Jackson Liller *Wireless and Sensor Systems Laboratory, University of Texas at Arlington, USA*
Trung Tran *Sungkyunkwan University, South Korea*
Phuc "VP" Nguyen *Wireless and Sensor Systems Laboratory, University of Texas at Arlington, USA*

Editor: Nirupam Roy

TOWARDS THE INTERNET OF LIVING TREES FOR PRECISION AGRICULTURE

Photo, istockphoto.com

I*oTree* is a low-cost, low-maintenance, long-lived wearable sensing solution for monitoring the health of trees, providing fully autonomous renewable-energy collection and parameter sensing, compression, and transmission from over a mile away. The IoTree system is battery-free and operates on an opportunistic, block-based intermittent-computing paradigm; when the system is able to harvest enough energy via renewable sources, the LoRa controller will produce samples from the nutrient sensor and transmit the data to a base station for further analysis. Initial laboratory trials for IoTree demonstrate 91.08% and 90.51% accuracy in detecting ammonia and potassium oxide levels, respectively. Furthermore, a 30-day farm trial showed that the IoTree system could capture measurements regularly in a grapevine farm deployment. IoTree is designed with open-source software, 3D models, and affordable off-the-shelf components, ensuring availability as a tool to educational institutes and hobbyists alike.

[MAKERS]

Global agriculture will need to produce more food in the next 50 years than was produced in the previous 10,000 years to feed the growing population [1]. In modern agriculture, a few staple crops are cultivated intensively for their higher yields [2]. Growing a few varieties of trees makes the food supply vulnerable to pests and diseases, leading to the overuse of fertilizers. Such chemicals make the farmland less productive, and the food we grow less nutritious [3-5]. Understanding how crops grow will help reduce the use of fertilizers, chemicals, and water, and pave the way for more sophisticated and sustainable agriculture techniques.

Existing nutrient-sensing solutions for precision agriculture rely on (1) sensors buried under the soil, (2) video processing from cameras, and (3) optical techniques to measure ions in hydroponic solution. The current sensor systems are orders-of-magnitude too costly and labor-intensive. Systems built from conventional components and materials cost over $500 per sensing node, measure >3m in height, and restrict equipment access to the crop. In addition, traditional soil sensing techniques and recent advanced soil sensing methods based on wireless signals, such as RFID, microwave, and radar only measure soil signals, not plant signals. Sensors attached directly to plants require large invasive sensing probes, resulting in wounding or other damage, e.g., xylem cavitation, which may result in plant death. The camera-based and light sensing-based methods provide a non-invasive way to infer a plant's condition based on its color and shape. Still, they cannot inform us of the internal physiological functioning of plants, e.g., vascular tissue (xylem, phloem).

To circumvent all the limitations of existing approaches, we developed a zero maintenance, battery-free, biocompatible, cost-effective, and intelligent sensing system that we named IoTree, to continuously monitor water flow and nutrient levels in the living plant. IoTree is a wind-powered, low-maintenance, battery-free, intelligent sensing system, all inside a cheap and easy-to-deploy package. The IoTree package is powered by a compact wind turbine that enables the block-based intermittent computing algorithm to capture data when the wind is blowing. Ideally, this technology would be well-suited to long-term remote deployment missions. However, there are still technical challenges to be solved, including: (1) Biosensors for agriculture are not mature as a technology. Robust and cost-effective sensor packages face real design challenges as most biosensors produced today are intended for human epidermis and not tree bark. (2) Unpredictable weather patterns can theoretically leave IoTree offline for unacceptable intervals since the system relies entirely on wind power. Adding battery-free avenues of gathering and managing scarce power to the system is an ongoing research topic.

