Measuring Kinetic Energy from Tree Movements Induced by Wind

Tomáš Bača, Ján Šumský, Michal Kubaščík, Peter Šarafín

Abstract—The movement of trees as a response to wind presents an underexploited renewable energy source. Wind as a renewable energy source is highly unpredictable. This research focuses on creating wireless sensors and data acquisition systems that are used to measure the dynamical properties of tree movements, such as amplitude and frequency. The sensors are based on the use of the IMU – Inertial Measurement Unit sensor and utilizes the newest MCUs from Espressif.

Keywords—Kinetic energy, Accelerometer, Gyroscope, Microcontroller, Bluetooth, WSN

I. INTRODUCTION

The quest for renewable energy sources is a global challenge. Traditional energy sources, such as fossil fuels, contribute significantly to environmental degradation and climate change. Renewable energy sources, while promising, often face challenges related to consistency and environmental impact. Wind energy, in particular, is abundant but highly unpredictable. This research addresses the potential of harnessing energy from the natural movements of trees, such as tree sway and leaf vibration, induced by wind. By developing wireless sensors and data acquisition systems to measure these movements.

A. Trees as a source of energy

The importance of finding sustainable energy sources cannot be overstated, given the environmental impact of conventional energy sources.

Energy harvesting from tree movements offers a unique opportunity to generate power in an eco-friendly manner.

By leveraging the natural sway and vibration of trees, we can develop a reliable energy source that mitigates the need for batteries in forest environments. Traditional batteries pose a risk of leaking chemicals, which can be detrimental to the ecosystem.

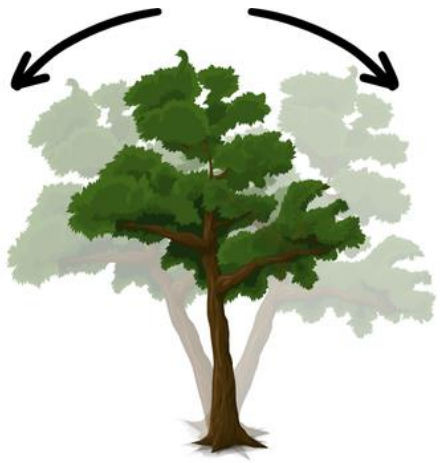

Figure 1-Tree sway

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B. Defining the sway

Tree sway refers to the back-and-forth movement of trees caused by wind. This natural phenomenon occurs when wind forces act on the tree, causing the trunk to sway and the branches to oscillate. The dynamics of tree sway depend on several factors, including tree height, trunk flexibility, branch structure, and wind speed. Understanding tree sway is crucial for developing systems that can harness this kinetic energy effectively. Measuring the amplitude and frequency of tree sway provides insights into the energy potential of this natural movement. [1][2]

C. Defining oscillation

Oscillation refers to the repetitive back-and-forth movement around a central point or equilibrium position. In the context of tree sway, oscillation describes the periodic motion of tree branches and trunks as they respond to wind forces. This movement can be characterized by two main properties: amplitude and frequency.

Amplitude: This is the maximum extent of the oscillation, measured from the equilibrium position to the peak of the movement. For trees, the amplitude of sway indicates how far the tree moves from its resting position when subjected to wind.

Frequency: This is the number of oscillations that occur in a given time period, typically measured in cycles per second (Hertz). In trees, the frequency of sway is influenced by factors such as the tree's height, mass distribution, and flexibility.

Understanding oscillation is critical for modeling the dynamic behavior of trees under wind load and for assessing the potential of harvesting kinetic energy from tree movements. By analyzing the amplitude and frequency of oscillation, we can gain insights into the energy transfer processes and the mechanical properties of trees, which are essential for designing efficient energy harvesting systems. [3]

D. Measuring tree movements

We begin by collecting data on the tree's movements. This involves deploying a series of wireless sensors that capture the dynamical properties of tree sway, such as amplitude and frequency. These sensors, including accelerometers and gyroscopes, are strategically placed at different heights and positions on the tree to ensure comprehensive data collection. The accelerometers measure the linear acceleration in three-dimensional space, providing insights into both horizontal and vertical movements, while the gyroscopes measure the rotational motion.

