Development of Low-Cost Iot for Tree Instability Detection System and Early Hazard Notification

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ABSTRACT

Urban tree failures have emerged as a growing safety issue in Malaysia, with nearly 5,000 reported incidents in 2023 that resulted in fatalities and considerable damage to surrounding infrastructure. Conventional monitoring methods, including manual inspections and GIS-based management systems, remain largely reactive, time-consuming, and costly to maintain. In response to these challenges, this study presents an Internet of Things (IoT)–based early warning system capable of detecting potential tree instability in real time. The system integrates MPU6050 motion sensors with ESP32 microcontrollers and employs LoRa communication technology for long-range, low-power data transmission. Collected data are automatically uploaded to cloud-based Google Sheets for continuous recording and analysis. When the measured tilt angles surpass a defined threshold, immediate alerts are transmitted to responsible personnel through a Telegram Bot interface. This integrated approach provides a practical, low-cost, and scalable solution that improves detection accuracy, reduces reliance on manual observation, and facilitates more proactive management of urban trees. The use of open-source platforms and readily available components also enhances system accessibility, making it suitable for implementation by local authorities and community-based environmental initiatives.

Keywords: Tree monitoring system, internet-of-things (IoT), alert system.

INTRODUCTION

The increasing unpredictability of weather in Malaysia, characterized by sudden thunderstorms, heavy downpours, and strong winds, has contributed to a worrying rise in incidents involving falling trees, particularly in densely populated urban environments [1], [5], [12]. From January to July 2024, the Malaysian Fire and Rescue Department recorded 2,575 cases of fallen trees, leading to 8 deaths and 27 injuries nationwide.

Urban trees are an important aspect of metropolitan life. They help cool the urban microclimate, enhance air quality, and provide visual and psychological benefits to communities [1]. However, in recent years Malaysia (and comparable urban settings) have seen a notable increase in tree-fall incidents under extreme weather such as sudden storms, heavy rain, and strong winds [5], [12]. These incidents have damaged property, impeded traffic, and, tragically, caused injuries and deaths. Over 2,500 tree-fall incidents were reported in the first seven months of 2024 alone, with eight people killed and 27 injured. These figures highlight a major safety concern that requires urgent attention, reinforcing calls for better monitoring of tree stability and failure risk [3], [4], [5], [12]. One key reason these occurrences persist is that most tree monitoring is still conducted manually, with alerts typically triggered only after public complaints or an incident has occurred; while some municipalities employ GIS-based inventories, these tend to be costly, maintenance-heavy, and not designed for real-time alerts [3]. With many aging trees near busy roads, buildings, and power lines, the risk profile remains elevated under increasingly volatile weather [3], [5].

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As a result, hazardous trees often remain undetected until they fail [3], [4], [5]. This monitoring gap leaves local governments with few options; some remove potentially risky trees based on precaution or general condition even when they may still be structurally sound, resulting in unnecessary loss of healthy urban greenery that mitigates heat islands, absorbs pollutants, and supports community well-being. Such practices also run counter to broader sustainability goals that emphasize data-driven stewardship of urban trees.

To address this, there is a pressing need for a low-cost, scalable, and intelligent solution that provides real-time insight into tree stability and detects early structural imbalance—an area where IoT/LPWAN and integrated sensing have shown clear promise [1], [2], [6], [7], [9], [14]. In the context of tree movement, two key indicators of risk are changes in pitch (forward/backward tilt) and roll (side-to-side tilt); these angles reflect how a tree sways or leans and can serve as early warning signs of uprooting, especially during high winds or soil instability [4], [5], [7]. Complementary modalities—UAV/remote sensing for canopy and phenology monitoring, machine-learning models for physiological signals, rainforest sensor networks for harsh environments, and specialized field devices—can reinforce a comprehensive monitoring architecture [8], [10], [11], [13], [15].