In this project, we make the following contributions. (1) We develop a biocompatible fiber-based sensor to monitor water and nutrient levels inside the tree body. (2) We derive a battery-free and low-power sensing algorithm from measuring signals inside the tree body reliably under multiple environmental conditions. (3) We design and implement a block-based intermittent computing algorithm allowing IoTree to fully utilize the harvested energy and perform its task with the optimal memory and energy requirements. (4) We prototype IoTree that opportunistically performs sense, data compression, and long-range communication without requiring any battery and maintenance. (5) We evaluate the system with in-lab and show that IoTree obtains 91.08% and 90.51 % of accuracy in measuring ten levels of nutrients, NH_3 and K_2O, respectively. When tested with Burkwood Viburnum and White Bird trees in the indoor environment, IoTree data strongly correlates with multiple soil stimuli (watering and fertilizing) events. We also deployed IoTree in the wild for 30 days, and the results show that the system can provide sufficient measurements every day. The system reports 558 measurements daily, up to 1.8 kilometers, without requiring batteries or maintenance.

IoTree SYSTEM

Fundamental of Tree Sensing

The IoTree system relies on the chemo-electrical relationship between nitrogen (N) and potassium (K) ions within the xylem sap of trees. Though several other minerals are necessary in the metabolism reaction, only nitrogen and potassium are considered for the current scope of the system. An electrode exposed to this sap can be monitored for an inductance response due to changes in the ion chemistry present. These ions are absorbed in the roots by transceptor proteins and transported through the tree in the form of nitrate, nitrite, ammonia, and potassium ions. For healthy trees, nitrogen levels in the tissues are 3-4% by mass [6] and potassium ion concentrations of 80-100 mM inside cells [7]. It has been demonstrated that a resistance-capacitance parallel circuit can be used to correlate ionic charges and inductive responses for nitrogen and potassium ions [8-13]. This means that, theoretically, a circuit can be constructed that could sense the ionic charge in the xylem sap of a tree and correlate that sensed charge to real-time nitrogen and potassium levels. To effectively perform this sampling, a biocompatible sensor must be developed and tested.

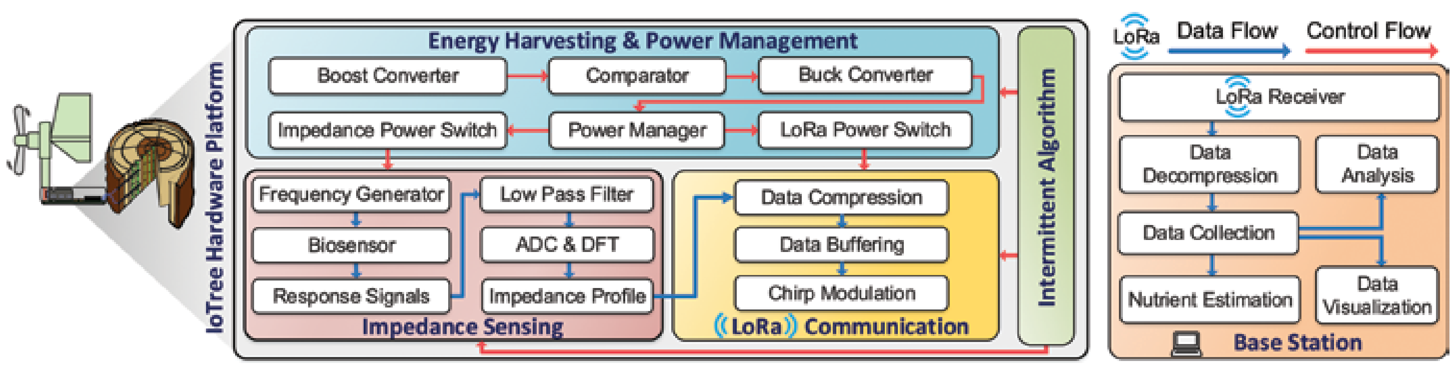

FIGURE 1. IoTree System Overview.

