Real-Time Monitoring of Plant Stalk Growth Using a Flexible Printed Circuit Board Sensor

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***Abstract*—Monitoring of plant growth within agriculture is essential for ensuring the survival of crops and optimization of resources in the face of environmental and industrial challenges. Herein, we describe a low-cost and easily deployable flexible circuit board sensor for measurement of plant stalk growth, providing for remote tracking of plant development on an industrial scale. Three circuit topologies and measurement strategies - "ladder-type," "multiplex-type," and "mixed-type" - are initially assessed off-plant in a simulated growth experiment. Further development of the "multiplex-type" sensor and on-plant validation demonstrates its ability to quantify stalk growth as a proxy for plant development.**

Keywords—Plant growth, circumferential sensor, mechanical sensing, multiplexer, crop monitoring, maize, electrode array

I. INTRODUCTION

Industrial agriculture presents challenges for monitoring and quantitative assessment of crop health and growth [1]. Prior work has focused on the use of satellite-based remote sensing approaches to estimate crop development over large areas through multispectral imaging [2]. Similar optical methods have been employed to monitor individual fields using terrestrial sensors [3-5]. Recently, the growing trends of sensor fusion and development of the "Internet of Things" (IoT) has also spurred interest in developing multimodal plant monitoring systems targeting arrays of individual plants, particularly in the context of greenhouse research [6]. In this context, a limited subset of "*sentinel plants*" can be outfitted with monitors to identify plant maturity, stress, and general health, serving as an indicator for other nearby plants. Plant growth is influenced by many environmental factors, including soil humidity, ambient light conditions, and nutrient availability. Sensors and methodologies for measuring these factors have been developed previously [7, 8], however it is challenging to directly relate these environmental parameters to physical crop development. Digital 3D reconstruction of plant geometry using photogrammetric techniques has been attempted [9, 10], however this method involves large amounts of data per plant and substantial data processing. Simpler 1D measurements using light reflectance can be rapidly performed by scanning an illumination source across rows of adjacent plants [11, 12], however the presence of artifacts and measurement variations due to differing plant orientations limits the usefulness of this approach. While measurement of plant dimensions provides direct

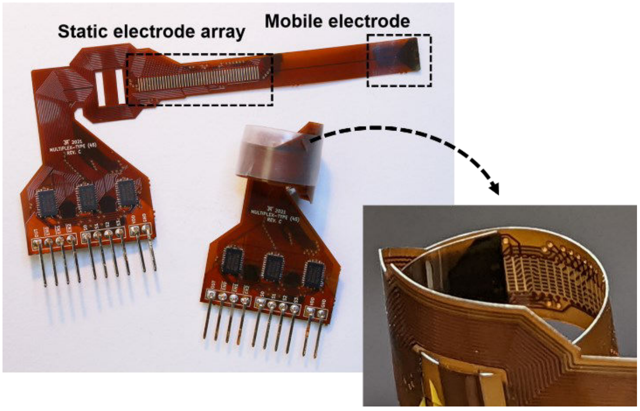

Fig. 1. "Multiplex-type" sensors in unfolded (left) and folded (right) configurations. A band of Parafilm® reinforcement, visible on the folded sensor, maintains the band shape for initial application to the maize stalk. (blowout) Luminal side of sensor shown to illustrate overlap of mobile and static electrodes which trigger signal in response to stalk growth.

quantification of plant growth, performing this measurement by hand is prohibitively labor intensive. Dendrometers can automate perimeter measurements for trees, but this equipment is large and expensive [13], rendering it unsuitable for smaller crops and broad crop-level distribution. Lightweight metal and carbon strain gauges have been demonstrated for measuring stalk elongation with up to micrometer-level resolution [14-16], though their limited elongation range limited tracking to less than 24 hours. Optoelectronic stalk perimeter sensors have allowed for dendrometer-style recording of crop species [17, 18], however the necessary transducer is still too large and heavy to permit use with crops which are smaller or earlier in development.

Using stalk perimeter changes as a proxy for growth, we demonstrate a compact, lightweight circuit capable of inexpensively monitoring maize growth in a minimally invasive manner, which can be deployed at scale to monitor growth of important crop species in real-time. **Figure 1** shows a prototype "multiplex-type" sensor band, consisting of a mobile electrode and passive electrode array connected to integrated circuit multiplexers. As shown, the transducer band is threaded through 2 eyelets in the circuit board forming a "belt" which is placed around the plant stalk.

