IoTree: A Battery-free Wearable System with Biocompatible Sensors for Continuous Tree Health Monitoring

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ABSTRACT

We present a low-maintenance, wind-powered, battery-free, biocompatible, tree wearable, and intelligent sensing system, namely *IoTree*, to monitor water and nutrient levels inside a living tree. *IoTree* system includes tiny-size, biocompatible, and implantable sensors that continuously measure the impedance variations inside the living tree's xylem. The collected data are then compressed and transmitted to a base station located at up to 1.1 miles away. The entire *IoTree* system is powered by wind energy and controlled by an adaptive computing technique called block-based intermittent computing, ensuring the forward progress and data consistency under intermittent power and allowing the firmware to execute with the most optimal memory and energy usage. *IoTree* opportunistically performs sensing, data compression, and long-range communication tasks without batteries. During in-lab experiments, *IoTree* also obtains the accuracy of 91.08% and 90.51% in measuring 10 levels of nutrients, NH_3 and K_2O, respectively. While tested with Burkwood Viburnum and White Bird trees in the indoor environment, *IoTree* data strongly correlated with multiple watering and fertilizing events. We also deployed *IoTree* on a grapevine farm for 30 days, and the system is able to provide sufficient measurements every day.

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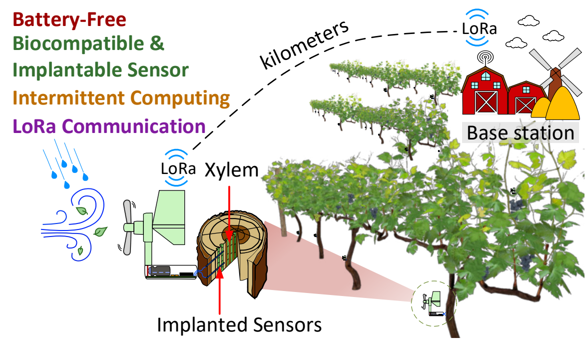

Figure 1: ***IoTree*'s Concept [7].**

1 INTRODUCTION

Global agriculture will need to produce more food in the next 50 years than in the previous ten thousand years to feed the growing population [1]. However, growing just a few varieties of trees makes our food supply vulnerable to pests and diseases, leading to the overuse of fertilizers. Such chemicals make our farmland less productive and the food we grow less nutritious [2]. In the U.S., more than 1,700 trillion BTU of energy was for agriculture annually [3], nearly 30% of this was for fertilizer production, yet the nitrogen fertilizer efficiency is 33% globally [4]. Understanding how crops grow will help reduce the use of fertilizers, chemicals, and precious resources like water and design novel and sophisticated growing techniques like intercropping [5] and cover cropping [6] to restore soil fertility and increase crop productivity.

In this project, we develop wind-powered, low maintenance, battery-free, biocompatible, implantable, tree wearable, and intelligent sensing system, namely *IoTree*, that continuously captures signals inside a living tree to infer the tree's water and nutrient levels (Fig. 1). *IoTree* system measures impedance variations inside the tree's xylem before compressing the collected data and transmitting to a base station. The entire *IoTree* system is powered by wind and controlled by an adaptive block-based intermittent computing algorithm. Such a battery-free sensing system for trees will provide an opportunity for ultra-long multi-day missions, low maintenance, and a lower ecological impact since battery-powered devices are unsuitable for a dense and long-term deployment.

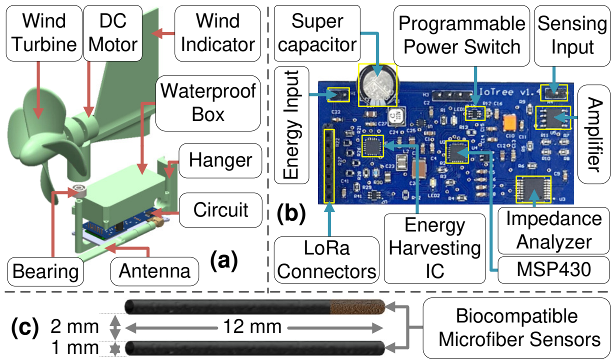

Figure 2: (a) *IoTree*'s model, (b) circuit, and (c) sensors.