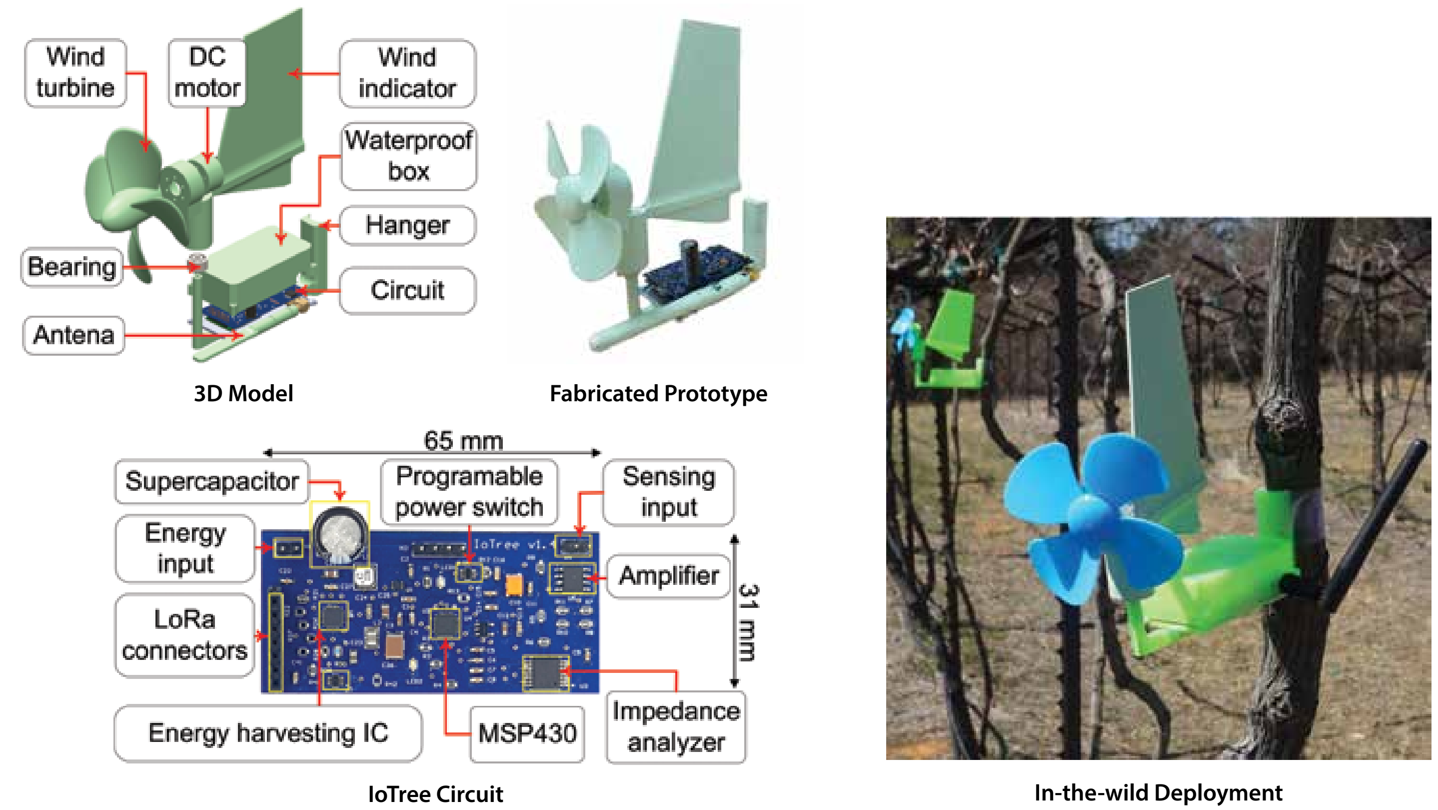

FIGURE 2. 3D model, fabricated prototype, integrated circuit, and real-world deployment of IoTree.

