

WIRELESS PLANAR CAPACITIVE SENSOR SYSTEM FOR MONITORING MOISTURE CONTENT IN PLYWOOD

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Abstract

This research paper presents the development of a wireless planar capacitive sensor system for monitoring moisture content in plywood. The proposed system consists of four parts: a planar capacitive sensor for sensing the level of moisture content in plywood, an electronic circuit for converting the capacitance of the sensor to voltage, a microcontroller with Wi-Fi support for converting voltage to the moisture content in plywood and sent to the dashboard via Wi-Fi, and a ThingSpeak application for monitoring and alerting to the user when the moisture content of plywood more than setting value. The proposed system is based on a capacitive sensing technique which dielectric constant of plywood is related to moisture content in plywood. For this system, we measure the capacitance of the planar capacitive sensor and then convert it to the moisture content in plywood by the proposed electronic circuit and microcontroller before sending it to the ThingSpeak application to monitor the level of moisture content in plywood and status for alert to the user via the online dashboard. The proposed system can measure and monitor the moisture content of the plywood in a range of 0-52.3%, including the environmental temperature and humidity measurement within the ranges of 0-50°C and 20-90%, respectively. These parameters help the user to analyse the causes of changes in the moisture content of plywood and find ways to prevent the increase in moisture content. The proposed system utilizes wireless technology and cloud storage for measurement data, allowing users to monitor and track plywood moisture content in real-time from anywhere. The experimental testing of the proposed system with twenty plywood samples by various moisture content values shows that the system can effectively measure and monitor the moisture content level in plywood with satisfactory accuracy. In addition, the proposed system can alert the user when the moisture content in the plywood exceeds the alarm set value, which the user can adjust.

Keywords: Moisture content, Planar capacitive sensor, Plywood, Wireless system.

1. Introduction

Plywood is a composite of several thin sheets of wood pressed together using glue as a fixing material and heat pressed. Plywood is a beautiful sheet with a continuous pattern of large sheets. Moreover, it has high load strength and dimensional stability [1-3]. Therefore, plywood is a material that can be used to create various works. Because plywood consists of varying layers or plies of wood, each layer of plywood components can absorb moisture from the air or direct contact with liquids or water. The moisture content is the quantity of water in the plywood. This relation affects the properties and quality of plywood by decreasing mechanical properties and increasing decay risk [4-7].

As mentioned above, the amount of moisture in the plywood is an important parameter that affects its quality. Therefore, tracking the moisture content in the plywood is helpful in easily monitoring changes in the quality of the plywood. There are two methods for measuring the level of wood moisture content: direct methods and indirect methods. For direct methods, the moisture content is measured by a gravimetric method based on water extraction or oven-drying [8-10]. However, this method is destructive to the wood sample and time consumption. Indirect methods use electrical property measurement techniques to measure the physical properties of wood, which are correlated to the moisture content level in wood.

Many indirect methods for measuring the wood moisture content have been proposed, such as electrical capacitance [9-12], electrical resistance [9, 12-15], time domain reflectometry [16], microwave [9, 17, 18], near-infrared spectroscopy [19], radiometric [9], spectrometric [9], and colour methods [9]. The capacitance and resistance methods are widely utilized for wood moisture content measurement and are commonly implemented in commercial devices [12]. However, a limitation of the resistance method is that it may cause surface damage when electrodes are affixed to the wood specimen.

From the details of the techniques for measuring moisture content in plywood mentioned above, all techniques are designed to temporarily measure the moisture content of the plywood under test. Many users need the system for real-time monitoring of the changes in plywood moisture content to use in plywood processing plants and warehouses. Nowadays, wireless communication technology is used in many applications, such as military, health, agriculture, industrial, urban, and environmental, due to its ease of installation and operation and reduced wiring and maintenance costs [20-23]. Therefore, this paper proposed a wireless planar capacitive sensor system for monitoring moisture content in plywood with the following main features:

- The proposed system is based on the planar capacitive sensor principle, which does not damage the surface of the tested plywood.
- The proposed system uses wireless connections between the measurement system and dashboard, which means that users can monitor and track the moisture content in plywood in real-time, anywhere.
- The proposed system uses cloud storage to keep data on the moisture content in plywood, including the environmental temperature and humidity data. These parameters allow the user to analyse the causes of changes in the moisture content of plywood and find ways to prevent the increase in moisture content.

- The proposed system can alert the user when the moisture content in the plywood exceeds the set value, which the user can adjust.

2. Literature Review

This section presents the current research on moisture measurement and monitoring systems for wood and plywood, focusing on using electrical property measurement techniques to guide further system development. Slávik et al. [24] have presented two methods of moisture measurement by electric resistance based on a simple resistor-capacitor (RC) circuit system improved with an ICM7555 chip and integrator circuit using a TLC71 amplifier. Both methods can long-term wood moisture monitoring in buildings for moisture contents above 8%. However, since the system uses a resistance method, the electrodes need to be embedded into the surface of the wood sample, which can damage the sample surface under test, so it is unsuitable for use in plywood.

Saban et al. [25] have proposed a wireless system for measuring the moisture content of wood based on a resistance measurement method, Bluetooth Low Energy (BLE) technology, and a web-based monitoring system. This system supports online monitoring of the moisture content of wood with a low-power consumption sensor node. However, this system is based on the resistance method, which can scratch the surface by attaching the electrode to the wood surface. Moron et al. [11] have presented a system for moisture content measurement in wood based on the capacitive sensor with two parallel-plate electrodes with a detecting circuit including an auto-oscillating circuit and a demodulator that gives the change of this frequency corresponding to the capacitance of the sensor. This system does not damage the sample under test. However, the sample size must be small enough to fit between the sensor plates.