Beyond mitigating immediate hazards, a modern tree-monitoring architecture should fuse low-cost inertial sensors for tilt/sway with sap-flow and stem-water measurements to capture physiological stress preceding mechanical failure [4], [7], [14]. LPWAN (e.g., LoRa) enables multi-kilometer connectivity at low power for continuous reporting and threshold-based alerts to municipal dashboards or messaging systems [2], [6], [9]. Overhead sensing from UAVs and high-resolution imagery can flag canopy dieback and phenological anomalies at the individual-tree level, guiding targeted ground inspections [8], [13]. Machine-learning models further improve forecasting of risk under volatile weather by learning patterns linking environmental drivers to instability signals [10], while distributed sensor networks hardened for tropical conditions demonstrate feasibility at scale in complex rainforest and urban environments [11].

METHODOLOGY

A. System Design

The process of development tree monitoring and alert system involves with three main phases which are developing, testing, and implementation. The process of developing the system starts with a thorough analysis of which suitable sensors such as MPU6050 which consist of accelerometer and gyroscope module. The gyroscope measures the rotational velocity (rad/s) which is the change of the angular position over time along the X, Y, and Z axis. The accelerometer measures the acceleration (rate change of velocity object) over X, Y, and Z axis. There are three main components in the system which is the Node where the MPU6050 is connected, the transceiver, and gateway as shown in Figure 1.

Figure 1: Three main components in system development.

The MPU6050 sensor will be connected to microcontroller as Node. This node will collect data in X, Y and Z axis as roll, pitch, and yaw. Figure 2 shows the direction of roll, pitch and yaw to detect the movement direction from a tree.

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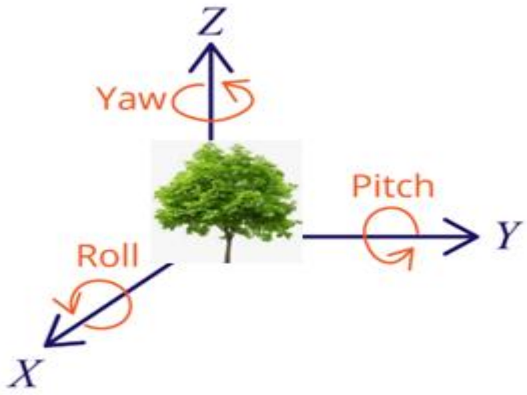

Figure 2: Direction of roll, pitch and yaw.

The formula for roll and pitch is given as below from accelerometer reading a_x, a_y, a_z:

$$Roll = \gamma = \arctan\left(\frac{a_y}{\sqrt{a_x^2 + a_z^2}}\right)$$

$$Pitch = \beta = \arctan\left(\frac{a_x}{\sqrt{a_y^2 + a_z^2}}\right)$$

In this project, only roll and pitch data are collected from each node as the yaw data is not necessary. These roll and pitch equation then are embedded into microcontroller on each node to get new parameter roll, and pitch parameter which represent rotation from front to back for roll, and rotation from side to side for pitch. All reading both are in translate in degree unit.

Figure 3 depicts the subsystem of three main components nodes, LoRa transceiver, and LoRa gateway. The nodes consist of ESP32 microcontroller, connected to MPU6050 to collect roll and pitch data. These data then are transmitted to LoRa transceiver through ESP-Now protocol. The development of transceiver consists of ESP32 and LoRa module. Data receive from node then is re-transmit using LoRa communication for long range capability up to several kilometre range. At the gateway, LoRa module receive roll, and pitch data together with node id. These data read by ESP32 micrcontroller and push data to the Googlesheet through Wi-Fi connectivity. Notification will be sent to Telegram if the changes of roll and pitch is bigger than threshold setting which is 1.5.

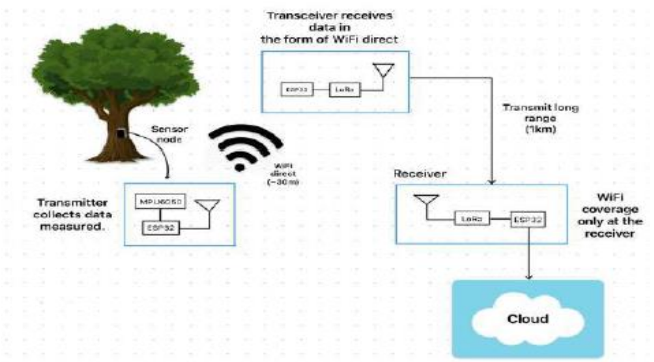

Figure 3: Subsystem of Nodes, LoRa Transceiver and LoRa gateway.