IoTree System Overview

IoTree system is designed and implemented with the following goals: (1) The sensors should be implanted onto the tree's tissue to capture the signals inside the tree; (2) The system must harvest wind energy for all operations to reduce maintenance operations like recharging or replacing batteries; (3) The operating system must optimize energy utilization by intrinsically reconfiguring the program into block operations; and (4) The IoTree system must be able to transmit data over long distances to allow deployment on typical farm-sized mission areas. The overview of Iotree System is shown in Figure 1.

Biocompatible sensor development. First, we will develop the details of the biocompatible sensor, followed by energy harvesting and power management, then long-range communication, and finally, block-based intermittent computing. A fiber-based impedance sensor was developed for this purpose. Conductive microfiber material is synthesized from reduced graphene oxide (rGO), polyurethane (PU), and silver nanowires (Ag-NWs) using a wet-spinning method [14,15]. These materials were dissolved or dispersed into a dimethylacetamide solution and injected into a distilled water coagulation bath through a single steel nozzle to form a microfiber gel. This gel is then reduced in ascorbic acid to produce conductive microfibers. Finally, this substance is dried in a vacuum oven for two hours at 120°C. The resulting microfibers are used directly as working electrodes. For a reference electrode, we coat final microfibers in silver chloride. These two electrodes are aligned parallel with a spacing of 2 mm to complete the impedance sensor. To ensure a functional impedance sensor, validation against a well-known sensor such as a VSP Potentiostat device can be used. When an excitation voltage is applied to one electrode of the impedance sensor, a resulting current develops on the opposite electrode.

Energy harvesting and power management. The IoTree system is powered by wind energy. A DC motor is fixed with turbine blades that capture energy from flowing air and spin the DC motor in reverse, turning it into a generator. The generated power is harvested using a custom circuit with power converters, storage capacitors, and state comparators that work together to determine when a threshold power requirement has been reached. After reaching this threshold, the computing circuit is activated, and sampling and transmission operations begin.

Long-range communication. IoTree supports long-range communication to ensure the system is easy to deploy in agricultural environments. As a secondary objective, a low-power communication protocol is desirable. Several solutions were examined for compatibility with these goals. Although low-power long-range solutions like LoRa Backscatter and modified-Bluetooth exist, the integration of these solutions into custom hardware projects simply was not mature during the first-generation prototyping phase; therefore, the mature LoRa module was chosen as the main communication method for IoTree due to its low power consumption and ideally 3-kilometer communication range.

Block-based intermittent computing. Intermittent computing is an area of computing science dedicated to accomplishing forward progress computation when energy is not reliably available. In normal computation, a program can make forward progress without needing to store information about the state of the program since it can be assumed that the program will complete before power to the computer runs out; however, during intermittent computing the power is assumed to run out before computations are complete. This means that the state of the program at any point must be stored in non-volatile memory such that it can be reconstructed after any power cycle event occurs. IoTree tackles this problem using two algorithms. These algorithms work by managing sections of code called "blocks," which are considered as atomic operations for the management of energy. Each block must be completed for the program to reach a state that can be restored after a power cycling event; if a block fails to complete before a power cycle event occurs, the work performed inside of that block is lost and the program reverts to the state in which the previous block was completed. The first algorithm in IoTree attempts to optimize the size of the blocks (i.e., the size of the task contained within a block) while the second algorithm handles the overhead of maintaining the state of the program between executed blocks. These algorithms and their corresponding API code are packed in a Block-based Library Implementation, allowing users to streamline the creation of tasks and scheduling of their execution. This approach allows a simple implementation of the functionality of IoTree: schedule the sensing, schedule the computation, and schedule the transmission of data. The block-based library will automatically handle the partitioning of these tasks into atomic blocks, manage the overhead of storing state data between blocks, and complete the execution of the tasks block-by-block so long as the power is available; and, if the power goes out, the program will be able to pick up where it left off automatically.