Oommen and Philip [26] have proposed a system for wood moisture content measurement using planar capacitive sensors with a spiral structure. This system uses a HIOKI IM 3570 impedance analyser to measure the capacitance of the sensor and convert it to the moisture content value by the proposed equation. However, this system uses a HIOKI IM 3570 impedance analyser to measure the sensor's capacitance, making it inconvenient to use on-site. Chetpattananondh et al. [10] have proposed a system for moisture content measurement in rubber wood based on an interdigital capacitive sensor, and the sensor detected by the modified bridge circuit with a range of moisture content of 6-70%. However, this proposed system cannot track the moisture content in plywood in real-time or through online monitoring.

Korkua and Sakphrom [27] have presented a system for moisture content measurement of an oil-palm-wood in real-time based on the capacitive sensor with two electrode structures, parallel-plate and coplanar electrodes with the detection circuit includes a square-wave-generator circuit, low-pass filter circuit, and signal-conditioning circuit. This system can monitor the moisture content of oil palm wood in real time but does not include environmental temperature and humidity data.

From the details of the current research on moisture measurement and monitoring systems for wood and plywood, each proposed system uses a variety of sensor schemes, measurement methods, and techniques for displaying the measurement results mentioned above. From the systems discussed above, each system has different advantages and disadvantages. Therefore, the author has selected the advantages of each system as a guideline for developing our system, with the following important

features: The proposed system uses a capacitive sensor structure for measurement to avoid scratching the surface by attaching the electrode to the wood surface. A new capacitance measurement circuit has been designed to provide a voltage output value related to the capacitance of the sensor. A wireless system is applied to connect the measurement system and the dashboard, which means that users can monitor and track the moisture content in plywood in real time anywhere.

The proposed system uses cloud storage to keep data on the moisture content in plywood, including the environmental temperature and humidity data. The proposed system can alert the user when the moisture content in the plywood exceeds the set value, which the user can adjust. The block diagram of the proposed wireless planar capacitive sensor system for monitoring moisture content in plywood is shown in Fig. 1. The system consists of a sine wave generator, amplifier I, planar capacitive sensor, capacitance detector, amplifier II, amplitude detector, filter, and microcontroller with Wi-Fi. The details of each part are illustrated in the next section.

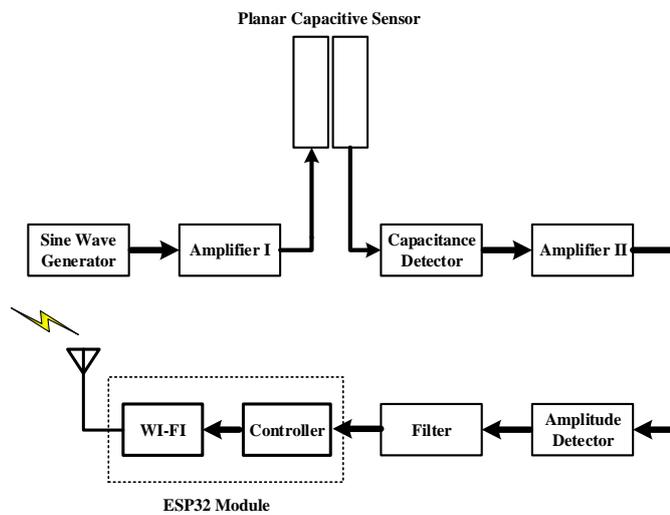


Fig. 1. The proposed wireless planar capacitive sensor system for monitoring moisture content in plywood.

3. Principle of Planar Capacitive Sensor

This section explains the principle of planar capacitive sensors. Planar capacitive sensors are non-destructive sensors used to measure the properties of a material by detecting the change in dielectric properties.

Figure 2 shows the basic structure of a planar capacitive sensor consisting of two conductor electrodes placed close together on the object under test or measurement. The capacitance value of the planar capacitive sensor (CCS) is shown in Eq. (1) [10, 28].

$$C_{CS} = \varepsilon_0 \frac{(\varepsilon_W + \varepsilon_S) K \left[\sqrt{1 - (a/b)^2} \right]}{2 K[a/b]} + 2\varepsilon_0 \varepsilon_W \frac{h}{a} \quad (1)$$

where CCS is the capacitance of planar capacitive sensor, ε_0 is the dielectric constant value in free space ($\varepsilon_0 = 8.8542 \times 10^{-12}$ F/m), ε_W and ε_S are the dielectric constants

value of plywood and the substrate, respectively. Parameters a , b , and h are the distance between electrode pairs, the substrate's width, and the electrode's thickness, respectively. In addition, $K\left[\sqrt{1 - (a/b)^2}\right]$ and $K[a/b]$ are the elliptic integrals of modulus $\sqrt{1 - (a/b)^2}$ and $[a/b]$, respectively [10, 24].

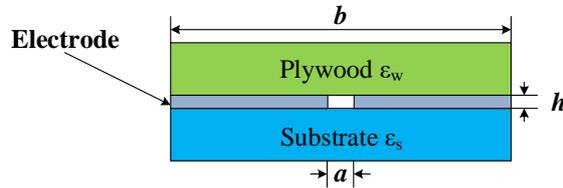
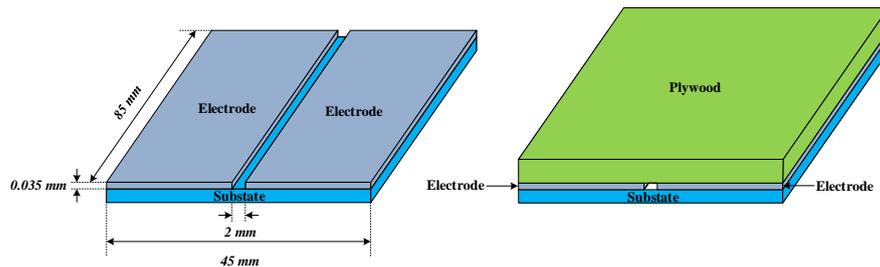


Fig. 2. The basic structure of a planar capacitive sensor.

