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A new low-cost sensing system for rapid ring estimation of woody plants to support tree management

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A B S T R A C T

Continuous monitoring of the diameter and rings of woody plants is required to evaluate agroforestry products such as timber. Manual measurement is still widely used to monitor tree growth but it is time-consuming. In addition, advanced equipment and software are available but they require technical skills and are costly for smallholders. However, we have developed a rapid and low-cost sensing system for estimating the diameters of woody plants. The apparatus includes a sensor and Internet of things (IoT) technology, which can be used under any network conditions. The apparatus was tested with various trees and the results were compared with those obtained by manual measurement. The findings using the newly developed system demonstrate a strong correlation ($R^2 = 0.99$) with the manually performed measurements. This rapid and low-cost diameter sensing system will be useful in the expansion of agroforestry sensing networks and beneficial to smallholders. Hence, the system will assist in informing foresters of potential problems in timely manner.

1. Introduction

In Indonesia, the majority of production forests are natural woodlands, which are exploited and planted with several varieties of tree species such as teak, mahogany, resin, rubber, and silk. The silk tree (*Albizia* sp.) is one of the most cultivated tree species in Indonesia and is widely grown by forestry managers in the private sector, government agencies, and smallholders. These trees are able to produce abundant timber in a short period of time [1,2]. As the demand for wood-related industries increases, foresters compete to plant as many trees as possible without considering the capacity and capability of the land for growing forests and, therefore, tree growth tends to be sub-optimal. One method of increasing the growth rates of the silk tree is to fertilize the growing plantation. However, improper application of fertilizer can increase the costs of tree maintenance.

In order to optimize fertilization and growth, forestry managers must occasionally observe the development of tree rings. Manual observations, tape-based measurements and use of the global positioning system (GPS) to locate trees are common methods for identifying tree-rings, diameters, and

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locations. However, these manual methods are inefficient due to the time-consuming nature of recording data in the field. Although several other procedures have been introduced for measuring tree-rings, these often require technical skills and equipment that are not widely available to farmers [3–9]. For example, several studies report that a remote sensing method using unmanned aerial vehicles (UAV) can be used to take censuses and estimate tree diameters, tree-rings, and tree heights in a given area [10,11]. However, the infrastructure required to conduct surveys using UAVs is expensive and requires considerable maintenance. As a result, farmers and smallholders who only have limited plantation areas will find it difficult to afford both the hardware and software required to run the systems. To accommodate the needs of farmers or smallholders for rapid and precise measuring instruments, the development of an inexpensive sensing system to measure tree diameters is required. To this end, the integration of a microcomputer, sensor, and controller may assist the development of cost-effective monitoring systems [12].

The goal of this study was to develop a new method of measuring the outer tree-rings (trunk diameter) of woody plants using the Internet of things (IoT) and incorporating an ultrasound sensor that concurrently monitors trunk diameters, records the coordinates, and notes the date of measurement. This system will provide a crucial decision-making tool, as it offers semi-automatic data collection, rapid transfer of information, and data processing of spatiotemporal information.

2. Materials and methods

2.1. Development of a low-cost tree-ring sensing system

The tree-ring sensing system comprises a holder, sensors, and some electronic components (Fig. 1). The holder is made of aluminum and can be adjusted to various sizes. An acrylic plate is placed on the end of a stick, which serves as a barrier and this is placed on the side of the trunk. Two parts of the holder are adjustable; firstly, the stick can be used to adjust the distance between the tree and the acrylic plate, and secondly the position of the sensor can be adapted to line up with the middle of the tree (Fig. 1a). The sensing system consists of an ultrasound sensor, GPS, Arduino microcontroller, real-time clock (RTC), Wi-Fi shield, secure digital (SD) card shield, and display. All components are powered by an external power bank via a universal serial bus. The Arduino controls all components and stores data on the SD card enabling transfer of collected data to an Android phone via Wi-Fi. The Bluetooth connection to an Android phone has previously been studied [13]. The price list of the components is shown in Table 1. The tree-ring sensing system costs less than US$ 25.

