Development of a Two Waveband Infrared Optical Sensor for the Measurement of Soil Moisture Content

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Abstract- Water is an essential element necessary for plant growth, crop production, and the biological and chemical activities in soil. In addition, a good knowledge of soil moisture content in an agricultural field optimizes water usage for irrigation. There are many methods can be used to measure soil moisture content, however, these are time consuming, invasive, and laborious. In contrast, remote sensing techniques are fast, non-invasive, requires less sample preparation, and could be integrated in an on-line measurement system. In this study, an optical near-infrared sensor to predict soil moisture content using two wavebands, 1300 and 1350 nm is presented. The developed sensor comprised of a QTH light sources, two bandpass optical filters, and a photo detector made of germanium. The sensor was calibrated against 8 different soil moisture levels of *Silt Loam*. A multiple linear regression MLR model was established for the sensor which showed a good prediction accuracy with an R^2 and RMSE values of 0.94 and 2.26, respectively. In addition, a 1:1 comparison plot showed a good fit between actual measurements of soil moisture content and the predicted measurements using the sensor with an R^2 and RMSE values of 0.95 and 2.19, respectively. Overall, the sensor provided rapid and accurate estimation of soil moisture content in one soil type (*Silt Loam*). However, in future, it is recommended to consider other soil types when calibrating the sensor to investigate its suitability to measure soil moisture content in all soil types.

Keywords – Near-infrared spectroscopy, Soil moisture, Optical filter, Multiple linear regression, NIR reflectance

I. INTRODUCTION

Soil moisture is a key element that affects various environmental processes such as, plant growth, soil biological and chemical processes, erosion, and land-atmosphere heat and water exchange [1]. Hence, a good estimation of moisture in the soil provides good knowledge for understanding and modeling those processes [2]. Near-infrared (NIR) is the region of electromagnetic spectrum that ranges between 750 and 2500 nm. The interaction of infrared light with different constituents in matters make it possible to retrieve quantitative and qualitative properties [3]. Near-infrared spectroscopy has been in use since the 1970's for the evaluation of foods and forages [4-5]. Furthermore, it has been used for the detection of various soil properties such as, soil [6-7], soil texture [8], soil minerals [9-10] and soil organic matter [11]. There are many advantages for using NIR spectroscopy for analysis over conventional methods. NIR spectroscopy is fast, requires no or minimal sample preparation, time efficient, non-destructive, don't require use of environmentally harmful chemical extracts, and can be integrated in an on-line measurement processes [3, 12].

The use of NIR spectroscopy for measurement of soil moisture content have been reported in many studies. Weidong et al. [6] studied the relationship between soil moisture and reflectance in the NIR domain of spectrum. They used a single stepwise linear regression to correlate soil moisture to absorption wavebands. Their results showed an RMSE value better than 0.002. The reflectance measurements were normalized to eliminate the effect of soil type, roughness and measurement configuration. Bowers and Hanks [13] reported two noticeable soil moisture absorption wavebands related to overtones and combinations of fundamental vibrations of O-H functional groups centered at 1450 and 1950 nm. Several studies described the relationship between soil moisture content and NIR soil reflectance, stating that soil reflectance generally decreases with the increase in soil moisture content [14, 15].

The main objectives of this study were: (1) Investigate the correlation between soil moisture content and NIR reflectance using a VIS-NIR spectrometer and identifying the best correlating wavebands; (2) Develop a two-waveband NIR sensor for predicting soil moisture content for one soil type at eight different levels of moisture content; (3) Evaluate the accuracy of predicting soil moisture content using the developed sensor.

II. METHODOLOGY

2.1 Preparation of soil samples –

A bulk amount of Soil was collected from the Agri-life Research Farm at the Impact Center at Texas A&M University. Using hand-feel method, the soil type was determined to be *Silt Loam*. The bulk soil was then divided into 8 smaller soil samples each of 120 g in weight. Then, all soil samples were oven dried at 105 °C for 24 hours. After that, water was added and uniformly mixed with soil to create soil samples with eight different moisture content: 0, 4, 8, 12, 16, 20, 25, and 30% w/w wet basis. The percent moisture content (wet basis) in each soil sample was calculated using equation 1.

$$SMC = \frac{TSW - DSW}{TSW} x100\% \qquad (1)$$

Where;
SMC is soil moisture content [%]
TSW is total soil weight [g]
DSW is dry soil weight [g]

2.2. VIS-NIR Reflectance measurments –

In order to determine the best correlated wavelengths to soil moisture content, Agrispec™ VIS-NIR spectrometer (Analytical Spectral Devices Inc., Colorado, USA) was used to acquire reflectance measurements for the soil samples. Three replicates were used per soil sample and each replicate was scanned two times. Hence, the total acquired measurements for all soil samples were 48. The reflectance measurements were taken by placing 20 g of soil sample in a transparent petri-dish. The sample was then exposed to VIS-NIR light spectrum (350 – 2500 nm) and reflectance was recorded. Figure1 shows the collected averaged spectra for the soil samples at various moisture content.