The structure of the planar capacitive sensor for use in the proposed system is demonstrated in Fig. 3. The parameter values of the proposed planar capacitive sensor for detecting moisture content in plywood were $a = 2 \text{ mm}$, $b = 45 \text{ mm}$, $h = 0.035 \text{ mm}$, and $l = 85 \text{ mm}$. From this structure, the capacitance CCS between two electrodes of the planar capacitive sensor is varied by the moisture content of plywood because two electrodes are attached to the dielectric medium of the plywood, which is related to the moisture content in plywood. For this system, the capacitance of the planar capacitive sensor CCS is measured and then converted to the moisture content in plywood by the proposed electronic circuit and microcontroller. From Fig. 3, the minimum area size of the plywood sample to be measured must be no less than the area size of the planar capacitive sensor.



(a) Planar capacitive sensor (b) Plywood attach to planar capacitive sensor

Fig. 3. The structure of the planar capacitive sensor for detecting moisture in plywood.

4. Electronic Circuit Descriptions

Practically, the capacitance of a planar capacitive sensor is very small, less than 100 pF, the electronic circuit for measurement must have high measurement sensitivity and low noise. Details of the electronic circuit measuring capacitance from the planar capacitive sensor used in the proposed system can be explained in this section.

4.1. Sine wave generator and amplifier I circuit

Figure 4 shows the sine wave generator and amplifier circuit used in the proposed system. A sine wave generator based on a commercial XR-2206 device generates

a sine wave signal at 100 kHz with an amplitude of 4 V_{p-p} before being sent to the amplifier I circuit to amplify the amplitude to 10 V_{p-p}. The output of the amplifier I circuit is sent to the planar capacitive sensor.

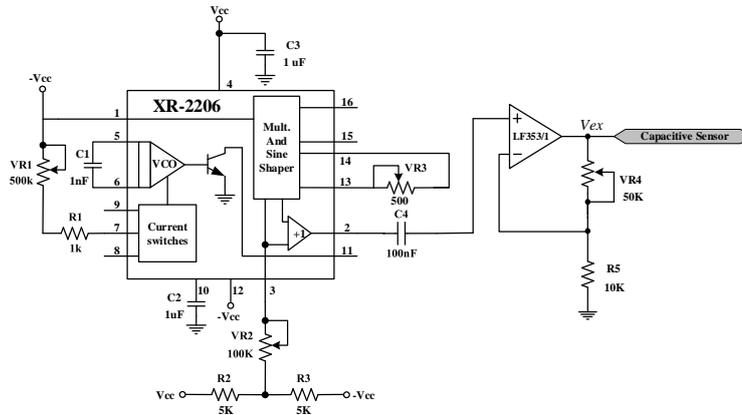


Fig. 4. Sine wave generator and amplifier circuit.

4.2. Capacitance detector circuit

A capacitance detector circuit based on the use of a charge amplifier [29] is shown in Fig. 5. The detector circuit consists of an operational amplifier (opamp) A1, fixed resistor (R_f), planar capacitive sensor (CCS), and fixed capacitor (C_f). The input voltage V_{ex} from sine wave signal generator is the excitation signal applied into detector circuit. Thus, the relation between input voltage V_{ex} and output voltage V_C of the detector circuit can be given by Eq. (2).

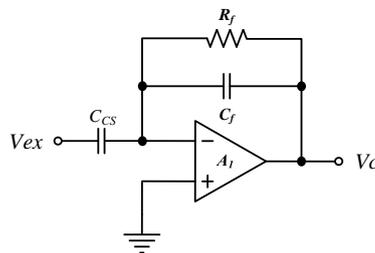


Fig. 5. Capacitance detector circuit.

$$V_C = - \frac{j\omega C_{CS} R_f}{j\omega C_f R_f + 1} V_{ex} \tag{2}$$

where ω denotes the angular frequency of the excitation voltage.

From Eq. (2). If $j\omega C_f R_f \gg 1$ is set, then the voltage V_C can be approximated as Eq. (3).

$$V_C = - \frac{C_{CS}}{C_f} V_{ex} \tag{3}$$

For this proposed system, the parameters of $R_f = 820 \text{ K}\Omega$, $C_f = 100 \text{ pF}$, and the excitation voltage frequency equals 100 KHz are chosen.

4.3. Capacitance detector, amplifier II, amplitude detector, and filter circuit

Figure 6 shows the capacitance detector, amplifier II, amplitude detector, and filter circuit for converting the capacitance of the planar capacitive sensor to voltage output. The voltage amplitude in the form of the sine wave signal from the capacitive sensor corresponding to the capacitance of the planar capacitive sensor is detected by the capacitance detector circuit. The signal from the capacitance detector circuit is sent to an amplifier II to amplify the signal to obtain level and decrease noise before being sent to the amplitude detector and filter circuit.

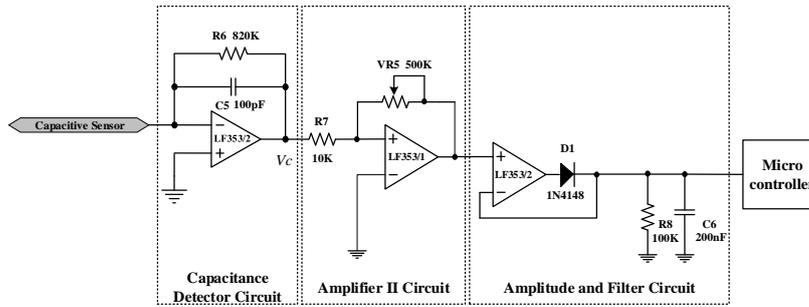


Fig. 6. Capacitance Detector, amplifier II, amplitude detector, and filter circuit.

