Agricultural soil moisture sensor based on U-bend Plastic Optical Fibre (POF)

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Abstract. Soil moisture has an essential role in agriculture. The growth of specific vegetation requires a certain level of soil moisture. Therefore, monitoring soil moisture is very important for farmers. In monitoring, the first essential component is the sensor. Nevertheless, the existing proper soil moisture sensor is an electric-based system sensor with low water resistance. It easily damaged in extreme environments which can reduce sensor ability. Based on these problems, we developed a soil moisture sensor based on plastic optical fibre with a U-bend structure. Optical fibre was developed as an alternative sensor due to low prices, immunity to water, and resistance to extreme conditions. U-bend optical fibre can measure soil moisture depends on changes in the refractive index. The changes of refractive index caused by changes in external force which causes a decrease in the optical fibre output power are following the concentration of water contained in the soil. Plastic material is used because of its high durability and high responsiveness in refractive index-based measurements. In this experiment, a plastic optical fibre with a U-bend radius of 30 mm and a wavelength of 930 nm is used. The result shows that the U-Bend structure plastic optical fibre sensor is highly potential to use as a soil moisture sensor with sensor sensitivity of $2.885 \times 10^{-10}$ W/%VWC, $R^2$ of 97.14%, and standard deviation of 0.6%.

1. Introduction

Soil moisture is the amount of water contained in the soil [1]. The soil moisture is dynamic due to evaporation through the surface of the soil, transpiration, and percolation [2]. Also, soil moisture is an essential factor for agricultural soils. If soil moisture level in agricultural land is low or deficit, it makes plants wilt. Growth of specific vegetation also requires a certain level of soil moisture. Therefore, soil moisture monitoring is essential for farmers. Meanwhile, there are still many farmers in Indonesia who have difficulty in monitoring soil moisture in agriculture.

Proper soil moisture monitoring requires a sensor component as a moisture measurement instrument for evaluation. Therefore, the accurate sensor is also needed in the monitoring system. The soil moisture sensor that is commonly used today is the capacitive soil moisture sensor. It uses an electrical system that is not suitable for geotechnical purposes due to the system's resistance to electromagnetic interference is low. Therefore, it has a high-risk of a lightning strike. Also, the electrical system in the geotechnical installation has a short usage period due to extreme chemical conditions that can cause corrosion.
Optical fibre has non-conductant properties, so it has immunity to electromagnetic interference [3] or damage caused by lightning. Some other advantages of optical fibre are low price, lightweight, high durability in extreme environments, low power usage, and high sensitivity. Leone had previously succeeded in making an optical fibre-based thermo-hygrometer sensor as a soil moisture monitoring system using Fibre Bragg Grating (FBG) [4]. However, the FBG system is quite challenging to make and has a high-priced installation for its measuring system. Meanwhile, besides having immunity to electromagnetic interference and chemical corrosion [5, 6], plastic optical fibre also low in price. The U-bend structure of optical fibre sensor will make the sensor have high responsiveness to the changes of environmental characteristics (physical and chemical components) [7].

Therefore, this research used plastic optical fibre with a U-bend structure to be implanted into the soil as a soil moisture sensor. High soil moisture indicates high water content in soil pores that increase the pressure to the plastic optical fibre sensor and affect the change in the measured plastic optical fibre power output. The purpose of this study is to prove that the U-Bend structure plastic optical fibre sensor is highly potential to use as a soil moisture sensor based on sensor performance. Meanwhile, the long-term goal is being able to build a monitoring system in real-time U-Bend plastic optical fibre based sensors.

2. Theory and Principle

2.1. Soil moisture
Soil moisture referred to as a water quantity indicator existing in soil and expressed as a percentage. The percentage is calculated by comparing the portion of water quantity to the solids in a soil sample [8]. Soil moisture has an essential role in plant growth. Soil moisture content increment leads to reduce plant transpiration. It also influences the growth of fibre and ultimately, fibre length [9].

Each plant has an optimum soil moisture level that differs based on the type and also the other external factors such as the weather, and temperature. For example, in rice plants, optimum soil moisture is at the values of 62.2 % (wet), 59.3% (wet), 45.5% (slightly wet), and 35.0% (dry) for the initial, vegetative, mid-season and end of season phases [10].

