Fabrication and verification of a small machined Granier sensor using precision processing technology

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Wataru Kameda[1], Fumiya Ino[1], Kyohei Terao[1], Hidekuni Takao[1], Tomomi Shiratori[2] and Fusao Shimokawa[1]

[1] *Division of Intelligent Mechanical Systems Engineering, Kagawa University, Japan*
[2] *Faculty of Engineering, University of Toyama, Japan*

Abstract

To improve the yield of high-quality agricultural products, growth method based on biological information (moisture dynamics) inside the plant is required. In this paper, we propose a small machined Granier sensor, manufactured using a precision processing technique, to monitor quantitatively the moisture dynamics in the stems of herbaceous plants, such as agricultural crops. The principle of the Granier method is sap flow measurement, which is the basis for this model. Copper is used as the probe material, which comprises the main part of the sensor. The probe is fabricated using the laser cutting method and then vertically bent to manufacture a 1/10 scale version of a commercial Granier sensor. After evaluating the responsiveness of the fabricated sensor by determining the relationship between sensor output and flow velocity in a mimicked plant setup, the moisture dynamics for a pepper (*Capsicum Annuum L.*) stem are measured daily. The results exhibit the same tendency as the results of sap flow measurement using the conventional sensor, indicating that the proposed sensor may be effective for measuring the moisture dynamics of agricultural products.

Keywords: internal biological information of plants; Granier method; sap flow sensor.

1. Introduction

At present, in many agricultural fields, the growth condition of plants is controlled by the producer's intuition and experience based on environmental changes. However, efficient crop growth method based on intuition and experience requires expert skill and can result in serious problems.

Hence, smart agriculture using information and communication technology has been attracting attention in recent years. However, sensing environmental information such as temperature, humidity, light intensity, and soil moisture content is mostly used in the field. A method to monitor the biological information (moisture dynamics) of crops directly has not been established. If it becomes possible to measure and monitor moisture dynamics inside crops directly in real time, it more efficient irrigation management is expected to be enabled by combining environmental information and plant internal moisture dynamics information, which will lead to improved crop yields and quality.

Thus far, several moisture dynamics sensors (e.g., the Granier sensor) have been developed for tree measurement. Based on the Granier sensor measurement principles, we fabricated and verified the feasibility of a micro-sensor that can measure the flow velocity at the end of a plant using micro electro mechanical systems (MEMS) technology [1,2]. However, these MEMS-type Granier sensors had a limited probe length of less than 1 mm, and there were issues regarding the application area, with the available stem diameter range being less than a few millimeters.

Therefore, the purpose of this study was to visualize the moisture dynamics of the entire individual including the terminal part of the herbaceous plant, which could not be measured by the commercially available Granier sensor or MEMS type Granier sensor.

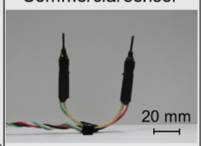
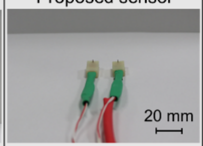
Hence, this study uses precision machining techniques produce small machined Granier sensors with adjustable probe lengths (1-5 mm) to extend the available range of application areas from a few mm to 8 mm and to test their effectiveness.

2. Sensor device design

2.1 Configuration of the proposed sensor

A comparison between the conventional (commercial Granier) and proposed (small machined Granier) sensors is shown in Table 1. Conventional sensors mainly measure woody plants. The length and diameter of the conventional probe are approximately 20 and 2 mm, respectively [4]. The length and diameter of the proposed probe are 3 mm and 0.3 mm, respectively. This decreased size enables the measurement of the details of the fruit, stalks, and ends of shoots of herbaceous plants that were previously unmeasurable.

Table 1
Comparison of conventional and proposed sensors

	Commercial sensor	Proposed sensor
		
Measuring object	Woody plants (φ100 mm–)	Herbaceous plants (φ5 mm–)
Dimensions of probe	Length : 20 mm Diameter : φ2 mm	Length : 2 mm Diameter : φ0.3 mm

2.2 Measurement principle of the proposed sensor

The measurement principle of the proposed sensor, based on the Granier method [4,5,6], is shown in Figure 1.