II. MATERIALS AND METHODS

A. Sensor Topologies

Three circuit topologies were prototyped and simulated off-plant to assess measurement characteristics and viability. All three topologies involve the motion of a single "mobile"

This work was performed with the assistance of the NCSU Phytotron. This work was supported by the United States Department of Agriculture-National Institute of Food and Agriculture (1015796) and the National Science Foundation (EEC1160483) through an NSF Nanosystems Engineering Research Center (NERC) for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST).

2022 IEEE Sensors | 978-1-6654-8464-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/SENSORS52175.2022.9967167

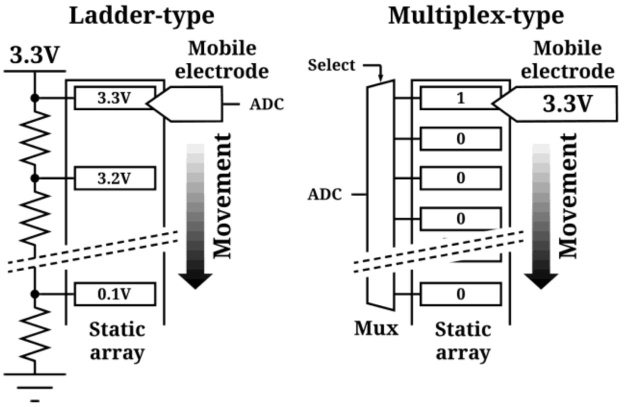

Fig. 2. Sensor topologies tested: "ladder-type" (left), and "multiplex-type" (right). "Mixed-type" topology not pictured.

electrode relative to a 45- or 51-pad static electrode array as the sensor band expands with stalk growth. Inter-electrode spacing allows for a sensor resolution of ~0.6 mm. Different transduction mechanisms were evaluated with each of the three sensor topologies. The number and spacing of electrodes incorporated into the sensor can be varied to accommodate various stalk size ranges as needed. The general measurement scheme for two of the investigated topologies is depicted in **Figure 2**. The first topology ("ladder-type") incorporates a 10 kΩ-per-step resistor ladder in which each static electrode is tied to a unique position in the ladder. When powered, each array position presents a unique potential between 3.3 V and 0 V, which is then read by an ADC via the mobile electrode to determine the mobile electrode's position.

In the second topology ("multiplex-type") the mobile electrode is driven to 3.3 V, while each static electrode in the array is connected to a unique input across three 16:1 multiplexers (74HC4067, Nexperia) present on the sensor. During a measurement, these multiplexers are toggled to successively connect each stationary electrode to the ADC input, allowing its potential to be measured. Electrode(s) in contact with the mobile electrode will be driven to 3.3 V, allowing for localization. The third circuit ("mixed-type") utilizes a hybrid approach, in which every tenth static electrode (the "ladder" electrode) is connected to a unique position on a resistor ladder, being transduced similar to the "ladder-type" circuit. Between these, intervening electrodes are connected to one of three common banks extending along the length of the array. If an intermediate analog voltage is absent during an initial sweep (indicating contact with a "ladder" electrode), an on-board 4:1 multiplexer (TMUX1204, Texas Instruments) is toggled to drive each bank of electrodes to 3.3 V in sequence, while the voltage on the mobile electrode is read-out. This topology minimizes sensor size by reducing the number of conductors required, while allowing for relative changes in position to be tracked based on movement from one electrode bank to the next, with absolute position determinable at each tenth electrode. For all three topologies, the interfaced microcontroller provides a regulated supply voltage, measurement capability using an internal analog-to-digital converter (ADC), and sensor control signals as needed.

B. Fabrication and Deployment of Sensors

Schematic capture and layout of sensors was done using an open-source electronic design automation package (KiCad). 2-layer, flexible printed circuit boards (flex-PCBs) were commercially fabricated (OSH Park "Flex" process) on a 0.1016 mm-thick polyimide substrate (Felios Polyimide, Panasonic) with an electroless nickel immersion gold surface finish. Electronic components were soldered onto the flex-PCBs using a lead-free reflow process, or manually where appropriate. A small amount of solder was manually applied to the entire surface of the mobile electrode on each sensor in order to produce an elevated conductive surface, ensuring reliable electrical contact between the mobile electrode and static electrode array. Assembled sensor bands were wrapped around the measurement target (a simulation mandrel or a live plant stalk) and tightened until a snug fit was achieved. A supporting layer of Parafilm C (Bemis), a proprietary, flexible and semi-transparent wax/polyolefin film, was wrapped around the deployed sensor avoiding premature stretching of the film. This Parafilm ring was then secured by sealing a small (~1/8") overlapping section of the ring to itself by repeatedly applying gentle pressure with a blunt tool.