2.2. Data processing flow

Two frameworks for data processing are involved in the system. In the first framework (Fig. 1c), the collected data from the tree-ring sensing system is transferred via mobile tether-

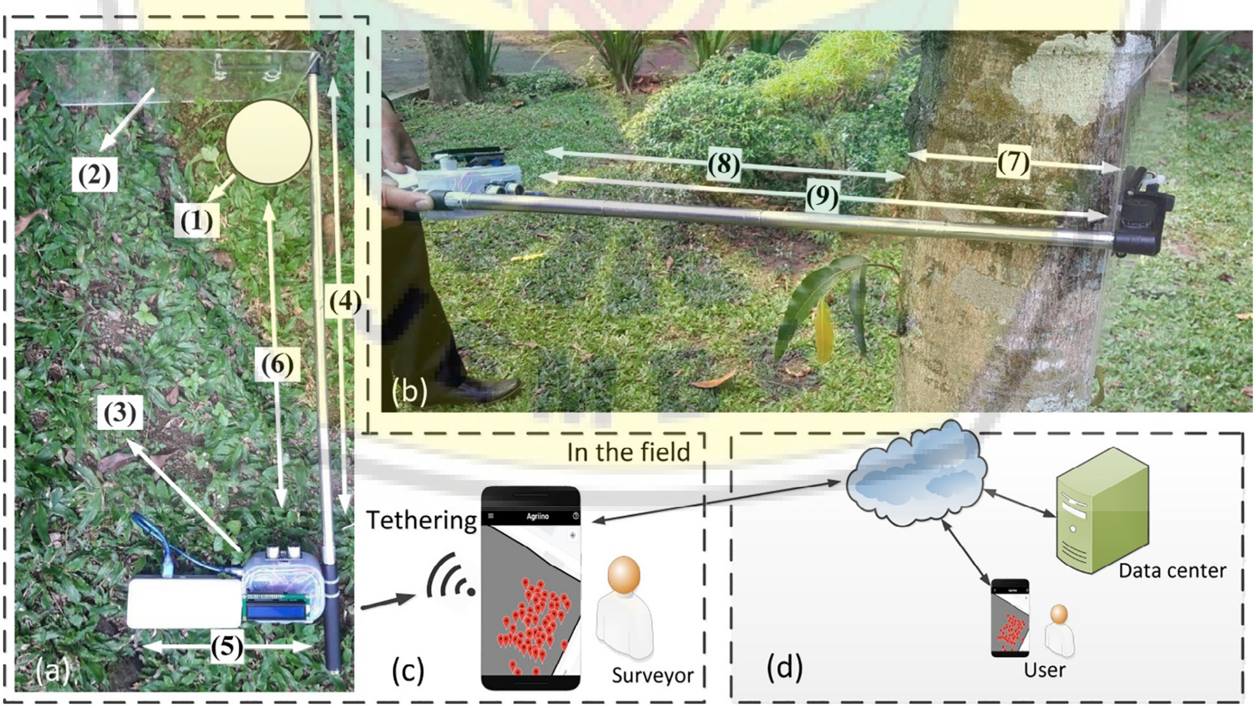

Fig. 1 – The position of the instrumentation for measuring tree rings and diameter using the newly developed tree-ring sensing system. (a) and (b): (1) Tree (located between the acrylic plate and sensor); (2) Acrylic plat; (3) Sensing system box (Arduino, GPS, Ultrasound, Wi-Fi, SD Card, and LCD); (4) Adjustable stick; (5) Adjustable sensor box; (6) Position of the sensor is adjusted to the size of the tree and then the sensor is aligned with the outer circle of the tree; (7) Diameter (D); (8) Distance between the sensor and tree (L1); (9) Distance between sensor and acrylic plate (L2). (c) and (d): Data processing and monitoring using a mobile application and Cloud.

Table 1 – Pricelist and components (as of June 2019).

No	Component	Q'ty	Price	Remark	Manufacturer
1	Arduino Uno R3 and RTC	1	5.530		Arduino, Shenzhen, Guangdong, China
2	LCD	1	2.419	16 × 2 display	
3	GPS module	1	7.603		
4	SD Card Module	1	1.037		
5	Wi-Fi Module	1	1.74	esp8266	
6	Ultrasonic sensor	1	1.382		
7	Jumper	1	1.175		
8	Project board	1	0.553		
9	Push Button	2	0.140		
10	Stick	1	1.382	Aluminum (total length: 125 cm; range between sensor and acrylic plate: 90 cm)	
10	Acrylic	1	0.691	Used for panel (20 × 30 cm)	
Total Price			23.582	US Dollars	

ing and the data is then processed and analyzed using an Android application. This method enables data to be processed without the need for an internet connection. Therefore, this framework is useful in areas with limited or absent internet availability. In the second framework (Fig. 1d), the collected data can be transferred to the Cloud to be processed and the server provides users and stakeholders access to the information. An internet connection is required at this stage so that information can be accessed in real-time.