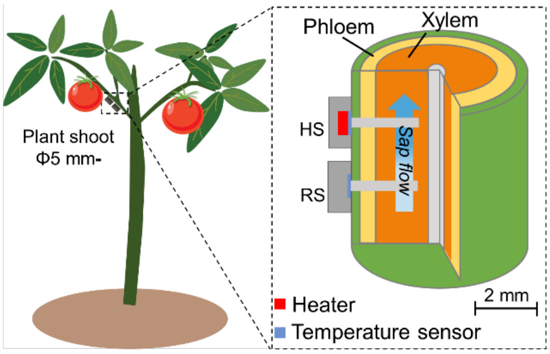


Fig. 1. Principle of the Granier method.

In the Granier method, a heater (HS) and temperature sensor (RS), which serves as a reference, are inserted into the target to measure the temperature. The temperature difference between the HS and RS is calculated as a function of the flow velocity, and the sap flow velocity, *u*, is expressed as follows:

$$u = \frac{1}{\alpha}\left(\frac{\Delta T_{max} - \Delta T_{(u)}}{\Delta T_{(u)}}\right)^{\frac{1}{\beta}} = \frac{1}{\alpha} \cdot K^{\frac{1}{\beta}} \qquad (1)$$

where *u* is the sap velocity (μm/s), ΔT(*u*) is the temperature difference between sensors (°C), ΔTmax is the temperature difference between sensors when *u* = 0, and α and β are the coefficients obtained experimentally. In addition, $\frac{\Delta T_{max} - \Delta T_{(u)}}{\Delta T_{(u)}}$ is defined as the sensor output, *K*.

The sap flow rate per stem, *F*, is determined using the sap flow rate determined by Eq. (1) as follows:

$$F = u \times A_s \qquad (2)$$

where *F is* the sap flow rate per stem (m^3/s), and A_s is the total area of the conduit (m^2).

3. Sensor device fabrication

Figure 2 shows the manufacturing process for the proposed sensor [7,8]. The metal plate with the probe consists of two functional elements: a heater and a pedestal. A temperature sensor can be attached to the pedestal, functioning as a thin needle that is minimally invasive when inserted into the plant. The metal plate is formed by two processes, laser cutting and bending, which are based on the cutting process of ultrafine grain steel [9].

The metal plate with the probe is made of copper with a thickness of 0.3 mm, which is laser cutting and then bent vertically (Figure 2) to insert the needle, heater, and plate into the plant. In Fig. 2a, a picosecond laser processing machine (Panasonic Production Engineering Co) and a laser oscillator (wavelength: 532 nm, pulse width: 15-25 ps, rated output power: 15 W) were used to create a laser trajectory pattern of the specified shape, and the laser was irradiated and cut along the trajectory to the material.

The metal plate is currently designed to be a 5 mm^2 square, similar to the surface area of the heater. The manufactured probe is fitted with a film-type temperature sensor and heater, and the entire device is protected by a resin package.

The HS device is manufactured by assembling: (A) a metal plate with a probe function, (B) a film-type temperature sensor (NFR-CF2-0305-30-100S-1-100TF-A-3, Netsushin Co), (C) 5 mm^2 square ceramic heater (MS-M5, SAKAGUCHI EH VOC CORP), and (D) a resin package.

In addition, the RS has a structure in which the heater is removed from the HS.

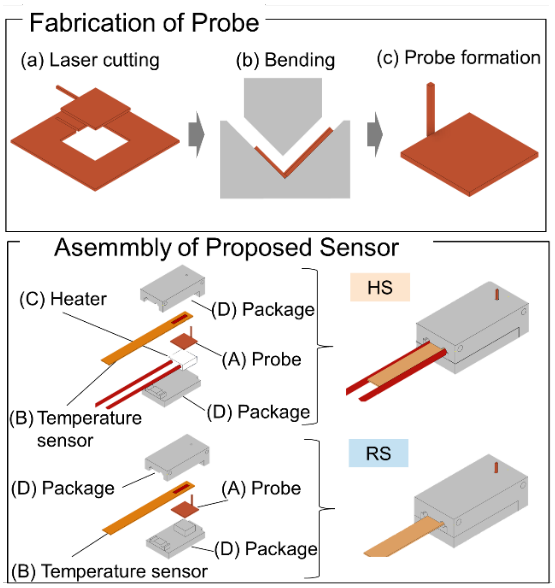


Fig. 2. Manufacturing process of the proposed sensor.