2.3. Statistical analysis for VIS-NIR reflectance measurements

Multiple linear regression analysis was used to correlate soil moisture content to reflectance measurements acquired by the Agrispec™ spectrometer. The correlation coefficient r and coefficient of determination R^2 were used to evaluate the correlation strength and thus identification of the best correlated wavelength to moisture content. Statistical analysis was performed using R Statistical Software (version 2.14.0; The R Foundation).

2.4. Optical sensor design and layout-

2.4.1 Optical components-

The developed sensor comprises of two light quartz tungsten halogen lamps (QTH) as a light source (20 Watt each), a photo detector made of germanium (FDG03, Thorlabs Inc., New Jersey, USA), two bandpass optical filters, 1300 nm and 1350nm both of 12.5 mm diameter and 12 nm FWHM (Edmund Scientific, New Jersey, USA).
Energy transmittance calculations (Table 1) showed that energy transmitted through the 1300 nm optical filter (Figure 1.a) is higher than that passes through the 1350 nm filter (Figure 1.b). Since one of the wavebands will be used as a reference, both optical filters must pass equal reflected energy to the photo detector. In order to resolve this and based on the calculations, a neutral density filter of 0.1 need to be placed in front of the 1300 nm bandpass filter to compensate for this difference and make sure that both optical filters pass equal energy.

Table-1 Energy transmitted through 1300 nm and 1350 nm optical filters and ND calculation

WV(nm)	I	R	I*R	S	I*R*S	%B	%G	%R
1300	0.18	0.33	0.0594	0.86	0.0511	0.84	0	0
1350	0.17	0.325	0.0553	0.9	0.0497	0.73	0	0

Wavelength [nm]	Energy	Energy ratio (1300/1350)	Nd
1300	0.0429	1.19	0.1
1350	0.0361		

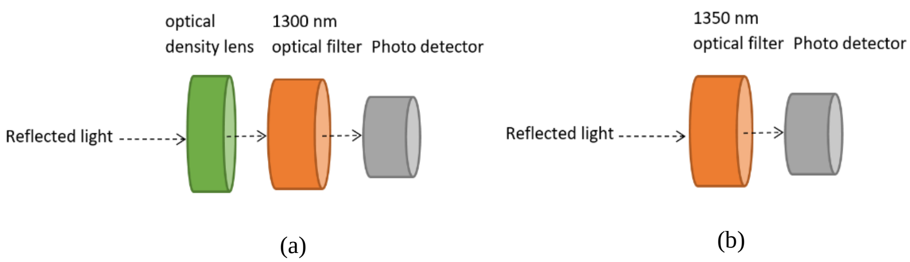

Figure1. Optical filters and photo detector assembly (a) 1300 nm (b) 1350 nm

2.4.2 Op-Amp Electrical circuit-

An Op-Amp circuit was designed to power the sensor and amplify the electrical signal produced by the photo detector. In addition, the circuit provides a filtering aid to minimize losses and improve signal to noise ratio. The Op-Amp circuit is comprised of an Op-Amp (LM2904), a resistor (75 kΩ), and a ceramic capacitor of 4700 pf (Figure 2). The supply voltage for the Op-Amp circuit is 12 VDC.

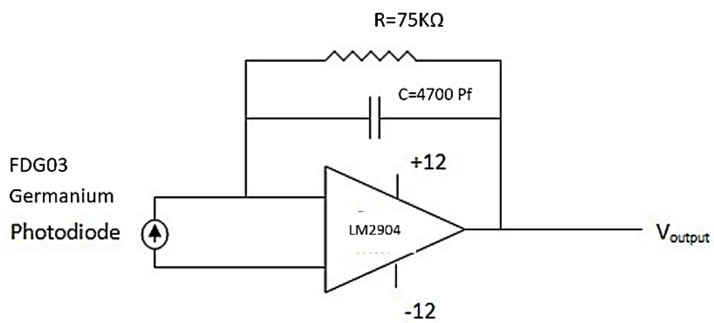

Figure 2. Sensor Op-Amp circuit

2.4.3.Overall sensor layout and experimental setup-

A metallic structure (housing) was fabricated to mount the optical filters assembly, photodiode, and the illumination sources (QTH lamps) above the soil sample tray (Figure 3). The photo detector is connected to the Op-Amp circuit and a voltage readout obtain the voltage output from the sensor.