2.2. Volumetric water content (%VWC)

Volumetric water content (%VWC) is a numerical measure of soil moisture. It is the ratio of water volume to soil volume. Below is the equation for %VWC [11]:

\[
\theta = \frac{V_{\text{water}}}{V_{\text{soil total}}} \times 100\%
\]  

Changes in water volume have the most significant effect on the total dielectric. Therefore, it commonly used capacitive soil moisture sensor to measures %VWC [11].
2.3. *Optical fibre*

An optical fibre or fibre optics is a waveguide that is used to transmit light. In the last 20 years, there have been rapid developments in the field of optoelectronics and fibre optics as a communication media, due to the nature of fibre optics which is more reliable and has better performance than copper-based telecommunications media [3]. Besides, optical fibre technology is well developed in the field of optoelectronics. Several advantages of optical fibre systems compared to electronic systems are resistant to electromagnetic wave interference, high sensitivity, lightweight, small size, low power, and reliability.

There are three main components of optical fibre. They are core, cladding, and coating. The structure of optical fibre can be seen in Figure 3.

![Figure 3. The general structure of optical fibre [3].](image)

The working principle of optical fibre is based on total internal reflection phenomena. The core of optical fibre that has a higher refractive index can transmit light by reflecting them when meeting at cladding that has a lower refractive index. This reflection occurs because the angle of light coming in the core passes through the critical angle, so the light rays which are generally refracted are reflected. This reflection continues to occur on the core so that light can be transmitted on optical fibres, as shown in Figure 4.

![Figure 4. The light transmission on optical fibre [7].](image)

As explained before, other than as a communication media, optical fibre is commonly used as a sensor. In general, optical fibre sensors work through the principle of power loss or more commonly referred to as loss caused by external interference. It should be remembered that the optical fibre itself has loss despite the absence of outside interference; this is caused by the attenuation of the optical fibre itself. Some common causes of loss in optical fibres are losses caused by macro and micro bending called micro bending and micro bending on optical fibres. External interference can cause bending, which can then be measured by measuring the loss of optical fibres.
Optical fibres can be divided based on light modes. The division of optical fibres based on modes of light as follows:

a. Singlemode: an optical fibre that can only be passed one mode of light at a time
b. Multimode: an optical fibre that can only be passed by several modes of light at a time

In addition, optical fibres can also be divided based on the core-cladding refractive index profile, which will affect light propagation. Figure 5 shows the direction of propagation and refractive index profile of the graded-index and step-index fibre optics.

2.4. U-bend fibre optics structure

Optical fibre works based on the total internal reflection phenomenon where the incident ray on the core has a smaller incident angle to the critical angle. The critical angle is determined by the refractive index of the two mediums. For the optical fibre, the two mediums are the medium of the core and the cladding. The calculation of critical angles of optical fibres can be found through the equation below:

$$\theta = \sin^{-1} \left( \frac{n_{\text{core}}}{n_{\text{cladding}}} \right)$$  \hspace{1cm} (2)

Where $\theta$ is the angle of incident ray taken from the normal plane [5]. Where $\theta$ is the angle of incident ray taken from the normal plane [5]. Plastic optical fibre sensor with a U-bend structure will experience several changes when subjected to external forces. It will respond with two possibilities. First, the optical fibre cross-sectional area becomes elliptical, or the second possibilities are that the optical fibre will be deformed. The cross-section area of optical fibre will be elliptical if the optical fibre is subjected to a uniformly distributed force. Optical fibres will have a change on its shape after it subjected to a transversal force centred in the middle. The deformation experienced by optical fibres due to the transversal force applied uniformly or centrally can be seen in Figure 6.

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Figure 5. Light propagation and refractive index profiles of the multimode index (top) and graded index (bottom) fibre optics [7].

Figure 6. Transversal forces that affect optical fibres are uniformly distributed [12].
When the optical fibre is subjected to external disruptions such as pressure, there will be a change in the refractive index of the optical fibre. The changes of the refractive index will cause changes in the mode propagation of the optical fibre, which results in a change to the output power of optical fibre. So when the soil moisture (%VWC) level increases, the amount of water content in the soil will also increase. This will cause an increase in the external force regarding the optical fibre and also an increase in optical fibre output power loss.

Figure 8. The diagram of macro bending loss on optical fibre [14].

2.5. Measurement reliability

Each measuring instrument has imperfections in the form of errors. Error is the deviation of the measured value with the actual value. Calculation of errors can be found in equation (3) [15]. By retrieving data repeatedly, the distribution of errors from the measurements will be seen. Based on the error distribution, the probability distribution of the error can be determined by the resulting standard deviation. The standard deviation can be determined through equation (4).

\[ \text{Error} = \text{Measured Value} - \text{True Value} \]  
\[ \sigma = \sqrt{\frac{\sum(x_i - \bar{x})^2}{N-1}} \]  

\( \sigma = \) standard deviation  
\( \bar{x} = \) mean  
\( x_i = \) the i-th value  
\( N = \) number of data

In a normal distribution, a value below \( \sigma \) will have a probability of 68.3%, and a value below \( 3\sigma \) will be found with a probability of 98.8%. Based on this explanation, a low standard deviation will produce good measurement reliability.
Sensitivity is the change $\Delta O$ in output $O$ for input unit change $\Delta I$ in input $I$. In the limit that $\Delta I$ tends to zero, this ratio tends to the derivative form, as shown in equation (5) [15].

$$Sensitivity = \frac{dO}{dI}$$

(5)

This formula shows the rate of change of the output $O$ to the input $I$.