Figures 3 and 4 present the appearance of the fabricated probe and the completed machined moisture sensor with the probe inside, respectively.

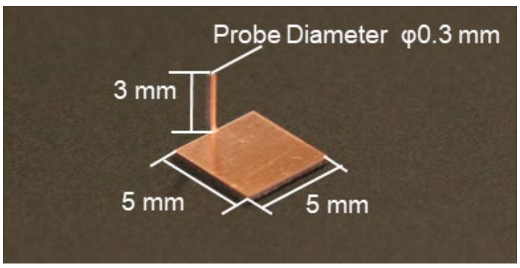


Fig. 3. Image of the fabricated probes.

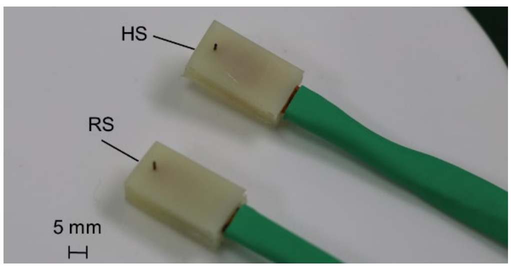


Fig. 4. Image of the mechanical moisture dynamics sensor.

The length and diameter of the probe are 3 and 0.3 mm, respectively, but the needle can be adjusted from 2 to 5 mm in length and to 0.1 mm in diameter. Therefore, the needle length can be adjusted according to the diameter of the stem to be measured, and it can be applied to various plant species and measurement sites.

4. Experimental procedure and results

4.1 Moisture dynamics experiments in mimicked plants

As shown in Figure 5, a function generator (TEXIO, FGX-2005) is used to supply voltage to the heater at the time of flow rate measurement. A data logger (midi LOGGER GL-840-WV, GRAPHTEC Co.) is used to acquire data from the temperature sensor. A micro-syringe pump is utilized to vary the flow velocity in the silicon tube with reference to the flow velocity range of a commercial Granier sensor.

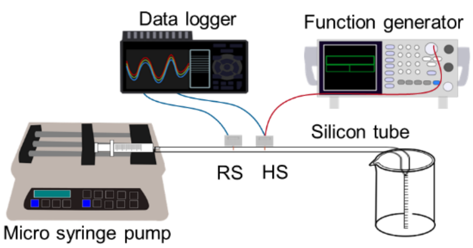


Fig. 5. Mimicked plants experimental setup.

Figure 6 shows the relationship between sensor output K and velocity u, obtained from the mimicked plant experimental setup shown in Figure 5. The response of the output of the proposed sensor to flow velocity u was measured in the range of 0–1500 μm/s, as shown in Figure 6.

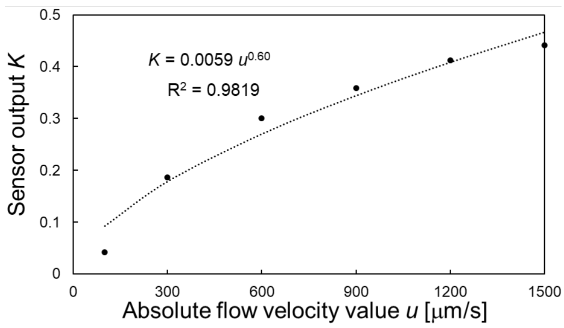


Fig. 6. Results of the flow velocity measurement.