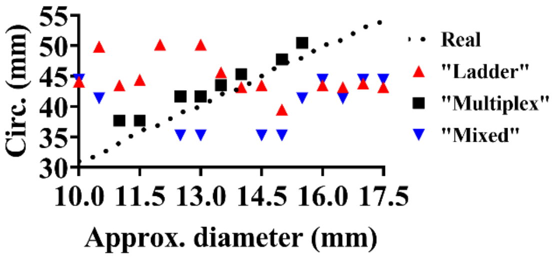

Fig. 3. Representative mandrel test results for all three topologies, reported circumference overlaid against approximate real diameter and circumference. "Multiplex-type" sensors show stronger correspondence with ground truth measurements, compared to the other topologies.

C. Off-Plant Simulation Mandrel Testing

To facilitate rapid benchtop testing of sensor outputs against known diameter targets, a tapered mandrel was fabricated using SLA 3D printing. The mandrel incorporates six flat sections, each wide enough to accommodate the entire sensor band, covering a 10 mm to 17.5 mm diameter range. The mandrel incorporates a smooth taper to allow for a gradual transition between flat sections. For each topology, the sensor was deployed on the thinnest section of the mandrel. Sensor data was collected at each flat section, as well as at two evenly spaced points along the taper between flat sections. These latter two data points were each approximated as representing 0.5 mm steps in mandrel diameter, allowing for 16 measurements to be taken along the entire mandrel.

D. On-Plant In Vivo Testing

"Multiplex-type" sensors were deployed on growing maize (Syngenta Agrisure Viptera, n = 9). Plant stalks were initially measured to be ~10-12 mm wide (approximate growth stage V2-V3). Sensor bands were wrapped around the developing stalks approximately 10 cm above soil level, and secured with Parafilm as previously described. Maize plants were watered using a nutrient solution and maintained under standard day-night growth conditions (16 h/8 h, 28 °C/22 °C, day/night) during the data acquisition. Manual perimeter measurements were acquired daily for a subset of maize plants (n = 4) from an area approximately 3 cm above the center of the applied sensor band. Sensors were removed from the stalks 12 days post-deployment, after all bands had exceeded the sensor measurement range.

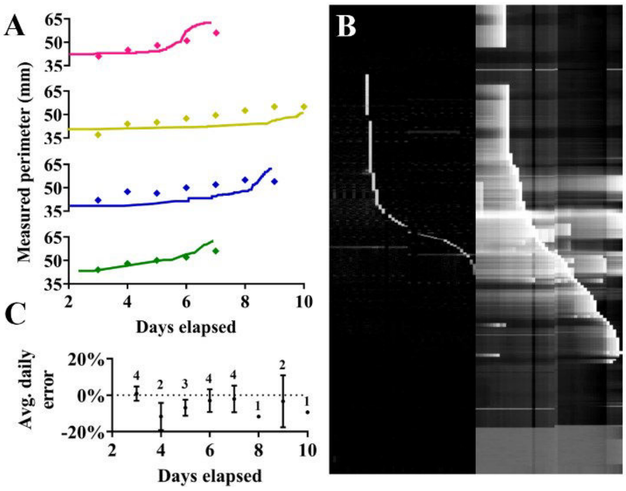

Fig. 4. A) Representative sensor data superimposed on manual perimeter measurements (diamonds) taken from the same plants. B) Example raw sensor output, plotted as measured voltage (white = 3.3 V, black = 0 V) across all array pads (x-axis: smaller perimeter left, larger perimeter right) throughout monitoring (y-axis: day 0 top, day 12 bottom); encapsulated/pulldown sensor left, unencapsulated sensor right. C) Sensor measurement error, averaged by day (n = number above each data point).