The amplitude detector and filter circuit convert the sine wave signal from the amplifier to the DC voltage output and then send it to the input of the microcontroller. From the above circuit explanation, the proposed circuit diagram for converting the capacitance of the capacitive sensor to voltage output (C/V circuit) can be shown in Fig. 7.

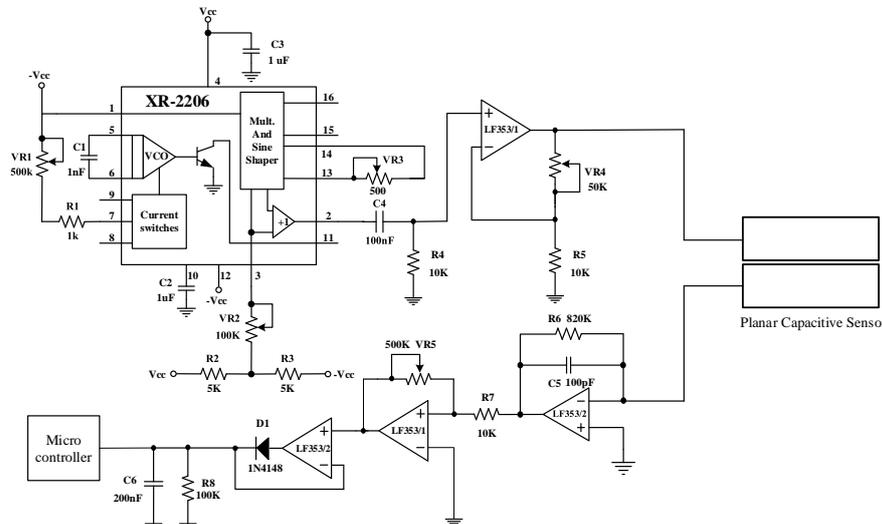


Fig. 7. Circuit diagram for converting the capacitance of the capacitive sensor to voltage output (C/V circuit).

5. ESP32 Module

ESP32 module is a commercial general-purpose microcontroller device with low-cost, low power consumption, and integrated Wi-Fi transceiver [30]. It is suitable for battery-powered portable electronic devices. The low power consumption property of the ESP32 module makes it suitable for application to devices used on the Internet of Things (IoT) system. Moreover, the ESP32 module integrates two 12-bit analog-to-digital converters (ADC) [31]. For this system, the ESP32 module converts the DC voltage value of the C/V circuit to the moisture content in plywood and sends it to the ThingSpeak application for online monitoring. In addition, the environmental temperature and humidity conditions are measured by the DHT111 sensor and also sent to the ThingSpeak application for monitoring. The connection diagram of the ESP32 module is shown in Fig. 8. The DC output voltage value of the C/V circuit is sent to ADC input channel 1 (ADC1) of the ESP32 module at pin 5 (GPIO36) while the output of the DHT11 sensor in digital form is sent to digital input at pin 24 (GPIO4).

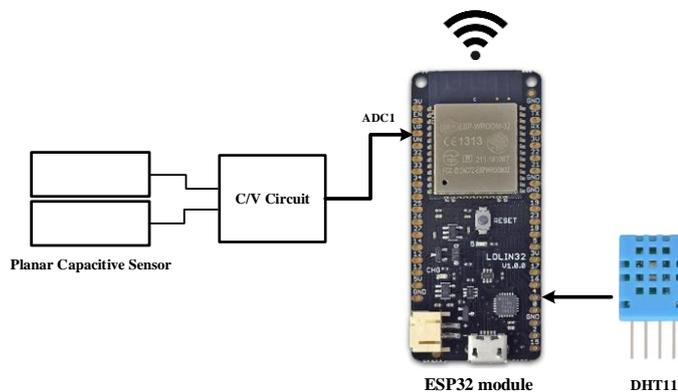


Fig. 8. The connection diagram of ESP32 module.

6. ThingSpeak

ThingSpeak is a simple platform for developing Internet of Things (IoT) devices and applications that allow users to control and monitor IoT devices via the internet system. This platform supports numerical computing software MATLAB from MathWorks allowing users to analyse data from IoT devices. For this system, ThingSpeak monitors the value of the moisture content in plywood using data from the ESP32 module and notifies the user when the moisture content exceeds the user setting. In addition, the environmental temperature and humidity conditions are included in the ThingSpeak dashboard. The dashboard for monitoring parameters of the proposed system based on ThingSpeak is shown in Fig. 9.

From Fig. 9, the dashboard for monitoring parameters of the proposed system based on the ThingSpeak application consists of three charts and one widget. The charts show the temperature, humidity, and moisture content of plywood. The widget is the alarm status lamp.

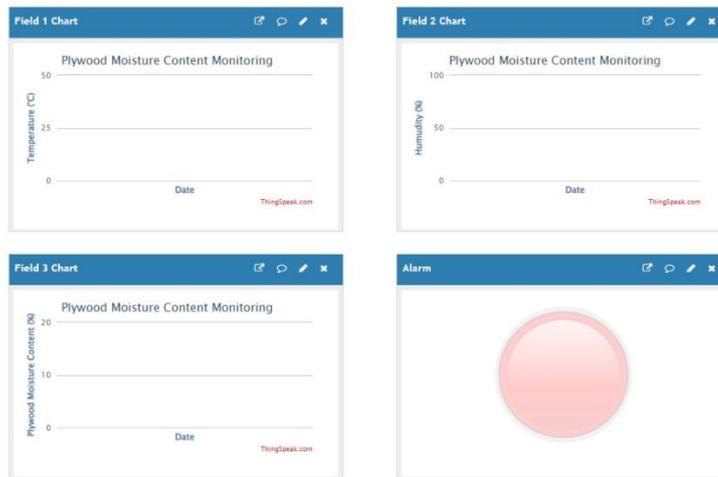


Fig. 9. The dashboard for monitoring parameters of the proposed system.