DESIGNING, FABRICATING, AND IMPLEMENTING IoTree PROTOTYPE

3D Modeling and Fabrication

IoTree is designed with common, off-the-shelf components and materials, making it accessible to hobbyists and researchers alike. The casing and structure of IoTree are 3D-printed. The 3D prototype is designed using SOLIDWORKS. The modeling for this structure consists of a housing for the LoRa and harvesting circuit, a hangar that helps anchor IoTree to the tree, a turbine shroud to house the DC motor/generator, and a wind vane that orients the shroud to maximize turbine efficiency. The shroud of the turbine is mounted on a vertical pole, which rests on a bearing block that can turn 180 degrees to allow the wind vane to reorient the turbine but prevent the power transmission lines from becoming tangled with repeated revolutions. The first-generation prototype's wind harvesting apparatus can generate 164.3 mW of power in this configuration. The entire system weighs 116 grams and has a footprint of 145 mm x 170 mm, making IoTree cheap and easy to manufacture and deploy.

Sensing Circuit Design and Implementation

The power harvesting circuit is an ASIC designed and fabricated in-house. The circuit uses an MSP430FR2433 as a master control unit (MCU), and a BQ25570 to harvest power from the wind turbine. The MCU communicates with the impedance analyzing circuit using the I2C on-board communication protocol and the RF components using the UART on-board communication protocol. These components are programmatically powered using integrated power switches (TPS22919DCKT IC) according to the program's needs to conserve power. This power management design decision couples with the block-based computation library to shut off power to devices that are not in use for the current block. For instance, the LoRa transmitter is not required for the sensing portion of IoTree's operation. Therefore, the LoRa transmitter is shut off using these integrated power switches while the impedance sensor is active.

Sensor Deployment

The impedance sensor must be carefully implanted into the tree to take effective readings. First, each sensor is calibrated against the VSP potentiostat. This step is necessary to calculate the calibration constant in the model since each sensor may suffer from manufacturing imperfections due to the in-house manufacturing process. After calibrating the sensor, two small holes are drilled into the tree at a depth of 3 mm. To prevent the tree from compartmentalizing the sensor (and thereby reducing the ability of the sensor to sense), 500 mg of catalase is injected into the hole. Additionally, 50 mg of conductive gel is injected to increase conductivity between the xylem sap and the impedance sensor. The electrodes of the impedance sensor are installed into the holes and shielded with adhesive tape to prevent foreign debris ingress into the sensing area.

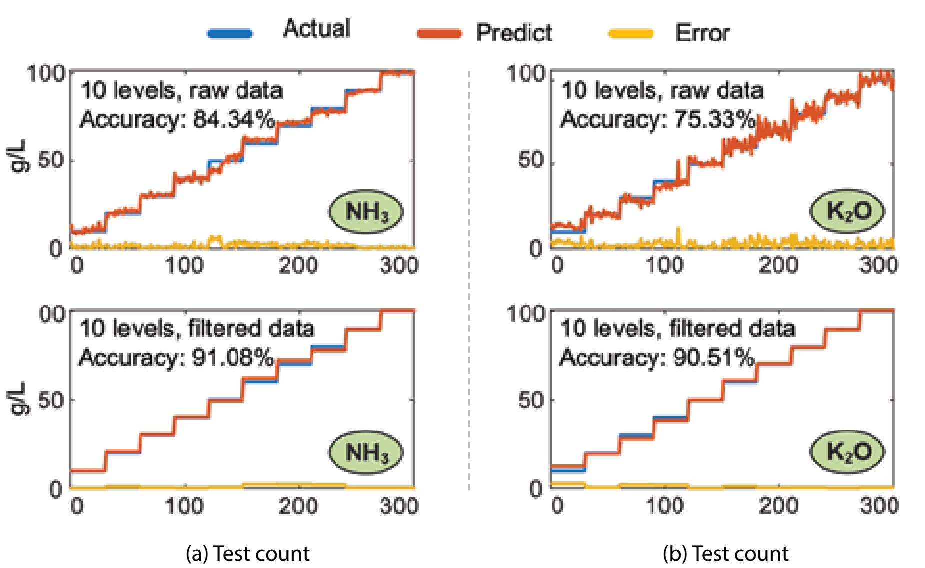

FIGURE 3. Accuracy of impedance response model at predicting nutrient levels in solution.