ESP-NOW is a proprietary wireless communication protocol introduced by Espressif for its ESP32 and ESP8266 microcontrollers. Operating at the data-link layer of the OSI model, it bypasses several upper layers of the conventional network stack, enabling lower latency and reduced communication overhead. The protocol is optimized for transmitting short data packets, allowing rapid and efficient exchange of small amounts of

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information. Communication in ESP-NOW is based on MAC addresses, utilizing the unique hardware identifiers of each ESP device for peer-to-peer connectivity. ESP-NOW is highly suitable for applications that demand fast, low-power, and direct wireless communication between ESP devices. It is particularly advantageous in scenarios involving small data packets and minimal network infrastructure, eliminating the need for routers or complex network configurations.

Several experiment for range is test between Nodes and Transceiver using ESP-Now protocol. From actual tree environment, it is found that the range of ESP-Now can dropped from 50m (in Line-of-sight) range to just 6.79m if the environment which have lot of trees block the signal. This condition is considered as heavy Non-Line-of-Sight condition (NLOS). From our record, in this situation the length can be up to just 6.79m before the communication between nodes and transceiver failed. The Nodes can be placed in star-network topology transmit data consist of node Id, roll, and pitch as shown in Figure 4.

Node Id (Refer to which tree)	Roll data	Pitch data

Figure 4: Node payload data send to transceiver.

LoRa, or Long-Range Wide Area Network (LoRa WAN), represents a significant advancement in wireless communication technology, particularly within the Internet of Things (IoT) ecosystem. It employs Chirp Spread Spectrum (CSS) modulation, which offers high resistance to interference and supports long-distance communication with extremely low power consumption. In this project, the SX1278 series LoRa module was selected primarily due to its cost-effectiveness for prototype implementation. Specifically, the LoRa RA-02 module from AI Thinker was chosen, and its key specifications are presented in Table 1.

Table 1. Specifications Of Lora Ra-02

Parameter	**Value/Range**
Operating Frequency	433MHz
Transmission output power	18+/-1dBm
Receiver Sensitivity	-141dBm
Antenna gain	0dBi

At the transceiver end, LoRa communication is employed to enable long-range data transmission to the LoRa gateway. Based on testing under Line-of-Sight (LoS) conditions, the LoRa communication achieved a maximum range of approximately 2.77 km. This indicates that the gateway can be strategically positioned within a Wi-Fi coverage area, while the transceiver units can be deployed in tree-covered environments where Wi-Fi connectivity is unavailable. Figure 5 illustrates the potential communication range and multi-network integration within the tree monitoring system.

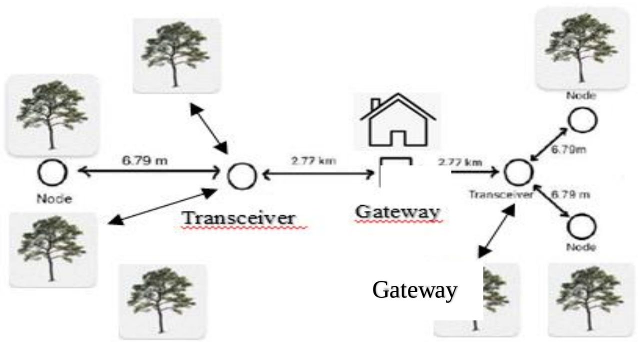

Figure 5: Implementation of tree monitoring system on tree area.

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Each node will be installed on a tree trunk. At an area, up to 5 nodes can be placed and will collect data of tree Id, roll, and pitch and send it to the same transceiver. All nodes are connected to the LoRa transceiver in star network topology. The range from nodes/tree to transceiver can be from 6.79m in worst case condition and in line-of-sight condition up to 50m range.

B. System Development & Implementation

Figure 6 shows the node is installed on the tree trunk, serving as the primary sensing unit for data collection and transmission within the monitoring system.

Figure 6: The node is installed on the tree trunk

The LoRa transceiver functions as the core communication module, responsible for transmitting and receiving data between the sensor node (mounted on the tree trunk) and the LoRa gateway. It enables long-range, low-power wireless communication, ensuring reliable data exchange even in remote or obstructed environments.