7. Experimental and Results

The performance of the proposed wireless planar capacitive sensor system for monitoring moisture content in plywood is tested in three parts. The first part is a test of the proposed planar capacitive sensor used to measure moisture content measurement in plywood. The second part is a test of circuits for converting the capacitance of the planar capacitive sensor to voltage output (C/V circuit). The third part is the microcontroller and the ThingSpeak for converting DC voltage from the C/V circuit to the moisture content in plywood and displaying it on the dashboard of the proposed system.

7.1. Planar Capacitive Sensor Experimental and Results

For this section, the planar capacitive sensor with the structure shown in Fig. 3 is used in the experiment with the plywood sample. The capacitance value of the planar capacitive sensor is measured by the LCR meter model HiTESTER 3522 from HIOKI. The standard wood moisture meter model UT377A from Uni-Trend Technology Co., LTD is used for the calibration of the proposed system. It is used to measure moisture content in plywood for reference and calibration. Twenty plywood samples with different moisture content are used to test the planar capacitive sensor and determine its capacitance relative to the moisture content, measured by a standard measuring device. The procedure for testing each plywood sample can be explained as follows:

- Prepare the plywood sample and specify the sensor placement location.
- Measure and record the moisture content in plywood using the standard wood moisture meter model UT377A.
- Repeat the measurement 10 times, find the average of the measurements, and record the measurement results.
- Replace the standard wood moisture meter model UT377A with the proposed planar capacitive sensor.

- Measure and record the capacitance of the proposed planar capacitive sensor by the LCR meter model HiTESTER 3522.
- Repeat the measurement 10 times, find the average of the measurements, and record the measurement results.
- Repeat steps 1 to 6 for 20 plywood samples.

After the finish of all twenty plywood samples tested using the proposed procedure, data of the moisture content and capacitance of the proposed planar capacitive sensor are used to find the relationship equation. The relationship equation between moisture content in plywood and the capacitance value of the proposed planar capacitive sensor can be obtained by applying the trend line equation in Microsoft Excel. The trend line equation is a formula that finds the best line to fit the data points. R Square (R²) is the coefficient of determination, which is used as an indicator of the goodness of fit equation.

Generally, R² of 0.95 or more is considered a good fit equation. For this experiment, we separate the relationship equation into 2 cases; the first case is the relationship equation between the moisture content in plywood and the capacitance value of the proposed planar capacitive sensor. The relation between the moisture content in plywood and the capacitance value of the proposed planar capacitive sensor is shown in Fig. 10. The relationship equation can be approximated by Eq. (4) with R² = 0.994.

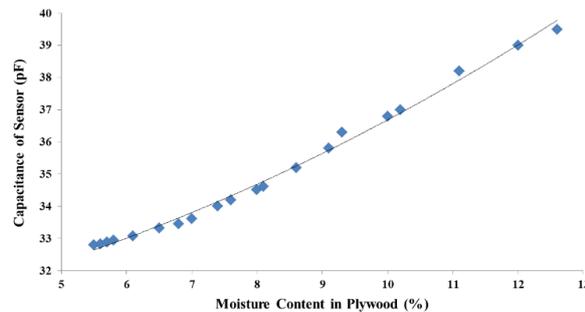


Fig. 10. The relation between the moisture content in plywood and the capacitance value of the proposed planar capacitive sensor.

$$y = 0.041x^2 - 0.26x + 29.97 \quad (4)$$

From Eq. (4), the parameters y and x are the capacitance value of the proposed planar capacitive sensor (pF), and the moisture content in plywood (%), respectively. The second case is the relationship equation between the capacitance value of the planar capacitive sensor and the moisture content in plywood. The relation between the capacitance value of the planar capacitive sensor and the moisture content in plywood is shown in Fig. 11. The relationship equation can be approximated by Eq. (5) with R² = 0.989.

$$MC (\%) = 36 \ln(C_{CS}) - 120 \quad (5)$$

From Eq. (5), the parameters MC and CCS are the moisture content in plywood (%), and the capacitance value of the planar capacitive sensor (pF), respectively. This equation converts the capacitance value of the planar capacitive sensor to the moisture content of plywood. The minimum and maximum capacitance of the

planar capacitive sensor can be measured by the proposed system as 28 pF for 0% of moisture content (completely dry plywood) and 120 pF for 52.3% of moisture content (wet plywood) due to the range of the proposed C/V circuit and ADC input of ESP32 module.

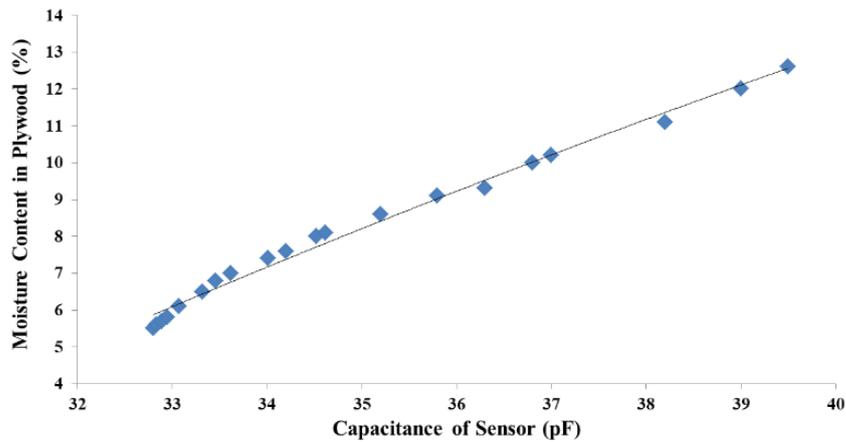


Fig. 11. The relation between the capacitance value of the planar capacitive sensor and the moisture content in plywood.