III. Results and Discussion

During mandrel testing, each of the investigated sensor types was evaluated for suitability for growth measurement (**Figure 3**). Of the three types, the "multiplex-type" sensor demonstrated the best performance, providing circumference estimates in 50% of tested positions in which a single large measured potential was present in the output data. For this topology, a small percent error was observed at each position (avg. 5.28%, SD 2.54%), and correlation with the approximated real circumference was high (R^2 = 0.989). In contrast, both the "ladder-type" and "mixed-type" sensors failed to accurately report mandrel circumference across the test range. With "ladder-type" sensors, circumference estimates were obtained at 87.5% of tested positions, however the observed correlation with mandrel diameter is poor (R^2 = -0.473, 21.76% avg. % error, SD 14.56%). Likewise, considering only intermediate potentials recorded using the "mixed-type" sensor (in which a ladder electrode is hit rather than a bank electrode), circumference estimates were obtained at 68.75% of positions tested, again with very little observed correlation with approximated real diameter (R^2 = 0.229, 19.87% avg. % error, SD 9.35%). This difference in performance is due to the quasi-digital nature of transduction using the "multiplex-type" topology. Though an ADC is used to record sensor output in all three cases, an ideal position signal "hit" in the case of the "multiplex-type" topology is equal to the ADC reference voltage, while a "miss" should report a zero. Observed on-plant data using "multiplex-type" sensors reveals that intermediate values are often observed, due to a combination of environmental noise and less-than-ideal contact between the mobile electrode and stationary electrodes. Topologies relying on intermediate potentials are less able to cope with these nonidealities because the difference between encoded values is smaller.

On-plant experimental results are shown in **Figure 4**. These sensors generated perimeter estimates over 44.19% (SD 25.83%, n = 9) of the full measurement window (timespan from the start of data collection to the point at which the maximum measurement range was reached) on average. Due to an inability to fully tighten each sensor band against the plant during deployment, early measurements tend to show a region of static growth, prior to when sufficient maize growth had occurred to fully engage the sensor band. Overall plant viability does not appear to be affected by application of the sensor bands (**Figure 5**). Superficial damage was occasionally observed at the exact site of application, usually manifesting as loss of a smaller leaf originating from the stalk near the point of application, or in the form of temporary discoloration of the plant surface underneath the sensor band. Full maize growth was achieved in all cases, relative to control plants without sensors. However, slight compression of the stalk at the site of sensor placement appears to skew measured perimeter values downward, as the section of stalk being measured by the band is slightly thinner than the remainder of the plant due the sensor's presence. Since this does not appear to be detrimental to growth, this effect may be able to be ignored and compensated for during measurement.

Fig. 5. Overall maize growth is unaffected by sensor placement (left). Sensor placed at beginning of trial (middle). Sensor at end of trial showing limited superficial damage to maize at application site (right).

An overall growth curve was derived for maize plants through interpolation of measured data. Signal interruptions and noise are presumed to be the result of ambient electrical noise, intermittent bridging of array electrodes due to electrolytes present in the nutrient solution applied to the maize, and intermittent loss of contact between the mobile electrode and array electrodes. Encapsulation of the multiplexers and interface electronics and inclusion of a pulldown resistor was observed to reduce sensor noise (see **Figure 4B**) compared to unencapsulated sensors. Due to the inclusion of automatically resettable positive temperature coefficient fuses in the sensor power supply circuit, any temporary bridging observed at the unencapsulated array electrodes merely results in intermittent loss of data rather than damage to the sensor. For these trials, sensor band geometry was tailored to allow for approximately 12 days of measurement, covering a ~27.5 mm perimeter range with ~0.6 mm resolution. This geometry and transduction circuit are easily modifiable to generate larger sensors for use with other plant types, or to increase or decrease spatial resolution.

IV. Conclusion

In this study, three types of sensors for measurement of plant stalk growth were fabricated and characterized using an off-plant approach to gauge suitability for field use. Of these, the best-performing sensor type was then tested on growing maize plants to establish biocompatibility in a relevant growth environment. Our results indicate that the "multiplex-type" sensor described herein is capable of accurately tracking changes in the perimeter of a cylindrical target object, and further that these sensors can be applied to growing maize to monitor stalk growth over the course of multiple days. Future work will focus on improving sensor linearity and expanding the available measurement window by optimizing sensor band geometry.

References

[1] A. Mehta and M. Masdekar, "Precision agriculture – a modern approach to smart farming," *International Journal of Scientific & Engineering Research,* vol. 9, no. 2, pp. 23-26, 2018.

[2] B. Wu, J. Meng, Q. Li, N. Yan, X. Du, and M. Zhang, "Remote sensing-based global crop monitoring: experiences with China's CropWatch system," *International Journal of Digital Earth,* vol. 7, no. 2, pp. 113-137, 2014/02/07 2014.