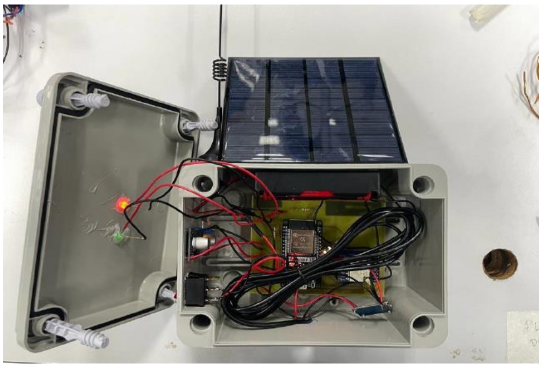

Figure 7: The LoRa transceiver functions as the centre communication module

Figure 8 depicts LoRa gateway that was developed in the WiBNet laboratory, serving as the central hub for receiving data from multiple LoRa transceivers. It aggregates and forwards the collected information to the server or cloud platform for further analysis, forming the backbone of the long-range communication network.

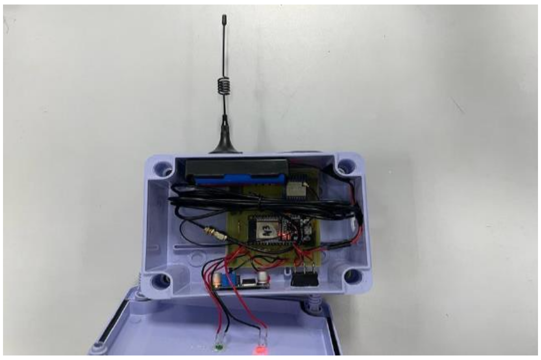

Figure 8: The LoRa gateway was developed in the WiB Net laboratory.

C. Line-of-Sight and non-Line-of-Sight Packet Loss for LoRa Data Transmission

The subsequent experiment investigated the impact of distance on packet loss in LoRa module data transmission under both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions. In this setup, data were transmitted from a LoRa Wi-Lo transceiver to a LoRa Gateway receiver using the SX1278 transceiver chip to establish connectivity between the two devices. The LoRa communication parameters were configured with a default Spreading Factor of 7 (SF7), providing an optimal balance between data rate and transmission range. The results, illustrating the number of lost packets and corresponding RSSI values for both LOS and NLOS scenarios at varying distances, are presented in Figure 9.

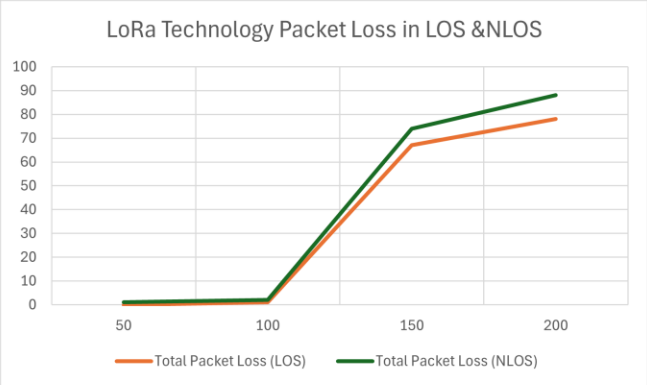

Figure 9: Packet Loss in LOS & NLOS Condition for Transmission Using LoRa

CONCLUSION

This research has successfully developed and demonstrated an IoT-based Early Warning Tree Monitoring System aimed at improving the safety and sustainability of urban environments. By combining MPU6050 motion sensors, ESP32 microcontrollers, LoRa long-range communication, and cloud-based tools such as Google Sheets and Telegram, the system provides a practical and affordable solution for detecting tree instability in real time. The results indicate that continuous monitoring of tilt variation particularly pitch and roll angles can serve as an effective early warning signal before structural failure occurs. Beyond enhancing situational awareness, the system reduces dependence on manual inspections and enables quicker responses to potential hazards, thereby supporting proactive management of urban greenery. In a broader sense, the proposed approach reflects how low-cost IoT technologies can strengthen municipal resilience and align with Malaysia's vision for sustainable and data-informed city planning. Overall, this work contributes to the growing field of intelligent environmental monitoring by bridging technology and sustainability for safer, smarter urban ecosystems.

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