7.2. C/V Circuit Experimental and Results

For this section, the proposed C/V circuit was tested with the standard capacitor instead of the planar capacitive sensor. The standard capacitor is used to test the performance and relative error of the proposed C/V circuit. The DC voltage output value of the C/V circuit corresponds with the capacitance value of the testing standard capacitor. The measurement of the output voltage value V_o and the relative output voltage error for the capacitance of the testing standard capacitor varied from 10 pF to 120 pF, shown in Figs. 12 and 13, respectively.

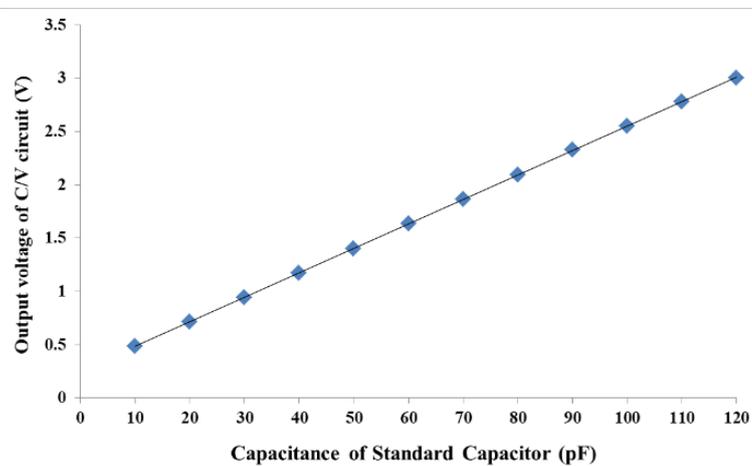


Fig. 12. The measurement of the output voltage value V_o for the capacitance of the testing standard capacitor varied from 10 pF to 120 pF.

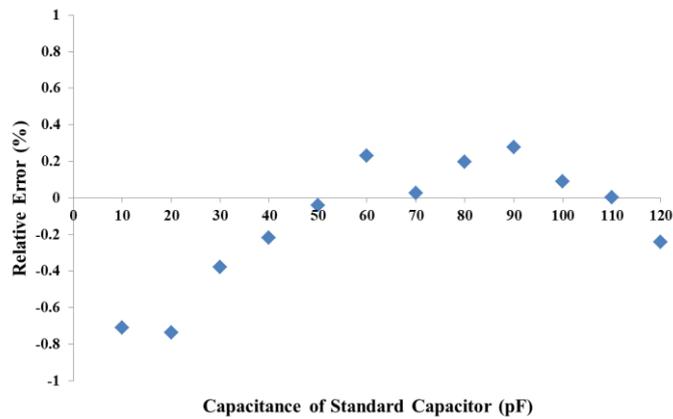


Fig. 13. The relative error of output voltage value for the capacitance of the testing standard capacitor varied from 10 pF to 120 pF.

Figure 12 shows the relationship between the capacitance value of the testing standard capacitor and the output voltage value of the proposed C/V circuit. This graph shows that the proposed C/V circuit can convert the capacitance value to DC output voltage value with high sensitivity and linearity. From Fig. 13, the maximum relative error of the proposed C/V circuit is about -0.74% in the range of the testing standard capacitance of 10 pF to 120 pF. The experimental testing and results show that the proposed C/V circuit is suitable for converting the capacitance value of the proposed planar capacitive sensors to the DC output voltage value. The relationship between the capacitance of the testing standard capacitor and the output voltage value of the proposed C/V circuit in Fig. 12 can be approximated by Eq. (6).

$$V_o = 0.0229(C_{CS}) + 0.2549 \quad (6)$$

From Eq. (6), the parameters V_o and C_{CS} are the output voltage value of the proposed C/V circuit (V), and the capacitance of the planar capacitive sensor (pF), respectively. Eq. (6) can be rewritten as Eq. (7) for use in finding values of C_{CS} by measuring the output voltage value of the proposed C/V circuit.

$$C_{CS} (pF) = (V_o - 0.2549)/0.0229 \quad (7)$$

Substituting C_{CS} into Eq. (5), the moisture content in plywood (%) can be rewritten as

$$MC (\%) = 36 \ln[(V_o - 0.2549)/0.0229] - 120 \quad (8)$$

Equation (8) shows that we can use the output voltage value of the C/V circuit to calculate the moisture content of the plywood (MC (%)). In this system, the output voltage value of the C/V circuit is sent to ADC1 via GPIO36 at pin 5 of the ESP32 module to calculate the moisture content of the plywood by Eq. (8). Then the moisture content of the plywood value obtained will be sent to be displayed on the ThingSpeak application for real-time monitoring. From Eq. (8), the proposed system can measure and monitor the moisture content of the plywood in the range 0 – 52.3%. Figure 14 shows the relation between moisture content in plywood and the output voltage value of the C/V circuit of twenty plywood samples with different moisture content.

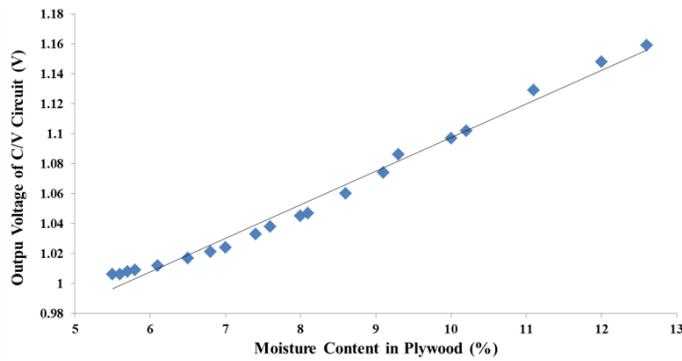


Fig. 14. The relation between moisture content in plywood and the output voltage value of the C/V circuit.