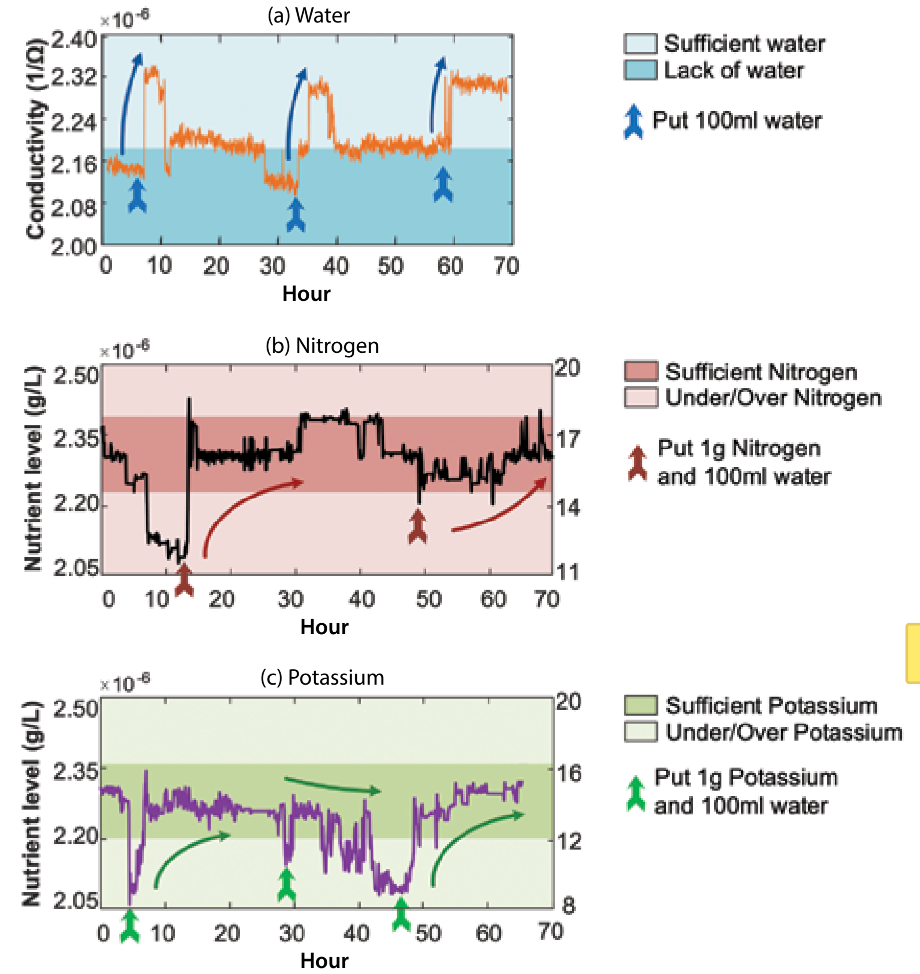

FIGURE 4. Water and nutrient sensing on living trees.

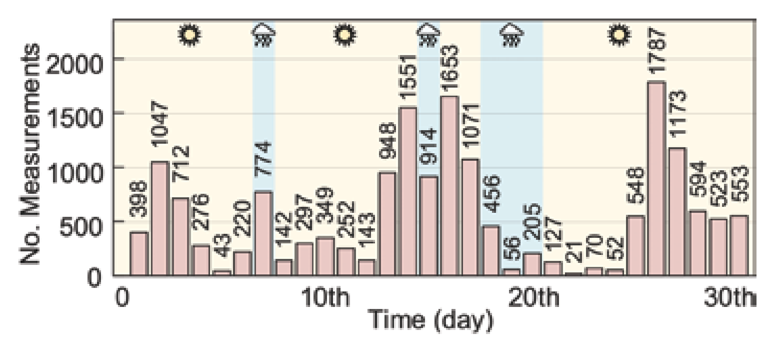

FIGURE 5. Weather conditions and sensor density during 30-day deployment of IoTree.