2.6. Preliminary research

During 2010-2019, several optical fibre-based humidity sensors have been developed, which can be seen in the following table:

| Reference | Sensing Techniques / Methods                                                                 | %RH Range | Sensor Sensitivity | Weakness                                                                 |
|-----------|------------------------------------------------------------------------------------------------|------------|--------------------|--------------------------------------------------------------------------|
| [16]      | Measurement of absorption of U-Bend plastic fibre optic membrane coated with Ag-Polyaniline material | 5-95       | 28.78 mV/%RH       | Need experts for interpretation and relatively high fabrication costs    |
| [17]      | SMS structure optical fibre sensor                                                             | 50-89      | 0.18 nm/%RH        | The small range for the sensing measurement                              |
| [18]      | Measurement of the intensity of multimode optical fibre with SiO$_2$ coating                  | 25-65      | 0.935 nm/%RH       | Need experts for interpretation and relatively high fabrication costs    |
| [19]      | Multimode optical fibre with indium tin oxide coating                                          | 20-60      | 2.7%RH/nm          | Need experts for interpretation and relatively high fabrication costs    |
| [20]      | Measuring power output from multimode fibre optic sensors with TiO$_2$ coating                | 24-95      | 27.1 mV/%RH        | Expensive fabrication                                                    |
| [21]      | Plastic fibre optic sensor with a bragg grating structure                                     | 30-90      | 33.6 pm/%RH        | Need experts for interpretation and relatively high fabrication costs    |
| [22]      | Power loss measurement transmitted by a single-mode graded-index fibre-optic sensor          | 40-90      | 0.196 dB/%RH       | The small range for measurement                                          |
| [23]      | Power loss measurement transmitted by a hybrid Bragg grating fibre-optic sensor with an interferometer | 20-60 | 0.026 dB/%RH       | Small range measurement                                                  |
| [24]      | Bragg grating fibre optic sensor                                                              | 0-37       | 2.1 pm/%VWC         | Complex fabrication and installation, small range measurement             |
| [25]      | Bragg grating fibre optic sensor with polyamide coating                                       | 15-75      | 12.6 pm/%RH        | Need experts for interpretation and relatively high fabrication costs    |
This research offers a sensing method using U-Bend plastic optical fibre structure to answer the shortcomings of previous studies of easy fabrication and installation as well as low cost. Sensor measurement range from 15% -90%.

3. Materials and Methods
The research method consists of several stages from beginning to end to achieve the objectives of this experiment. The overall research procedure is illustrated in the following flow chart.

![Research flow chart](image)

**Figure 9.** Research flow chart.

3.1. Design and manufacture of U-bend fibre optics
The design of U-Bend plastic optical fibres is the determination of optical fibre parameters, including U-Bend curvature diameter. The diameter of the curvature used is 30 mm. The next step is the manufacture of U-Bend plastic optical fibre which will be used as a soil moisture sensor. U-Bend optical
fibre is made by peeling a jacket of plastic optical fibre using a fibre stripper, then cleaned by alcohol. Then, warping it according to the specified curvature variations, 30 mm.

3.2. Experiment set-up
Research Set-up Scheme can be seen in Figure 10.

![Figure 10](image)

Figure 10. Experiment set-up.

In this experiment, we used an electrical sensor that is connected to Arduino-un0 to collect true soil moisture value. Arduino-un0 is connected to a PC/Laptop which already has a soil moisture sensor coding program. The sensor is implanted into the soil sample which will be measured its soil moisture value (VWC) by connecting the sensor legs to the ground pin, VCC 5 volts, and pin A1 on Arduino. After obtaining %VWC output of the sample soil, then optical data is taken from the sample soil using an optical fibre sensor by implanting the optical fibre sensor into the sample soil. U-Bend plastic fibre optic sensor output power is measured using PM 100. The environment temperature of each experiment is set in 26°C. The depth of sensor implanted at each measurement is set at the same depth.