[3] D. Cui, M. Li, Y. Zhu, W. Cao, and X. Zhang, "Monitoring Crop Growth Status Based on Optical Sensor," in *Computer And Computing Technologies In Agriculture, Volume II*, Boston, MA, D. Li, Ed., 2008// 2008: Springer US, pp. 1397-1401.

[4] H. Liu, H. Sun, B. Mao, M. Li, M. Zhang, and Q. Zhang, "Development of a Crop Growth Detecting System," *IFAC-PapersOnLine,* vol. 49, no. 16, pp. 138-142, 2016/01/01/ 2016.

[5] J. Wu, "Crop Growth Monitoring System Based on Agricultural Internet of Things Technology," *Journal of Electrical and Computer Engineering,* vol. 2022, p. 8466037, 2022/05/09 2022.

[6] R. Rayhana, G. Xiao, and Z. Liu, "Internet of Things Empowered Smart Greenhouse Farming," *IEEE Journal of Radio Frequency Identification,* vol. 4, no. 3, pp. 195-211, 2020.

[7] J. Hadabas, M. Hovari, I. Vass, and A. Kertész, "IoLT Smart Pot: An IoT-Cloud Solution for Monitoring Plant Growth in Greenhouses," in *CLOSER*, 2019.

[8] B. Yimwadsana, P. Chanthapeth, C. Lertthanyaphan, and A. Pornvechamnuay, "An IoT Controlled System for Plant Growth," in *2018 Seventh ICT International Student Project Conference (ICT-ISPC)*, 11-13 July 2018 2018, pp. 1-6, doi: 10.1109/ICT-ISPC.2018.8523886.

[9] S. Gupta, A. Mudgil, and A. Soni, "Plant Growth Monitoring System," *International Journal of Engineering Research & Technology,* vol. 1, no. 4, 2012.

[10] A. Paturkar, G. Sen Gupta, and D. Bailey, "Plant trait measurement in 3D for growth monitoring," *Plant Methods,* vol. 18, no. 1, p. 59, 2022/05/03 2022.

[11] J. D. Luck, S. Pitla, and S. A. Shearer, "Sensor Ranging Technique for Determining Corn Plant Population," presented at the American Society of Agricultural and Biological Engineers Annual International Meeting, Providence, RI, 6/29/2008, 2008, 084573.

[12] J. S. Schepers, K. H. Holland, and D. D. Francis, "Automated Measurement of Maize Stalk Diameter and Plant Spacing," *Advances in Animal Biosciences,* vol. 8, no. 2, pp. 220-223, 2017.

[13] D. M. Drew and G. M. Downes, "The use of precision dendrometers in research on daily stem size and wood property variation: A review," *Dendrochronologia,* vol. 27, no. 2, pp. 159-172, 2009/01/01/ 2009.

[14] S. Khan and M. M. Hussain, "IoT enabled Plant Sensing Systems for Small and Large Scale Automated Horticultural Monitoring," in *2019 IEEE 5th World Forum on Internet of Things (WF-IoT)*, 15-18 April 2019 2019, pp. 303-308, doi: 10.1109/WF-IoT.2019.8767309.

[15] J. M. Nassar, S. M. Khan, D. R. Villalva, M. M. Nour, A. S. Almuslem, and M. M. Hussain, "Compliant plant wearables for localized microclimate and plant growth monitoring," *npj Flexible Electronics,* vol. 2, no. 1, p. 24, 2018/09/10 2018.

[16] W. Tang, T. Yan, J. Ping, J. Wu, and Y. Ying, "Rapid Fabrication of Flexible and Stretchable Strain Sensor by Chitosan-Based Water Ink for Plants Growth Monitoring," *Advanced Materials Technologies,* vol. 2, no. 7, p. 1700021, 2017/07/01 2017.

[17] W. Slamet, N. M Irham, and M. S. A. Sutan, "IoT based Growth Monitoring System of Guava (*Psidium guajava* L.) Fruits," *IOP Conference Series: Earth and Environmental Science,* vol. 147, p. 012048, 2018/05 2018.

[18] M. Thalheimer, "A new optoelectronic sensor for monitoring fruit or stem radial growth," *Computers and Electronics in Agriculture,* vol. 123, pp. 149-153, 2016/04/01/ 2016.