PERFORMANCE EVALUATION

The evaluation of IoTree took place in three stages: in-situ, in-vivo, and on-the-farm.

The in-situ experiment consisted of validating the ability of the manufactured impedance sensors to accurately sense the nutrient levels within a nutrient solution. For ammonia and potassium oxide both, solutions ranging from 10 g/L to 100 g/L were measured and recorded for the construction of a numerical model of the impedance response of the manufactured sensors. The model results are shown in Figure 4; further, the model reaches an accuracy of 91.08% for ammonia and 90.51% for potassium oxide. This proves the reliability of the sensor to measure these nutrient levels, completing the in-situ experiments.

IoTree IS DESIGNED WITH OPEN-SOURCE SOFTWARE, 3D MODELS, AND AFFORDABLE OFF-THE-SHELF COMPONENTS

For the in-vivo experiments, IoTree was deployed on Burkwood Viburnum and White Bird trees. The soil was given 100 ml of water and the impedance response of the trees was observed; a clear response to each watering event appeared in the conductivity response. After withholding fertilizer for two weeks, the soil was injected with a 10 g/L solution of ammonia. The impedance response clearly indicated the uptake of the ammonia; later, when the impedance response indicated a nitrogen deficiency another injection was given, and a corresponding impedance response showed the uptake of nitrogen. This proc[illegible]s repeated with potassium oxide with [illegible]r results. Figure 5 summarizes the results of these trials.

Finally, [illegible]-the-farm experiments took place on a l[illegible]rm. Figure 6 shows relevant data for this trial. IoTree was deployed on grapevines using three prototypes and a base station to collect the data from each node. The base station was 0.8 kilometers from the deployed prototypes, and the system was left for 30 days. The system was able to capture data each day, with an average of 558 readings per day. Further, several rainstorms occurred during the trial with no adverse effects on the prototypes. As a generalization of the data collected, it was observed that the grapevine accumulated nutrients during the day and consumed nutrients at night. This is consistent with nutrient uptake described in the literature and considered successful deployment.

CONCLUSION

This paper presents IoTree, a battery-free wearable system with biocompatible and implantable sensors for a living tree to continuously monitor. The system includes a biocompatible fiber-based sensor implanted inside the xylem of a living tree. The entire system is powered by wind energy. To cope with the unpredictability of wind energy, we implement a block-based computing method to allow the system to fully utilize the energy with minimum memory overheads. IoTree is evaluated through in-lab and real-world deployment for 30 days and the system reports 558 measurements on average a day with up to 1.8 kilometers without requiring any batteries or maintenance. ■

Jackson Liller is a PhD student in Computer Engineering at the Wireless and Sensor Systems Laboratory, University of Texas at Arlington. His research interests include cyber-physical systems, unmanned aerial vehicles, and battery-free computing.

Trung Tran is a research professor in Advanced Materials Science and Engineering at Sungkyunkwan University. His research interests include flexible-stretchable electronic devices and their application in wearable human-activity monitoring and personal.

Phuc "VP" Nguyen is an assistant professor of Computer Science and Engineering at the University of Texas at Arlington, where he directs the Wireless and Sensor Systems Laboratory. His research interests include mobile/wearable computing, wireless communication, and embedded systems.

REFERENCES

[1] "Feeding 9 billion," *National Geographic*. 2022. http://www.nationalgeographic.com/foodfeatures/feeding-9-billion/

[2] Acga Cheng, Sean Mayes, Gemedo Dalle, Sebsebe Demissew, and Festo Massawe. Diversifying crops for food and nutrition security – a case of teff. 92(1):188–198.