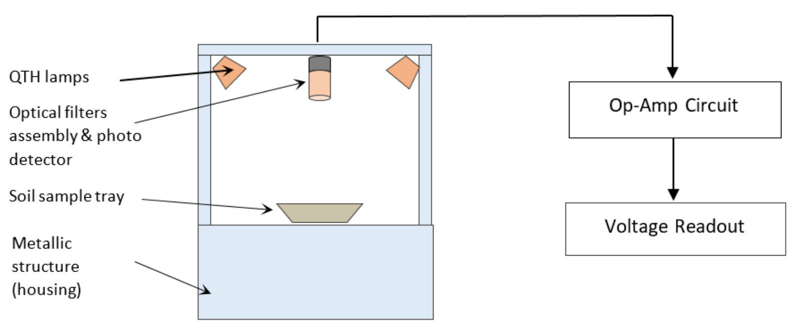

Figure 3. Overall sensor design and layout

2.5. Sensor measurements & statistical analysis-

Soil samples of *Silt Loam* with eight different soil moisture content were prepared. Those were: 0, 4, 8, 12, 16, 20, 25, and 30 % w/w wet basis. The measurement started by placing a100 g of a soil sample in the soil sample tray. Then, the soil sample was illuminated using the QTH lamps and the reflected light from the soil surface then received by the photo detector through the 1300 nm and the 1350 nm optical filters, sequentially. Two replicates per soil sample were used which makes the total measurements to 16. At the end of each measurement, the sensor voltage output was recorded which indicates the sensor's response to intensity of reflected light energy from the soil surface (Table 2).

Multiple linear regression analysis was used to correlate soil moisture content to sensor voltage output corresponding to 1300 nm and 1350 nm wavebands for all measurements using the Minitab statistical software. These analyses were used to establish a prediction model, and evaluate the sensors prediction accuracy using values of coefficient of determination R^2, and root mean of squared errors (RMSE).

III. RESULTS & DISCUSSION

3.1. NIR reflectance Spectra of soil samples-

Figure 4 depicts the reflectance spectra for all soil samples along the VIS-NIR spectrum from 355 to 2500 nm. It shows two main absorption bands for water in soil around 1450 nm and 1950 nm. This result conforms to findings by Bowers and Hanks [13], and Bogrekci and Lee [16]. Furthermore, it shows that soil samples with higher moisture content have lower reflectance whereas soil samples with lower moisture content have higher reflectance. The lowest reflectance occurred for soil sample with 30% w/w moisture content, whereas dry soil sample with 0% w/w moisture content produced the highest reflectance. Reflectance spectra for all soil samples had similar unique features with two obvious water absorption bands, around 1450 and 1950 nm.