We made the following contributions: (1) manufacturing biocompatible sensors to capture signals inside the tree's xylem, (2) deriving a low-power sensing algorithm to provide reliable measurements, (3) implementing a block-based intermittent computing technique to intrinsically re-configure the program into blocks with the most optimal energy and memory usage, (4) developing a large-scale extendable and battery-free system that works reliably under various weather conditions, and (5) achieving accuracies of 91.08% and 90.51%, respectively, in measuring 10 levels of NH_3 and K_2O.

2 *IOTREE* SYSTEM OVERVIEW

We design and implement *IoTree* with the main components, including (1) biocompatible sensors, (2) energy harvesting & power management, (3) long-range communication, and (4) block-based intermittent computing, as depicted in Fig. 2, to tackle the following goals. First, the sensors should be implantable into the tree's tissue and capture the signals inside the tree's xylem. Second, *IoTree* must require the least maintenance since frequent charging or replacing batteries on a large scale is not practical in agriculture settings. Thus, the system has to harvest and optimally use the collected wind energy by intrinsically re-configuring the program into blocks. Last but not least, *IoTree* must be able to transmit data at a long distance, particularly at a distance of typical farm sizes.

Biocompatible Sensors. We develop impedance-based sensors that consist of two biocompatible fiber electrodes. The sensing circuit generates sweeping frequency signals and measures the responses. Multiple pairs of sweeping frequencies and the value calculated from DFT are used to establish impedance profiles to infer water and nutrient levels.

Energy Harvesting & Power Management. *IoTree* system operates fully based on energy harvested from the wind. We design a lightweight wind energy harvester, including a custom-built wind indicator to maximize the harvested power.

Long-range Communication. Since *IoTree* will be deployed on-farm settings, it needs to reliably transmit data on the farm to the base station. We adopt LoRa communication due to its reliability, low noise, and low-power communication with a distance of up to 1.1 miles (approximately 1.8 kilometers).

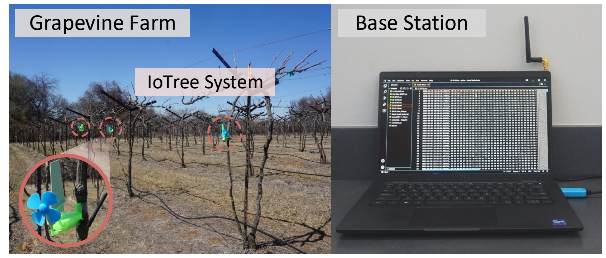

Figure 3: Deployment of *IoTree* on the grapevine farm.

Block-based Intermittent Computing. We propose a block-based intermittent computing approach that is able to intrinsically change the number of blocks and the size of each block to minimize the memory overhead and wasted energy compared to state-of-the-art intermittent computing solutions (i.e., task-based and checkpoint-based approaches). After rebooting, *IoTree* can recover from the last executed block in the task instead of restarting from the beginning of that task.

3 *IOTREE* DEMONSTRATION

Deployment Results: We deploy *IoTree* systems by attaching three prototypes to three grapevine trees, while a laptop interfacing with the LoRa receiver is located at a distance of 0.5 miles (approximately 0.8 kilometers) away from the farm, as shown in Fig. 3. The number of data transmissions varies each day depending on the weather condition ranging from 21 to 1787, which is sufficient for agriculture applications.

Setup & Demonstration: This demo aims to show the feasibility and reliability of *IoTree* to be a continuous tree health monitoring platform. The demo setup will be a more miniature version of the deployment setup, with two *IoTree* prototypes attached to two small trees and one laptop. The biocompatible sensors implanted inside the tree's xylem are connected to a battery-free, wind-powered, intermittent computing sensing system for continuous and real-time data collection. To demonstrate the system's feasibility, the author will simultaneously power *IoTree* prototypes to perform their tasks (i.e., sensing, computing, and communication) using wind from an electric fan. The received data from both devices with corresponding IDs will be visualized in real-time on the laptop (i.e., base station). We will also demonstrate the system's reliability at different distances, wind speeds, and wind directions. Besides that, we will apply multiple soil stimuli, and the observed signal variations will be presented and discussed.

4 ACKNOWLEDGMENTS

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