The data is then transmitted for analysis and modeling.

II. Ways to Measure Tree Movements

There are several ways to measure the movements of trees, some well-known and others less so. Let’s explore some of these methods.

A. IMUs

Inertial Measurement Units (IMUs) combine multiple sensors, including gyroscopes and accelerometers, to provide comprehensive data on tree sway and vibration. Tilt sensors, also known as inclinometers, can measure the angle of tilt or inclination of the tree trunk from a vertical position. The gyroscope within the IMU can measure tilt and rotational motion, while the accelerometer measures linear acceleration, capturing the dynamic properties of tree movements.

B. Accelerometers

Accelerometers measure the acceleration of the tree trunk in different directions. By setting up an accelerometer directly on the tree, the device can directly measure the trunk's sway. This data is crucial for analyzing how different parts of the tree move in response to wind forces, capturing both horizontal and vertical movements. [4][5]

C. Strain Gauges

Strain gauges measure the deformation, or strain, of the tree, allowing monitoring of how the tree's shape changes in response to wind and other forces. This method is useful for understanding the stress distribution within the tree structure.

D. Magnetic Sensors

Magnetic sensors can measure the displacement of tree branches by capturing small movements over a limited distance. However, installation can be challenging due to the need for precise alignment and calibration.

E. Optical Measurement Techniques

Lasers and other optical measurement techniques can be used to measure tree movements by detecting changes in distance or position with high precision. These methods are typically more expensive but offer high accuracy.

Each measurement method offers unique benefits and challenges, and the choice of sensor depends on the specific requirements of the study, including the type of data needed, the environment, and the available budget.

F. Working with IMUs

To effectively measure the movement of trees, we employ IMUs, which integrate accelerometers and gyroscopes. IMUs provide a detailed analysis of both linear acceleration and rotational motion.

1)Accelerometers

Accelerometers measure the acceleration of an object in one or more axes. When attached to a tree, they can detect changes in velocity as the tree moves back and forth due to wind forces. Inside an accelerometer, a small mass is suspended by springs. When the device accelerates, the mass shifts, causing a change in the electrical signal proportional to the acceleration. This signal helps determine the direction and magnitude of the tree's movement.

2)Gyroscopes

Gyroscopes measure the rate of rotation around the axes, capturing the tilt and rotational motion of the tree trunk and branches. This is essential for understanding the twisting and turning movements that occur in response to wind.

G. Types of Data Harvested

Accelerometers provide several types of data essential for analyzing tree movements:

1)Linear Acceleration

This measures the rate of change of velocity in three-dimensional space (X, Y, and Z axes). For trees, this data helps in understanding how different parts of the tree move in response to wind forces, capturing both horizontal and vertical movements.

2)Amplitude of movement

By integrating the acceleration data over time, we can determine the displacement of the tree. The amplitude gives us the maximum extent of the tree's sway, which is crucial for estimating the energy that can be harvested.

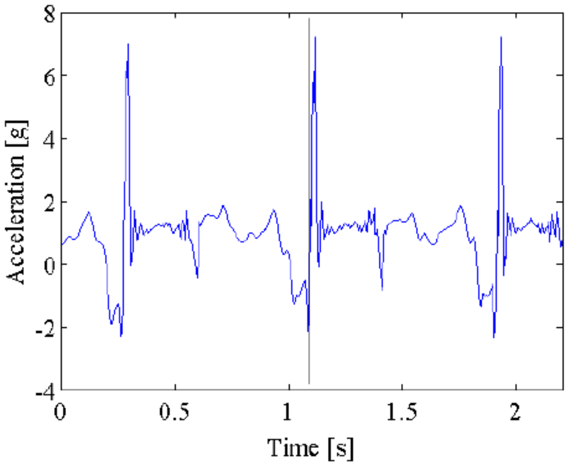

Figure 2- Accelerometer data example [6]

H. Frequency of sway

The accelerometer data can be analyzed using Fourier transforms to determine the dominant frequencies of the tree's movement. This information helps in identifying the natural oscillation patterns of the tree, which can be correlated with wind speed and direction.