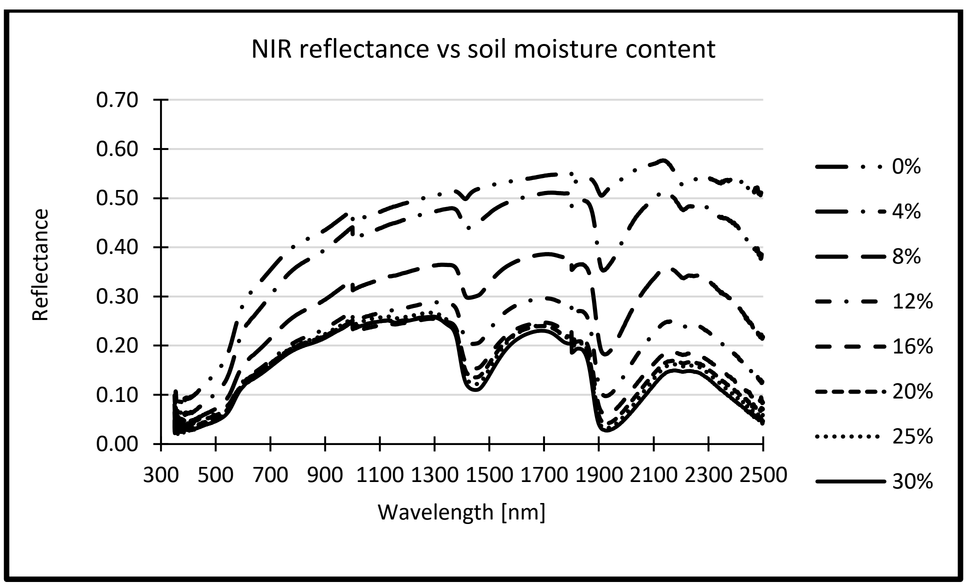

Figure 4. NIR reflectance of soil surface with various moisture content

3.2. Selecting the best correlated reflectance wavebands to soil moisture content-

Figure 5 shows correlation coefficient for correlating soil moisture content to reflectance along the VIS-NIR spectrum. The results show that, there is a negative correlation between soil moisture content and reflectance. In addition, the maximum correlation occurred around 1450 nm and 1950 nm whereas the lowest occurred around 600 nm. Due to considerations of high cost and lack of availability of optical components associated to 1450 and 1950 nm wavebands, it was decided to choose two alternative wavebands that have comparable good correlation with soil moisture content but with easy access to optical components and reasonable cost. These two wavebands are 1300 and 1350 nm.

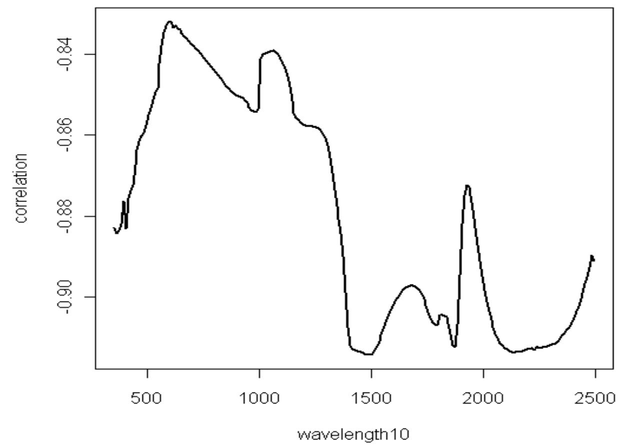

Figure 5. Correlation coefficient (r) between soil moisture content and reflectance along VIS-NIR spectrum

3.3. Results of the developed NIR optical sensor measurements and analysis-

3.3.1. Correlation of SMC and sensor voltage output using individual wavebands-

Table 2 shows soil moisture content in % w/w wet basis and the corresponding sensor's output voltage in mV for both wavebands, 1300 nm and 1350 nm collected using the developed sensor. Linear regression analysis was used to evaluate the response of the sensor and strength of correlation between soil moisture content and the sensor voltage output for both wavebands, individually. The results indicated an R^2 values of 0.94 and 0.87 for 1300 nm and 1350 nm wavebands, respectively (Figure 6). Furthermore, increasing soil moisture content, decreases the sensor voltage output for both wavelengths which indicates an inverse relationship.

Table-2 Sensor's voltage output at different levels of moisture content using 1300 and 1350 nm wavebands

SMC (%)	Voltage (mV)	
	1300 nm	1350 nm
0	16	24
0	18	26
4	14	24
4	16	24
8	15	30
8	15	24
12	12	20
12	12.2	20
16	7.8	12
16	5	12
20	3.8	6
20	3.8	6
25	2	8
25	2	6
30	0	2
30	0	2

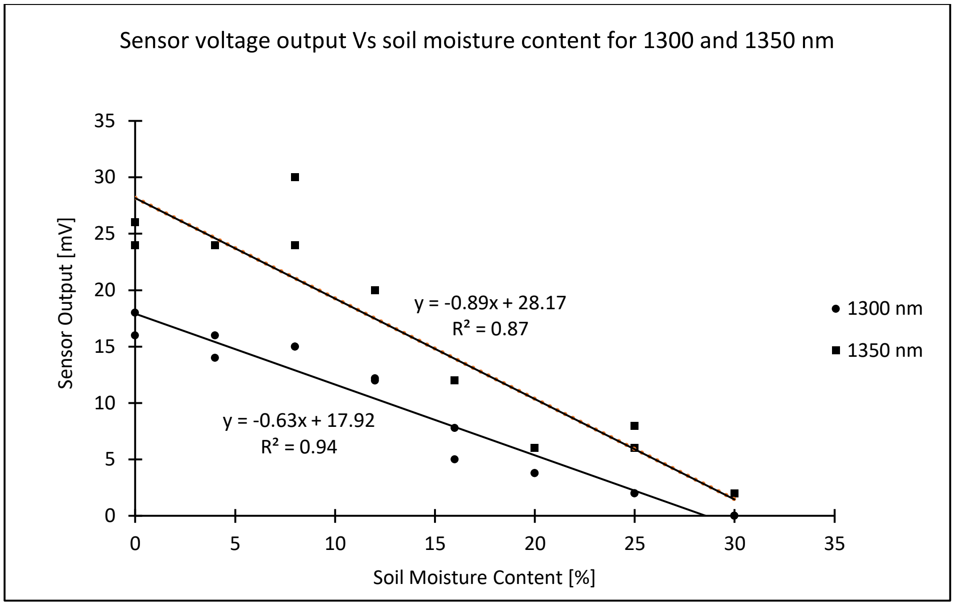

Figure 6. Regression lines of sensor output voltage and soil moisture content for 1300 & 1350 nm wavebands