The working principle of using the newly developed tree-ring sensing system is shown in Fig. 1b. The predicted tree rings and diameter are obtained from formulas (1) and (2).

$$\pi \times D_{(actual\ or\ predicted)} \quad (1)$$

$$D_{predicted} = L - L_1 \quad (2)$$

where π = the ration of the circumference of a circle to its diameter (~3.14); $D_{(actual\ or\ predicted)}$ = the diameter obtained by manual measurement (D_{actual}) or the predicted value ($D_{predicted}$) obtained using the newly developed sensing system; L = distance between the acrylic plate and ultrasound sensor; L_1 = distance between the ultrasound sensor and tree. The procedure for using the tree-ring sensing system follows the workflow presented in Fig. 2.

2.3. *Field testing and analysis*

The newly developed tree-ring sensing system and a manual measuring tape were used to obtain the diameter of a tree.

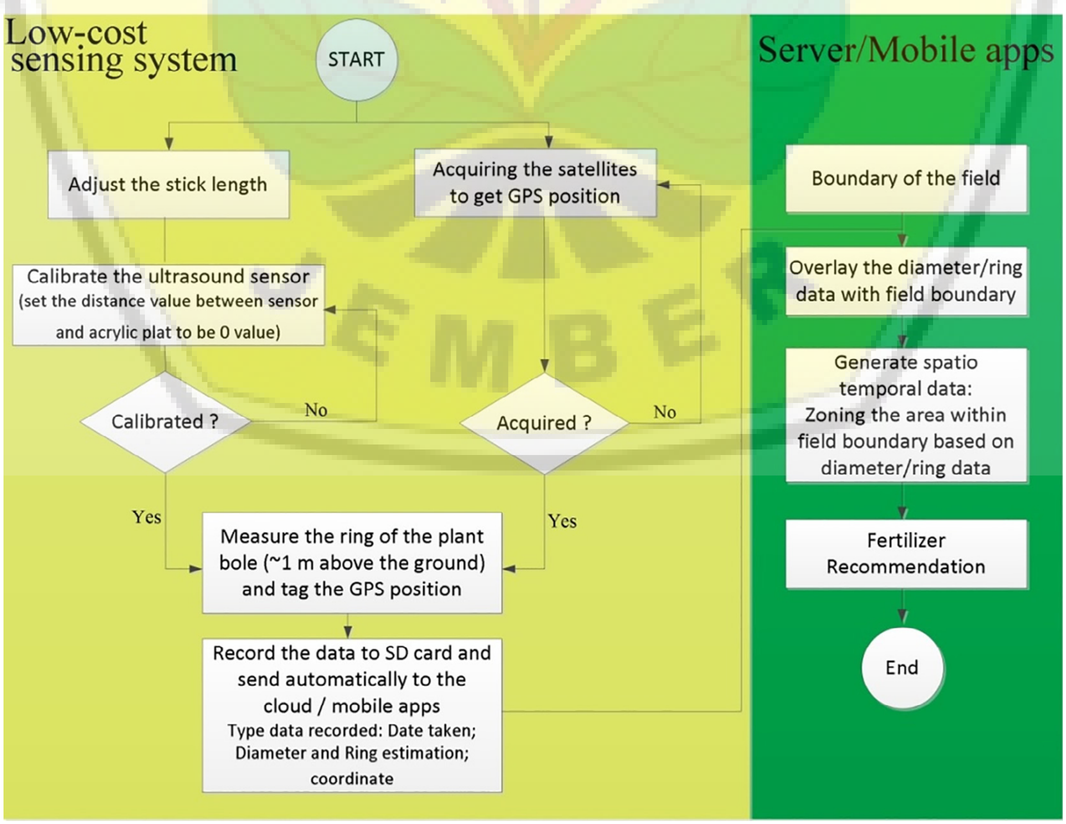

Fig. 2 – Workflow for using the tree-ring and diameter sensing system.