From Fig. 14, the solid line shows the trend line created by a linear equation in Microsoft Excel. The trend line shows the linearity of data measurement between moisture content in plywood and the output voltage value of the C/V circuit.

7.3. ESP32 Module and ThingSpeak Experimental and Results

In this Experimental setup, we connect the DHT11 sensor and C/V circuit with the planar capacitive sensor to the ESP32 module. The proposed ESP32 module and ThingSpeak are tested by two conditions of moisture content of plywood: normal condition and alarm condition if the moisture content of plywood is more than 10%. Figure 15 shows a dashboard for monitoring the parameters of the proposed system in case of normal conditions when the moisture content of plywood is less than 10%. Figure 16 shows the dashboard for monitoring the parameters of the proposed system in case of alarm conditions when the moisture content of plywood is more than 10%.

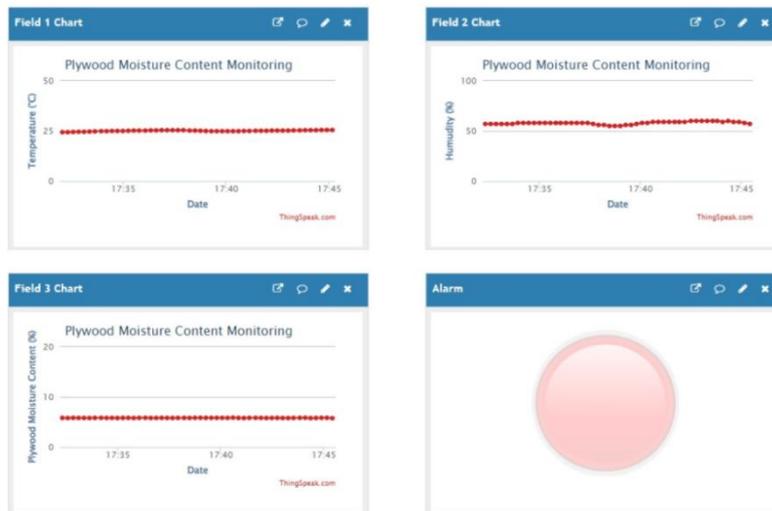


Fig. 15. The dashboard for monitoring parameters of the proposed system in normal conditions when the moisture content of plywood is less than 10%.

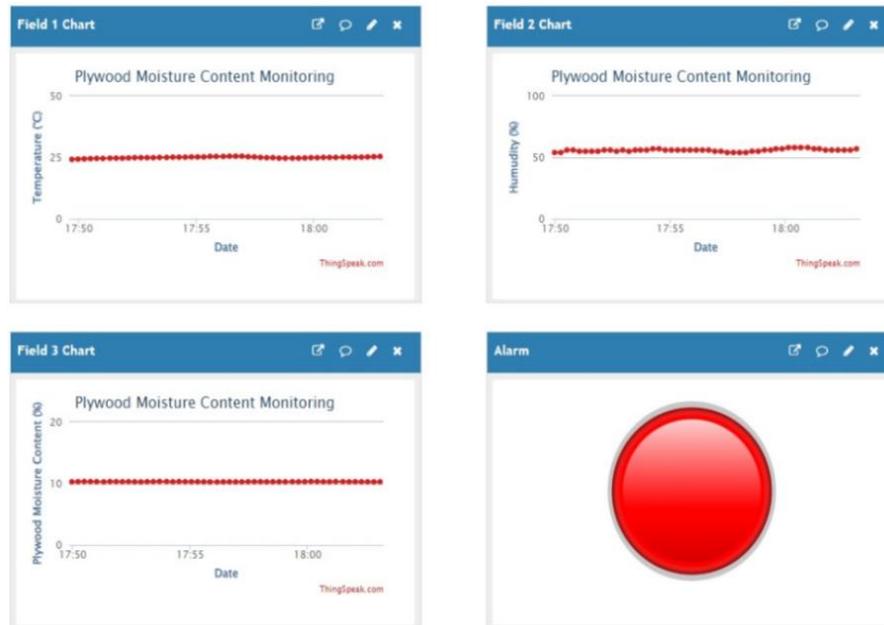


Fig. 16. The dashboard for monitoring parameters of the proposed system in alarm conditions when the moisture content of plywood is more than 10%.

8. Result and Discussion

The experimental results of the proposed wireless planar capacitive sensor system for monitoring moisture content in plywood can be separated into three parts.

For the first part, the planar capacitive sensor experimental and results show that the minimum and maximum capacitance of the planar capacitive sensor can be measured by the proposed system as 28 pF for 0% of moisture content (completely dry plywood) and 120 pF for 52.3% of moisture content (wet plywood) due to the range of the proposed C/V circuit and ADC input of ESP32 module. The range of moisture content in plywood can be measured by the proposed system, which covers the range in commercial plywood. In addition, the proposed system includes the environmental temperature and humidity measurement by DHT11 with measurement ranges of 0-50 °C and 20-90 %, respectively.

For the second part, the C/V circuit experimental results show that the proposed C/V circuit can convert the capacitance value to DC output voltage value with high sensitivity and linearity. The maximum relative error of the proposed C/V circuit is -0.74% in the capacitance of the testing standard capacitor range of 10 pF to 120 pF.

For the third part, the ESP32 Module and ThingSpeak experimental results show that the ESP32 Module can send data on the moisture content in plywood, the environmental temperature, and humidity to the ThingSpeak platform. The design dashboard can monitor all parameters and show alarm conditions when the moisture content in plywood exceeds the alarm setting point. In addition, all measurement parameters can be used to perform online analysis and process data as data comes in.