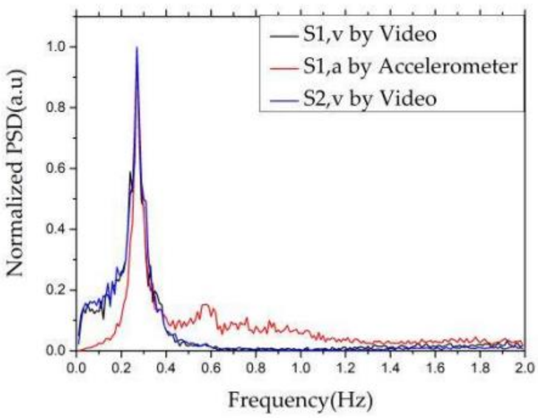

Figure 3- Frequency Spectrum example [7]

I. Vibration analysis

Accelerometers are sensitive enough to detect minute vibrations. This capability allows us to study not only the large-scale movements but also the small vibrations that can provide insights into the structural health of the tree and its response to varying wind conditions.

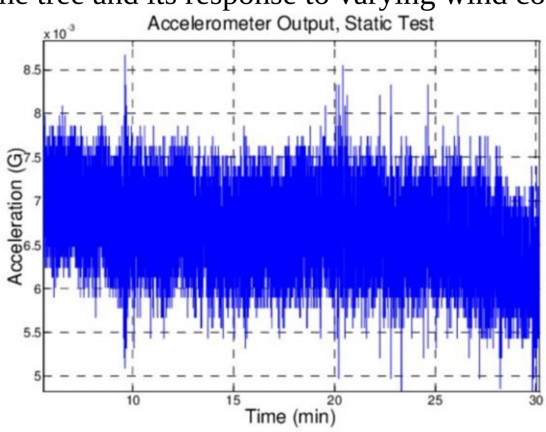

Figure 4- Vibration graph [8]

We are planning to also use an anemometer in order to know the wind speed. This will allow us to correlate the wind speed with the measured sway of the trees. By comparing this data with the accelerometer readings, we can establish a detailed understanding of how different wind speeds and gusts influence tree movements. Understanding the relationship between wind speed and tree sway will also help in optimizing the placement of sensors and enhancing the overall efficiency of the energy harvesting system.

III. METHODOLOGY

This section details the methodology used to measure the dynamic properties of tree movements. We utilize a Wireless Sensor Network (WSN) consisting of sensors, microcontrollers, and data storage systems, each playing a specific role in capturing and processing the data. The components involved include Measurement Nodes (M-Nodes), Anemometer Nodes (A-Nodes), Sleepers, Communication Nodes (COM-Nodes), Wi-Fi Nodes (WIFI-Nodes), and a Communication Module (COM-MODULE). [9]-[12]

A. Types of Sensors

We use a variety of sensors to capture the necessary data:

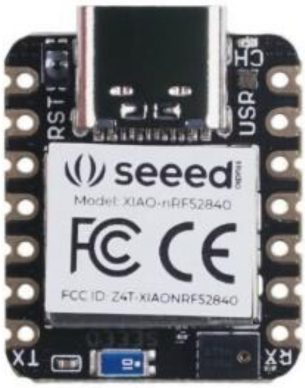

Figure 5- Xiao seeed nRF52840 [13]

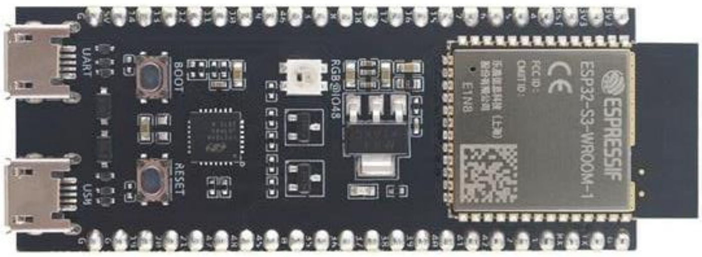

Figure 6- ESP32-S3 [14]

1)M-Nodes

These are nRF sensors equipped with accelerometers. We use four such sensors, each attached to different parts of the tree to measure various aspects of its movement. The nRF sensors transmit their data wirelessly to the COM-node. The accelerometers measure linear acceleration in three axes, providing comprehensive data on the tree's sway and vibration.