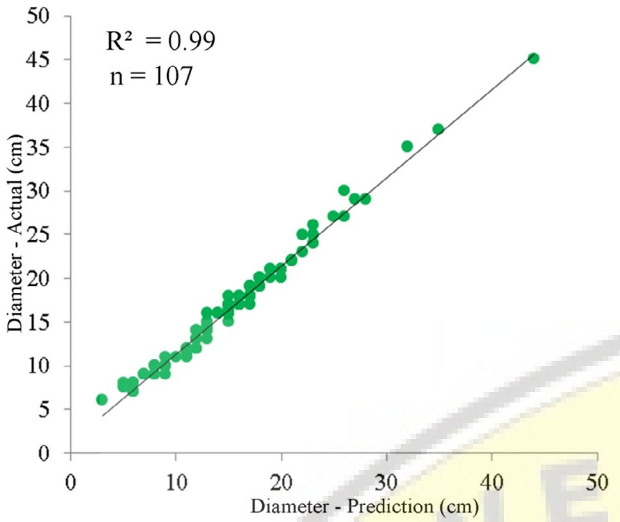

Fig. 3 – The relationship between the actual diameter as measured using a tape and the predicted diameter as measured using the ultrasound sensor.

The tree-ring sensing system was tested on several commonly planted tree species including teak (*Tectona grandis*), mahogany (*Swietenia mahagoni*), and silk (*Albizia chinensis*). The field measurement was accompanied by manual measurement using a tape and GPS. Sampling locations were in the area of Jember University (−8.1617393, 113.7093914). The diameters of the measured trees ranged from 6 to 45 cm. The measurement height from the ground was ~4.5 feet. The height was measured as described earlier [14], i.e., approximately 4.5 feet along to the center of the trunk axis at a right angle to the trunk.

The measurements obtained using these two methods were compared using two types of dataset, namely, calibration and validation datasets, respectively. To ensure the performance of the calibrated model, the model obtained from the calibration step was validated. To evaluate the performance of the tree-ring sensing system, a regression analysis was performed to evaluate the relationship between the measurements obtained from the tree-ring sensing system and the manual measurements.

3. Results and discussion

3.1. *Calibration of the newly developed tree-ring sensing system*

The diameter and tree-rings of 107 trees from three different species (teak, mahogany, and silk) were collected for the calibration dataset. The result shows a strong relationship between the predicted tree diameter obtained using the sensing system and the manually measured tree diameter with a coefficient of determination (R^2) of 0.99 (Fig. 3).

In addition, this study compared both predicted and actual diameter values with the actual tree rings. Fig. 4 shows that both the predicted and actual diameters demonstrate a strong relationship to actual tree-rings with R^2 values of 0.97 and 0.98, respectively. Based on the statistical analysis shown in Figs. 3 and 4, the R^2 provided in Fig. 4 was found to be lower because the tree rings were not all round in shape and therefore there was more of a significant difference between tree-rings measurements based on predicted and actual values (corresponding to the arrow in Fig. 4).

3.2. *Validation of the newly developed tree-rings sensing system*

The model was implemented in an Arduino microcontroller to be used for validation through field testing. To test the model obtained from the calibration, a set of 70 data points were collected from a silk tree plantation and used for validation. The range in diameters in the collected data was 6–28 cm. Fig. 5 demonstrates that the model is very accurate in predicting the tree-ring diameter with an R^2 value of 0.97.

3.3. *Performance of the whole system*

The data was transferred and processed by an android application and made available for further processes using a cloud

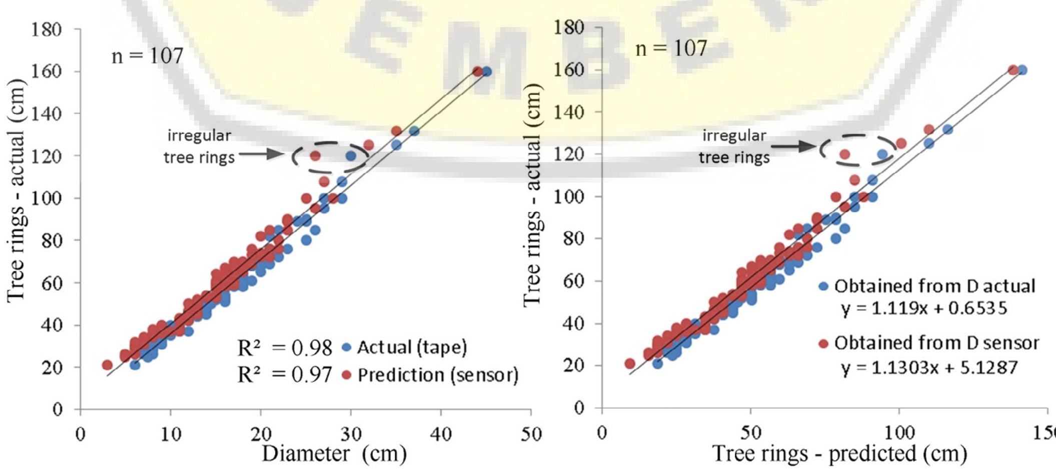

Fig. 4 – The relationship between actual tree rings and diameter (left); The relationship between actual tree rings and predicted tree rings (right). The arrow indicates the significant difference seen between the values due to the non-round shape of the tree rings.

