasonic sensing, GPS positioning and IoT-driven emergency alerts to assist individuals who are blind. The system was constructed on the basis of ESP32 microcontroller and could reliably detect obstacles at the distance of up to 40 cm. Indoor testing was more precise and recalls were also higher compared to outdoors testing. The system achieved an F1-score of 84.31% indicating that the system could strike the right balance between accuracy and reliability.

The GPS module was 5 meters in the open areas and 10 meters in urban areas, averagely, which is what you would expect with a consumer-grade GPS unit. Internet of Things (IoT) notifications that were sent via Blynk and Twilio demonstrated reasonable latency of 3.5 seconds indoors and 5.2 seconds outdoors. This was the case with all tests.

The prototype was functioning as intended, but it had certain issues. To illustrate, it was unable to see potentially dangerous objects coming at very high speed in a distance and it was unable to see objects on the ground such as potholes and GPS was not highly accurate in the busy cities. The proposed study area to be explored in future studies is the combination of multi-sensor fusion, augmented detection ranges and multi-GNSS modules in enhancing the resiliency and applicability to real-life situations. In the end, the findings confirm the idea that the smart footwear with the IoT capability can be used as an option to improve the mobility, autonomy, and safety of visually impaired people.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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ABOUT THE AUTHORS

Juanda Hakim Lubis obtained him master's degree in Informatics Engineering from Universitas Sumatera Utara, Indonesia, in 2012. He is currently a doctoral student in the Department of Computer Science at Universitas Sumatera Utara. His research interests include Software Engineering, Database Management Systems, and Data Science.

Akhyar Lubis obtained his Master's degree in Computer Science (M.Kom) from Universitas Amikom Yogyakarta, Indonesia, in 2017. He is currently a Lecturer in the Computer Engineering Study Program at Universitas Pembangunan Panca Budi. His research interests include Cloud Computing, Internet of Things (IoT), and Infrastructure as Code (IaC).

Fajrul Malik Aminullah Napitupulu is a Lecturer in Computer Science at Institut Modern Arsitektur dan Teknologi, Indonesia. He earned his Master's degree in Information Technology from Universitas Sumatera Utara in 2024. His research interests include Web Technologies, Mobile Applications, and Artificial Intelligence.

Nahdah Salsabiil Damanik is a Lecturer in Informatics Management at AMIK ITMI, Indonesia. She earned her Master's degree in Informatics Engineering from University of North Sumatera in 2024. Her research interests include Security, Artificial Intelligence, and Machine Learning.

Lathifah Tsamratul Ain is a Lecturer in Informatics Management at AMIK ITMI, Indonesia. She earned her Master's degree in Informatics Engineering from University of North Sumatera in 2024. Her research interests include Security, Artificial Intelligence, and Machine Learning.