3.3.2. Correlation of SMC and Sensor voltage output using both wavebands -

Multiple linear regression analysis MLR were used to produce a prediction calibration model for soil moisture content using both wavebands. The model's accuracy was evaluated using values of adjusted R^2 and RMSE. The results of the MLR analysis produced a highly linear model with an R^2 value of 0.94 and RMSE value of 2.26. The produced calibration model is shown in equation 2.

$$SMC = 27.2 - 1.84\, V_{1300} + 0.236\, V_{1350} \qquad (2)$$

Where;
SMC: Moisture content [% w/w]
V_{1300}: Voltage output using the 1300nm waveband [mV]
$V_{1350:}$ Voltage Output using the 1350nm waveband [mV]

3.3.3. 1:1 line of actual vs. predicted soil moisture content measurements-

A 1:1 line was used to compare the sensors predicted soil moisture measurements to the actual soil moisture measurements to evaluate the sensor's accuracy (Figure 7). The results show a strong linear correlation between sensors predicted soil moisture content using the developed sensor and the actual soil moisture measurements. The coefficient of determination R^2 and root mean of squared errors RMSE values were used to assess the sensor's accuracy compared to actual measurements. The plot shows high accuracy of prediction with an R^2 value of 0.95 and RMSE value of 2.19.

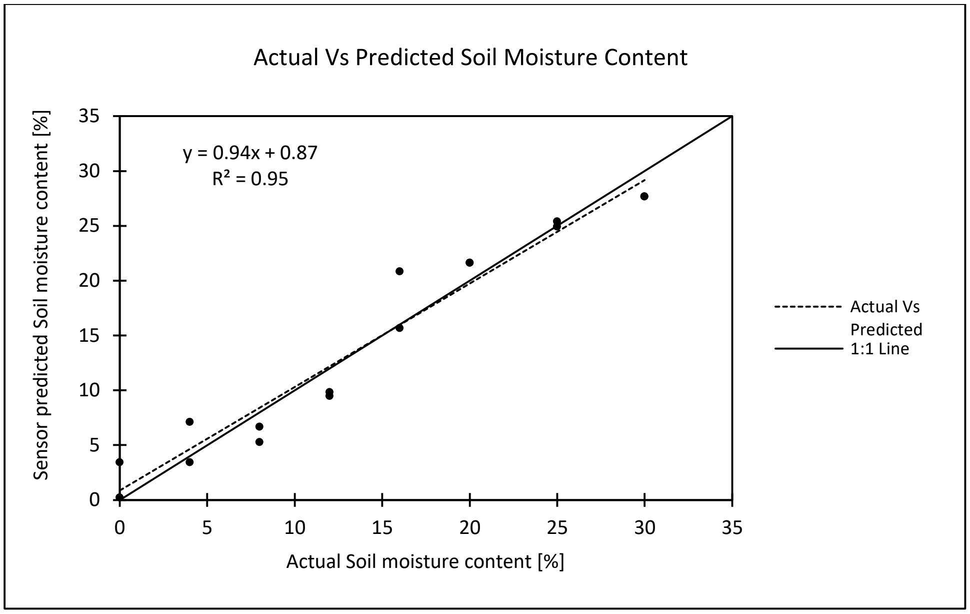

Figure 7. 1:1 line of sensor's predicted and actual soil moisture content measurements

IV.CONCLUSION

In this study, a two waveband optical infrared sensor was developed capable of estimating soil moisture content with high accuracy. The sensor uses two wavebands to predict soil moisture content, 1300 and 1350 nm. Based on statistical analysis, the sensor performed at high prediction accuracy with an R^2 and RMSE values of 0.94 and 2.26, respectively. In addition, a plot of the sensor's predicted and actual measurements of soil moisture content showed a good fitness with an R^2 value of 0.95 and RMSE value of 2.19. The developed sensor has the advantage of being able to be used for portable in-situ measurements of soil moisture content in a field or to be installed in an on-line measurement and control system that provides instantaneous and continuous measurements of soil moisture content in an automated process. However, the developed sensor was only calibrated to predict moisture content for one soil type (*Silt Loam*) and does not account for variations that may arise when used to estimate moisture content in other soil types. Thus, in future, it is recommended to calibrate the sensor against more types of soils to produce a universal model.

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