2)A-Nodes

An anemometer is used to measure wind speed, providing essential data for understanding the external forces acting on the tree. The anemometer sends this data to the COM-node as well.

Figure 7- Anemometer with a fin [15]

3)Sleepers

These are nRF modules placed on the branch stump, equipped with batteries. They enter a sleep mode to conserve energy and periodically wake to measure the voltage and transmit this data. This helps in monitoring the power supply and ensuring the longevity of the system.

4)COM-Nodes

The ESP32-S3 microcontroller serves as the Communication Node, receiving data from the nRF sensors via Bluetooth Low Energy (BT LE). The COM-Node processes the data before sending it to the Wi-Fi Node.

5)WIFI-Nodes

The other ESP32-S3 microcontroller acts as the Wi-Fi Node, responsible for storing the processed data on an SD card. This ensures that we have a robust and reliable record of the tree's movements and the corresponding wind conditions.

6)COM-Module

The COM-Module refers to both ESP32-S3 microcontrollers working together to collect, process, and store the data from the sensors.

B. Sensor Placement

The placement of sensors is crucial for accurately capturing the dynamic properties of tree movements. By strategically positioning sensors, we can ensure that the data collected is both accurate and representative of the tree's natural movements.

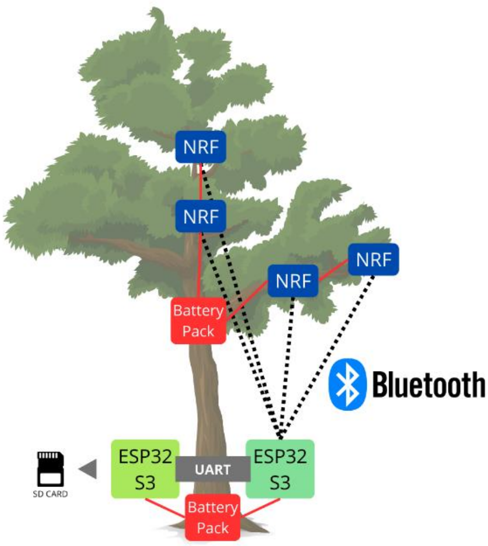

Figure 8- Sensor placement

1)M-Node Placement

M-Nodes are placed at various heights and locations on the tree to capture comprehensive movement data. By positioning these sensors on the trunk and major branches, we can measure the tree's sway and vibration across different parts of the tree. This helps in understanding the distribution of movement and the impact of wind forces.

2)A-Node Placement

The A-Node, or anemometer, is positioned in an open area near the tree to measure wind speed without obstruction. Accurate wind speed data is essential for correlating tree movements with external wind forces.

3)Sleeper Placement

Sleepers are placed on the branch stump to monitor the power supply. These nodes wake periodically to measure voltage and ensure that the sensors are functioning correctly and have sufficient power.

4)COM-Node and WIFI-Node Placement

The COM-Node (ESP32-S3) is positioned within the range of the nRF sensors to receive data via BT LE efficiently. The WIFI-Node (ESP32-S3) is located nearby to facilitate data storage on an SD card, ensuring minimal data loss and reliable long-term storage.

C. Data Transmission and Storage

The collected data from the M-Nodes and A-Nodes is transmitted to COM-Node (ESP32-S3) via BT LE. The COM-Node further processes the data and transmits it to the WIFI-Node (ESP32-S3), where it is stored on an SD card for offline analysis. This multi-stage data transmission process ensures data integrity and reliability.

