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Development of a Low-cost Multi-Depth Real-Time Soil Moisture Sensor Using Time Division Multiplexing Approach

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ABSTRACT Soil moisture (SM) is an integral parameter for scheduling irrigation. The precise and real-time measurement of SM is difficult due to its complex nature. The purpose of this study was to determine whether the time division multiplexing (TDM) approach would effectively estimate SM content. We developed a sensor to detect SM from four soil depths (10, 20, 40, and 60 cm) simultaneously by using the TDM technique. This is a type of EM sensor that indirectly estimates the SM on the basis of the dielectric properties of soil. Three types of soil samples were used to calibrate the sensor. The calibration models were established using polynomial (3^{rd} order) fitting equations. The performance of the sensor was evaluated both in laboratory and *in situ* conditions. The sensitivity of the sensor was examined in a micro-control irrigation system. The sensor measured SM contents in a soil box were compared with HYDRUS-2D simulated wetting patterns. The results were in the optimal range, and coefficient of determination (R^2) ranged from 0.97 to 0.99 and root means square error (RMSE) from 0.72 to 2.01. The TDM detection circuit based sensor R^2 value was 0.97, and its RMSE was 2.78. Whereas the independent detection circuit R^2 values ranged from 0.93 to 0.96 and RMSE from 4.09 to 5.07. The results determined that the sensor could be used for continuous SM measurements, which would be advantageous for planning the irrigation practices in arid and irrigated regions.

INDEX TERMS Dielectric sensor, multi-depth, micro-control irrigation, soil moisture, time division multiplexing

I. INTRODUCTION

Soil moisture (SM) is an integral part of plant life, which directly affects crop growth and yield, as well as, irrigation scheduling. The vertical profile of SM is very complex and driven by various factors such as soil texture, irrigation, environmental conditions, and it varies with depth, significantly. Therefore, the continuous and precise *in situ* SM measurement poses various challenges [1-6]. In recent years substantial advances have been made in the field of SM measurement technology. Generally, proximal and remote sensing measurements have been used to quantify the available amount of SM in the vertical profile [7-10]. Since the late 1980s, advancements in technology have made SM measurements more practical especially dielectric methods are very effective. Various electromagnetic (EM) approaches have been applied to measure the SM on a commercial scale, which gained much popularity due to less cost and training. The EM sensors monitor SM on the basis of electrical signal response. They typically consist of plastic access tubes, inserted vertically into the soil to measure the moisture content. The capacitance sensors function on frequency signals, which are affected by soil dielectric constant [1, 4]. Capacitance and time domain reflectometry (TDR) sensors are widely used for SM monitoring. Some other popular SM sensors include multisensory capacitance probes (MCAP), surface capacitance insertion probes (SCIP), impedance probes, tensiometers, resistance blocks, heat dissipation sensors, ground penetrating radars (GPR), and electrical resistivity tomography (ERT) [7-9, 11, 12]. However, the *in situ* precise and long-term SM measurements have not been satisfactory through the available sensors. This is either because of their high cost, uncanny accuracy or high time-consumption. TDR is influenced by the irregular bulk density of porous medium and expensiveness. ERT sensors are complex and cause erroneous measurements in the deep soil profile [13, 14]. Performances of four EM and a neutron sensor were investigated during different seasons. Moreover, EM sensors readings were influenced by the heterogeneous dry and wet zones, resulting in misestimations (over/under-estimations) even when site-specific calibrations were used [15-18]. Furthermore, EM tube based sensors are not economical as they require 2 to 72 sensing tubes (or even more for drier soils) to measure SM precisely. Apart from that, the installation location of the access tube could also affect the sensor accuracy. It was observed that capacitance sensors produce erroneous results due to soil bulk density, conductivity, temperature as well as variation in soil structure [19, 20]. In addition, complex circuitry paraphernalia is also an issue with multi-depth moisture sensors, which is caused by the mutual interference of the multiple circuits. Capacitance sensors are also affected by their circuits' internal temperature discrepancies and electronic noise [8, 15, 21]. Multiple circuits also cause erroneous measurements in long-term installations. Moreover, EM field exhibits interferences when the electrical statistics of the material changes [22]. Micro-control irrigation system is very popular in arid regions due to high water use efficiency. In this system, a spongy, permeable tube is installed at a certain depth in the soil, and the surface normally remains dry. The installation depth drives the moisture distribution. In recent studies, sensor measured SM contents in the soil box have been compared with the HYDRUS-2D simulated wetting patterns [23, 24]. HYDRUS-2D is Windows-based computer software used for numerical simulation of the moisture, heat, or solute distribution around the variably-saturated porous tubes installed at different soil depths. The dielectric sensors have significant advantages as they can measure the moisture contents from multiple soil depths using high-density electrodes with minimum soil disturbance. The use of high-low frequency measurements and other popular methods have been studied extensively. However, time division multiplexing (TDM) based capacitance sensors have hardly been considered [25].