The results demonstrate a strong correlation between the sensor output and the flow velocity in the tube. u can be obtained from the value of K as follows:

$$u = 169 \times 10^{-4} K^{1.67} \tag{3}$$

4.2 Measurement of plant moisture dynamics in the field

To evaluate the performance of the proposed sensor further, we conducted a moisture dynamics experiment on actual plants in the field. When moisture dynamics are measured in the field, it is necessary to consider the effects of changes in the external environment, such as temperature, light intensity, and humidity, on the sensor output. In particular, the proposed sensor measures changes in heat content; hence, the effects of heat content changes in temperature and light intensity need to be reduced. Therefore, to suppress the change in the heat content of the device itself owing to changes in the external environment, a heat insulating sheet (MS1-03N) was attached to the resin package of the sensor fabricated in Figure 4.

In this experiment, the daily flow rate of a pepper (*Capsicum annuum L.*) stem was measured at three points that were relatively close to the base of the root. The experimental system is shown in Figure 7.

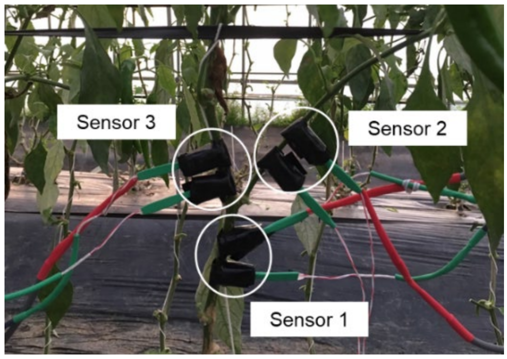


Fig. 7. Image of the field experiment setup.

As shown in Figure 7, Sensor 1 was attached to the main stem, and Sensors 2 and 3 were attached to each of the two stems branching from the main stem. The flow velocity was measured for 24 h. Environmental information was obtained simultaneously to evaluate the validity of the obtained data. The relationships between the flow velocity data obtained using the proposed sensor and the vapor pressure deficit and the irradiance were observed.

The sensor output, K, of Sensor 1 obtained in the field experiment was converted into velocity u using equation (3), and the graph comparing it with the daily variation of the vapor pressure deficit and the irradiance is shown in Figure 8.

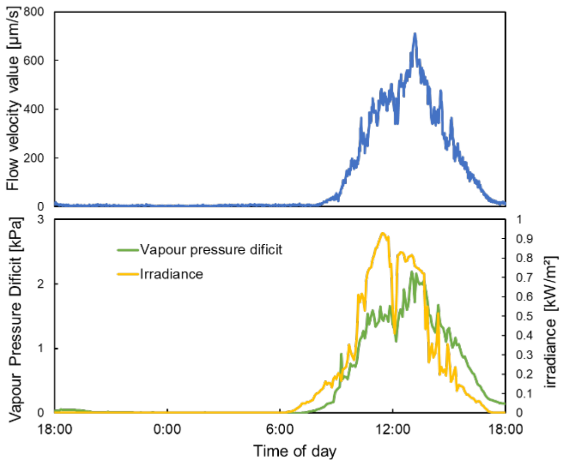


Fig. 8. Result of the plant moisture dynamics measurement.

Figure 8 shows that the velocity change is small at night and increases with sunrise. It was also found that the flow velocity changes are delayed by approximately 10 min in response to rapid environmental changes in a short period of time, corresponding to the changes in vapor pressure deficit and irradiance, respectively, in Figure 8. Previous studies conducted on trees have shown that sap velocity varies in response to the vapor pressure deficit and irradiance [10], and the results of the present measurements demonstrated similar trends.

4. Conclusions

In this study, we applied the Granier method of sap flow measurement to fabricate and evaluate a small machined Granier sensor that could be applied to the stems of herbaceous plants, such as agricultural crops. The probe structure was formed using a precision processing technique by laser cutting and bending a copper metal plate. This manufacturing process made it possible to adjust the probe length and expand the applicable stem diameter range easily.

After confirming that the sensor was capable of validating minute changes in the flow velocity in a pseudo-plant system, the moisture dynamics were measured in actual crops. These experiments succeeded in demonstrating a trend similar to the diurnal changes in flow velocity in trees that have been obtained in previous studies, thereby further verifying the effectiveness of the sensor.

In, future study, we will optimize the sensor configuration with the aim of accurate flow velocity measurement that is not affected by the external environment.

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