[3] William C. Wetzel, Heather M. Kharouba, Moria Robinson, Marcel Holyoak, and Richard Karban. Variability in plant nutrients reduces insect herbivore performance. 539(7629):425–427. 7629, Nature Publishing Group.

[4] Qingyun Zhao, Wu Xiong, Yizhang Xing, Yan Sun, Xingjun Lin, and Yunping Dong. Long-term coffee monoculture alters soil chemical properties and microbial communities. 8(1):6116. 1, Nature Publishing Group.

[5] 2019. *Sustainable Agriculture Research & Education*. "Rotations and Soil Organic Matter Levels." November 2021.

[6] The Mosaic Company. Nitrogen in Plants, September 2021. https://www. cropnutrition.com/nutrient-management/nitrogen.

[7] Fernanda Campos Mastrotti Pereira, Reuben Tayengwa, Pedro Luis Da Costa Aguiar Alves, and Wendy Ann Peer. 2019. Phosphate status affects phosphate transporter expression and glyphosate uptake and transport in grand eucalyptus (eucalyptus grandis). *Weed Science*, 67(1):29–40.

[8] C. Day, S. Søpstad, H. Ma, C. Jiang, A. Nathan, S.R. Elliott, F. E. Karet Frankl, and T. Hutter. November 2018. Impedance-based sensor for potassium ions. *Analytica Chimica Acta*, 1034:39–45.

[9] Seyed Alireza Ghaffari, William-O Caron, Mathilde Loubier, Charles-O Normandeau, Jeff Viens, Mohammed S. Lamhamedi, Benoit Gosselin, and Younes Messaddeq. 2015. Electrochemical impedance sensors for monitoring trace amounts of no3 in selected growing media. *Sensors*, 15(7):17715–17727.

[10] Rafael F. Muñoz-Huerta, Antonio de J. Ortiz-Melendez, Ramon G. Guevara Gonzalez, Irineo Torres-Pacheco, Gilberto Herrera-Ruiz, Luis M. Contrera Medina, Juan Prado-Olivarez, and Rosalia V. Ocampo-Velazquez. 2014. An analysis of electrical impedance measurements applied for plant n status estimation in lettuce (lactuca sativa). *Sensors*, 14(7):11492–11503.

[11] Li Wang, Jishi Zhao, Xiangming He, Jian Gao, Jianjun Li, Chunrong Wan, and Changyin Jiang. 2012. Electrochemical impedance spectroscopy (eis) study of lini1/3co1/3mn1/3o2 for li-ion batteries. *Int. J. Electrochem. Sci*, 7(1):345–353.

[12] Javed Ahmad, SH Bukhari, M Qadeer Awan, M Ehsan Mazhar, and AR Makhdoom. 2018. Dielectric and impedance spectroscopy of k+-doped mgal2o4 nanoparticles. *International Journal of Modern Physics B*, 32(15):1850189.

[13] Li Meiqing, Li Jinyang, Mao Hanping, and Wu Yanyou. 2016. Diagnosis and detection of phosphorus nutrition level for solanum lycopersicum based on electrical impedance spectroscopy. *Biosystems Engineering*.

[14] Van Long Huynh, Tran Quang Trung, Montri Meeseepong, Han-Byeol Lee, Trong Danh Nguyen, and Nae-Eung Lee. 2020. Hollow microfibers of elastomeric nanocomposites for fully stretchable and highly sensitive microfluidic immunobiosensor patch. *Advanced Functional Materials*, 30(46):2004684.

[15] Shanshan Yao, Ping Ren, Runqiao Song, Yuxuan Liu, Qijin Huang, Jingyan Dong, Brendan T. O'Connor, and Yong Zhu. 2020. Nanomaterial-enabled flexible and stretchable sensing systems: processing, integration, and applications. *Advanced Materials*, 32(15):1902343.