All measurement parameters can be exported to a Comma Separated Values file (CSV) for data analysis via MATLAB or Microsoft Excel. From the above experimental results and discussion, it can be seen that the proposed system can be used to measure the moisture content in plywood very well with the following advantages:

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- The proposed system is based on the planar capacitive sensor principle, which does not damage the surface of the tested plywood.
- The users can monitor and track the moisture content in plywood in real-time anywhere with wireless communication.
- Data on the moisture content in plywood, including the environmental temperature and humidity data are kept on the cloud storage. These parameters are useful to analyse the causes of changes in the moisture content of plywood and find ways to prevent the increase in moisture content.
- The proposed system can alert the user when the moisture content in the plywood exceeds the set value, which the user can adjust.

The limitation of the proposed system is that the minimum area size of the plywood sample to be measured must be no less than the area size of the planar capacitive sensor. Since the proposed technique uses the capacitive sensor principle, the environment temperature change will affect the dielectric constant of plywood, resulting in an error in the measured moisture content value. Therefore, further development of the C/V circuit is needed to compensate for the effects of temperature.

9. Conclusions

This paper has proposed a wireless planar capacitive sensor system for monitoring moisture content in plywood. The implemented system consists of a planar capacitive sensor, electronic circuits for converting capacitance planar capacitive sensor to voltage (C/V circuit), the ESP32 module for converting the DC voltage from the C/V circuit to moisture content in plywood value, and a ThingSpeak application for monitoring moisture content in plywood, including the environmental temperature and humidity, and alarm status.

The proposed system can measure and monitor the moisture content of the plywood in the range of 0-52.3%, including the environmental temperature and humidity measurement with measurement ranges of 0-50 °C and 20-90%, respectively. The proposed system is based on a wireless system and keeps measurement data in cloud storage, which means that users can monitor and track the moisture content in plywood in real time anywhere.

The experimental testing of the proposed system with twenty plywood samples by various moisture content values shows that the proposed system can measure and monitor moisture content in plywood and status with satisfied values.

Acknowledgments

This work was financially supported by King Mongkut's Institute of Technology Ladkrabang Research Fund [Grant number: KREF186328].

Nomenclatures

A_1	Operational amplifier (opamp)
a	Distance between electrode, m
b	Substrate width, m
C_{CS}	Capacitance of planar capacitive sensor, Farad
C_f	Fixed capacitor
h	Electrode thickness, m
l	Electrode length, m
R_f	Fixed resistor

Greek Symbols

ε_0	Dielectric constant in free space, 8.8542×10^{-12} F/m
ε_s	Dielectric constants of substrate
ε_w	Dielectric constants of plywood, mm

Abbreviations

ADC	Analog-to-Digital Converter
C/V	Capacitance to Voltage convertor
GPIO	General Purpose Input/Output
IoT	Internet-of-Things
MC	Moisture Content
V_o	Output voltage
V_{p-p}	Peak-to-Peak voltage

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Appendix A System Program

A. 1. Program Structure and Description of Subroutines for Proposed System

Arduino program and ThingSpeak application are used in the programming of the proposed wireless planar capacitive sensor system for monitoring moisture content in plywood. The flowchart of the main program for use in the proposed system is shown in Fig. A-1.

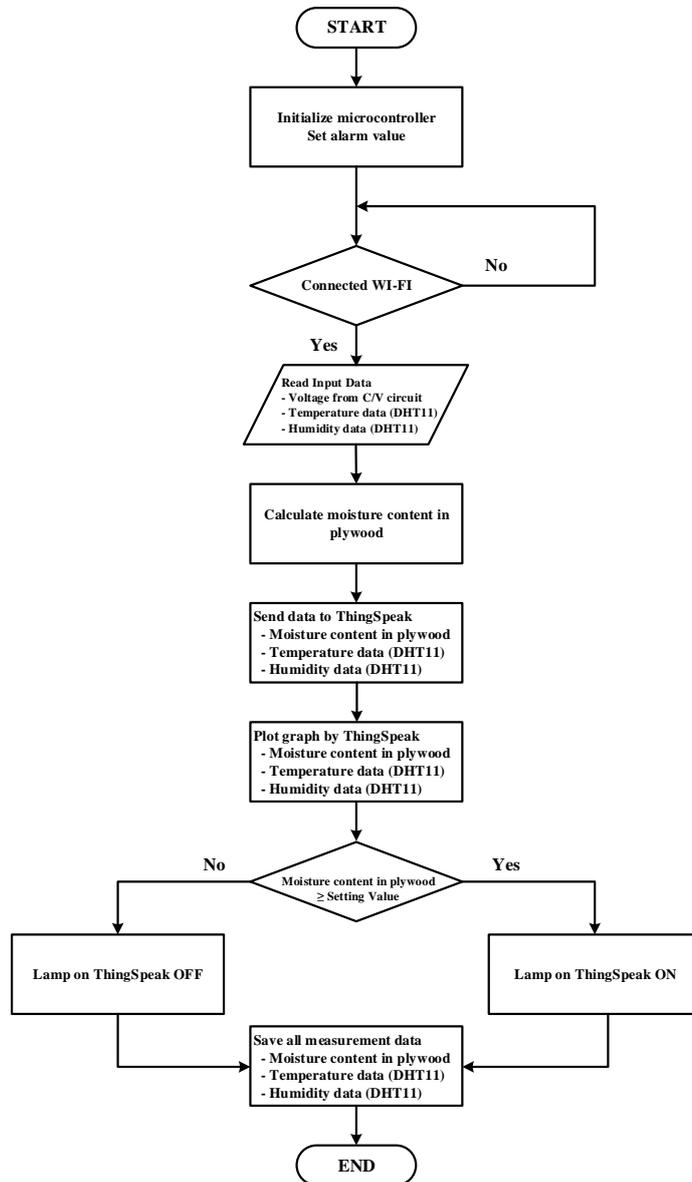


Fig. A-1. Flowchart of the main program for use in the proposed system.