U-Bend optical fibre sensor testing was carried out on variations of soil volumetric water content (%VWC). Soil Volumetric Water Content (%VWC) that used as test samples are 15%, 30%, 45%, 60%, 75%, and 90%. Then to adjust the RH of the test soil, we were mixing the soil with water. Testing required tools and materials as follows:

- 930 nm light source (LED)
- Plastic optical fibre
- Test sample (soil moisture with %VWC: 15%, 30%, 45%, 60%, 75%, and 90%)
- Optical Power Meter (OPM)
- PC/Laptop
- Sample place
- Heating plate (to reduce the soil moisture by heating the sample soil)
- Water

In this research, the u-Bend optical fibre was implanted into the soil sample. Both ends of the optical fibre are connected to the light source and OPM; then output power is displayed on the PC. Testing is done by taking 3000 data on each variation of %VWC, with a time interval of 0.01 seconds. The data generated is the relationship between the sensor output power and variations in %VWC of the sample soil.
Data obtained from the sensor testing process is in the form of fibre output power. The results of data processing are displayed in graphical form to make analysis easier. Conclusions and suggestions are based on the results of data analysis and discussion to answer the research's objectives.

4. Results and Discussion
In this work, soil moisture sensing using U-Bend plastic optical fibre was purposed and demonstrated. From the 3000 data obtained, the average value is calculated for each RH, and the linear regression is done. From the results of linear regression, the $R^2$ value of 97.14% is obtained, which proves that there is a high correlation between the optical fibre output power and the level of soil moisture.

The high correlation between optical fibre output power with soil moisture level (%VWC) shows that the higher value of %VWC makes the higher output power loss in U-Bend plastic optical fibre sensor. The soil moisture level (%VWC) increase the amount of water content in the soil accordingly. This, in turn, causes the increase of pressure regarding the U-Bend plastic optical fibre that implanted in the soil. U-Bend plastic optical fibre that subjected to pressure cause a change in the refractive index of the optical fibre. The changes of refractive index cause a change in the light mode propagation inside the optical fibre. This, in turn, causes the change of optical fibre's output power. Changes in the refractive index that occur in optical fibres can be calculated using the equation below:

$$\Delta n = \frac{n_i}{2} [P_{12}^2 v (P_{11} + P_{12})]$$

where

- $n_i$ = refractive index of core or cladding
- $P_{11}, P_{12}$ = optical strain coefficient (0.12 and 0.27)
- $v$ = Poisson Ratio (0.17)
- $\varepsilon$ = axial strain

The result of the linear regression of the optical fibre output power is equation (7) that can be used to determine the estimated soil moisture value (%VWC) based on the optical fibre output power.

![Regression of Sensor's Optical Data](image-url)
\[ P = (2.846 \times 10^{-10}) \times \%VWC + (1.02 \times 10^{-7}) \]

\[ \%VWC \text{ measurement} = \frac{P - (1.02 \times 10^{-7})}{(2.846 \times 10^{-10})} \] (7)

Based on the data obtained, the sensitivity of the sensor is \(2.885 \times 10^{-10} \text{ W/}%\text{VWC}\) based on equation (5). The distribution of error values can be determined by reducing the measured \%VWC value with the actual \%VWC as written in equation (3). The distribution of error values can be seen in Figure 12 where the fitting is carried out on the normal distribution curve. Based on the results of the fitting, the standard deviation obtained is 0.64.

![Figure 12](image)

**Figure 12.** Normal distribution of measurement error values.

A high \(R^2\) value indicates that plastic fibre optic has high potential to be used as a soil moisture sensor. Also, linear regression results show that there will be no overlap between the two power outputs. Another supporting factor is the reasonably low error rate distribution as an optical fibre sensor. Based on equation 4, 99.8\% of \%VWC measurement data errors will be below 1.921035.

### 5. Conclusions and Recommendations

Based on the results of measurements and data processing, it can be concluded that plastic optical fibre with U-bend structure has high potential to be used as a soil moisture sensor with a sensitivity of \(2.885 \times 10^{-10} \text{ W/}%\text{VWC}\) within \%VWC range from 15\% to 90\%. The Coefficient of Determination obtained from this measurement is 0.97, with a standard deviation value of 0.64. Some recommendations related to this research are listed as follows:

a. For minimising the presence of environmental disturbances by temperature is better to use the ratiometric measurement for the next research. The use of reference optical fibre as a ratiometric measurement can minimise environmental disturbances in the form of temperature.

b. Ensure that the soil is mixed well before repeated measurements

c. Provide holes to place the fibre optic when taking experimental data using optical fibre. This is better than having to push it to the ground because it can reduce measurement accuracy.
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