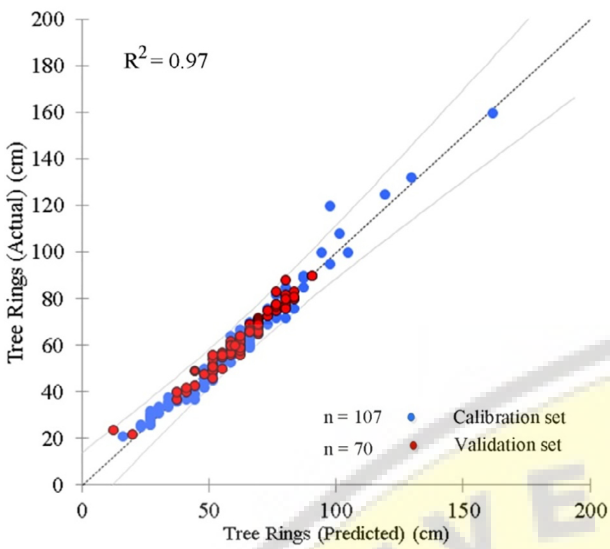

Fig. 5 – The calibration and validation results for the tree-ring prediction model.

application. Spatiotemporal data can be generated by combining the GPS coordinates of the tree location and a geotagged value of tree-rings and their diameters. The spatiotemporal data can be processed further in light of fertilizer use.

Fig. 6 shows that the geotagging data are acceptable for use in the application. However, the GPS positions are inaccurate

Fig. 6 – Measurement results showed in the android application.

as plantation spacing is 3.5 × 3.5 m. In addition, some geotagging data points were placed outside the field boundary. This will be a problem in forests with dense canopies. According to [7], the limitation of using GPS may cause duplication in plant monitoring values. For long-term monitoring and accuracy of plant positions, a QR code containing coordinate information may be attached to each tree [15].

Other systems, such as the UAV, can be used to estimate the health of a tree by monitoring its height, diameter, and carbon stock [11,16–18], but they require sufficient resources (server, post-processing software, and UAV). Based on a previous study [11], the measurement of tree diameter at breast height correlates with the size of the canopy and tree height and therefore using this new apparatus has the potential to estimate the canopy size and tree height in various tree varieties in real-time by ground-based measurements. Thus, the apparatus developed in this study can be used as an alternative to or in hybrid with an aerial system (UAV) for managing trees and forests.

4. Conclusion

The results presented in this report show that the newly developed tree-ring sensing system can potentially be used as an effective, rapid, low-cost (<USD 25) dendrometer for smallholders. The sensing system data correlated strongly with results obtained by manual measurement, as evidenced by a series of field measurement tests on both the calibration and validation datasets. Limitations included the fact that the minimum tree diameter that can be measured using the tree-ring sensing system is 6 cm. In addition, the use of embedded GPS aids to estimate the tree coordinates in a field can lead to inaccuracies. However, the use of QR technology is recommended for small-scale plantations/forest areas to enable precise monitoring over time.

Future research is encouraged to develop a system for advising on variable-rate fertilizer application in small-scale forests like silk tree plantations. Moreover, to accommodate for sloping terrain, a sensor such as the degree of freedom (DOF) sensor should to be added to the instrument. The DOF sensor is useful to check the measurement angle between the stick and the tree. The DOF value is used to calibrate the instrument for horizontal measurement. In addition, multiple ultrasound sensors may be considered useful to assess the differences between tree surfaces and sensors. Thus, the manual adjustment of the sensor position toward the outer part of the tree could be skipped. Finally, the addition of an ultrasound sensor in a nadir position to may be useful for obtaining the measurement of height or distance from the ground.

This rapid and low-cost diameter sensing system will be useful to the agroforestry industry and will benefit smallholders. The system will assist in informing agencies involved in forestry management of potential problems in timely manner.

Declaration of Competing Interest

The author declares that there is no conflict of interest.

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