D. Data Analysis

The data stored on the SD card is analyzed to understand the dynamic properties of tree movements. Key parameters such as linear acceleration, amplitude of movement, frequency of sway, and vibration are extracted. Fourier transforms are applied to determine the dominant frequencies of the tree's movement, providing insights into natural oscillation patterns. The relationship between wind speed and tree sway is also analyzed to optimize the placement of sensors and enhance the overall efficiency of the energy harvesting system.

E. Energy consumption

The energy consumption of the WSN could be decreased by putting the M-Nodes into deep sleep and waking them up only when the A-Nodes measure winds with speed above a certain threshold. This is known as event-driven measurement. The other way how to save energy could be the use of compressed sensing which however has its own problems. [16]-[18]

Another way to decrease the power consumption of the M-nodes is by using low power wireless communication technologies. We are currently using the Bluetooth Low Energy for communication between the M-nodes and COM-node. But other alternatives for low power wireless communication could be LPWAN, Sigfox or LoRaWan. [19][20]

IV. Possibilities and Recommendations for Measurement on Real Trees

Implementing measurement systems on real trees involves several considerations and recommendations to ensure accurate and reliable data collection. [21]

Sensor placement: It is crucial to strategically place the sensors at various heights and positions on the tree to capture a comprehensive range of movement. Sensors should be secured firmly to prevent detachment due to high winds or other environmental factors.

Power supply: Powering the sensors in a forest environment can be challenging. Options include energy harvesting from tree movements themselves, or long-lasting batteries. Each method has its own set of advantages and limitations that need to be evaluated based on the specific site conditions. The usage of sleep function on the nRF can greatly improve the span of life of the battery, which means that it does not require as much energy as a full-time working device. [22]

Environmental protection: The sensors and associated electronics must be protected from harsh weather conditions, including rain, snow, and extreme temperatures. Waterproof enclosures and robust materials are essential for the longevity and reliability of the measurement system.

Calibration and validation: Regular calibration of sensors is necessary to ensure data accuracy. Additionally, it is recommended to validate the sensor data with other measurement methods or reference devices to confirm the reliability of the readings.

V. Future research direction

The preliminary phase of next step involves selecting the appropriate tree for sensor placement and deciding the mode of data communication. Initial experiments will focus on choosing an optimal tree based on factors such as size, location, and accessibility. Data collected from the sensors can be stored either on an SD card for offline analysis or transmitted via Wi-Fi for real-time monitoring.

Early analyses of the collected data will help in understanding the dynamics of tree sway and the effectiveness of different sensors in capturing this movement. The insights gained from these initial results will guide further refinement of the sensor setup and data collection methods.

Future research will extend beyond the deployment of sensors to include the development of energy harvesting systems that can capture and store the energy generated from tree sway. While this paper focuses on the implementation and analysis of tree sway sensors, subsequent studies will explore the integration of energy harvesting technologies to convert the mechanical energy of tree movements into usable electrical energy. This comprehensive approach aims to establish a sustainable method for harnessing renewable energy from natural sources like tree sway.

VI. CONCLUSION

In conclusion, the movement of trees in response to wind represents a new and underexploited source of renewable energy. This research demonstrates the feasibility of using wireless sensors and data acquisition systems to measure and analyze the dynamic properties of tree movements. By employing forecasting algorithms, we can predict the availability of this energy source based on weather conditions. The successful implementation of this system in real-world conditions requires careful consideration of sensor placement, power supply, data transmission, environmental protection, and regular calibration.

Future work will focus on refining these systems and the implementation of the project through initial tests. These tests will be conducted on several trees to evaluate the performance and reliability of the sensors and data acquisition systems under different conditions. Additionally, further development of forecasting algorithms will be undertaken to improve the accuracy and predictability of energy harvesting potential.

Ultimately, the goal is to develop a robust and scalable solution that can be deployed in forests worldwide, contributing to the global effort to harness renewable energy sources and promote sustainable development.

The energy storage subsystem in this solution will use supercapacitors and maximum power point tracking (MPPT) algorithms to achieve small energy losses during energy storage and a sufficient amount of recharge cycles of the energy storage subsystem.[23]

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