The objectives of this study were: (i) to design and develop a low-cost and high-resolution TDM sensor to quantify moisture contents from four vertical soil depths, i.e. 10, 20, 40, and 60 cm; (ii) to analyze the effects of micro-control irrigation on the sensor's sensitivity; (iii) to compare the sensor measured SM values of a micro-control irrigation system with the HYDRUS-2D simulated wetting patterns; (iv) to calibrate the sensor with different soil types, and evaluate the performance of the sensor in heterogeneous moisture conditions; and (v) to compare TDM detection approach with the available multi-depth detection circuits.

The structure of this paper is as follows. Section I introduces the motivation of this study and also some relevant literature. Section II describes the system composition and development of the sensor, mainly including the measurement principle, TDM approach. Section III includes soil sampling and sensor calibration process. Section IV predominantly includes the sensor performance tests (laboratory and open filed), sensitivity evaluation in micro control irrigation system and HYDRUS simulations. In Section V, some results and discussion of different tests are provided, while Section VI shows the conclusions of the research.

II. METHODOLOGY

A. SYSTEM COMPOSITION

The developed sensor consists of data acquisition, wireless communication, a cloud server, and the user terminal. The sensor includes various units such as sensor acquisition unit (SAU), detection tube, radiofrequency (RF), wireless communication unit (Wi-Fi/GPRS), micro-processing unit (MCU), A/D conversion and voltage signal. The data acquisition unit processes the collected data and transmits to the user terminal via Wi-Fi/GPRS. The power supply unit (PSU) provides power to other modules. The input voltage of PSU is provided with 3.6v batteries and equipped with photovoltaic cell for charging the batteries. PSU is elevated from 3.6v to 5v through a voltage pump in order to supply power to SAU. The sensor can measure SM and temperature at 10, 20, 40, and 60 cm soil depths, simultaneously. Figure 1 shows the block diagram of the sensor. For the experiment, the sensor with four perception rings was housed in PVC assess tube having 36 mm inside and 39 mm outside diameter. The tube was enclosed by identical stainless steel moisture sensing rings Cx1~Cx4 and four temperature sensitive resistors RT1~ RT4. The perception rings formed a capacitor that generated an EM field around the tube, which depended on dielectric constant. Figure 2 shows layout of the sensor whilst practical installation of the sensor is shown in figure 3. The sensor output was in DC voltage, which was converted to SM by the calibration equations, already embedded into the sensor.

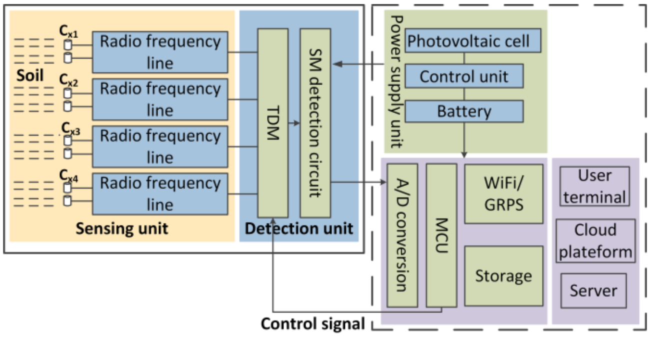

FIGURE 1. System block diagram.

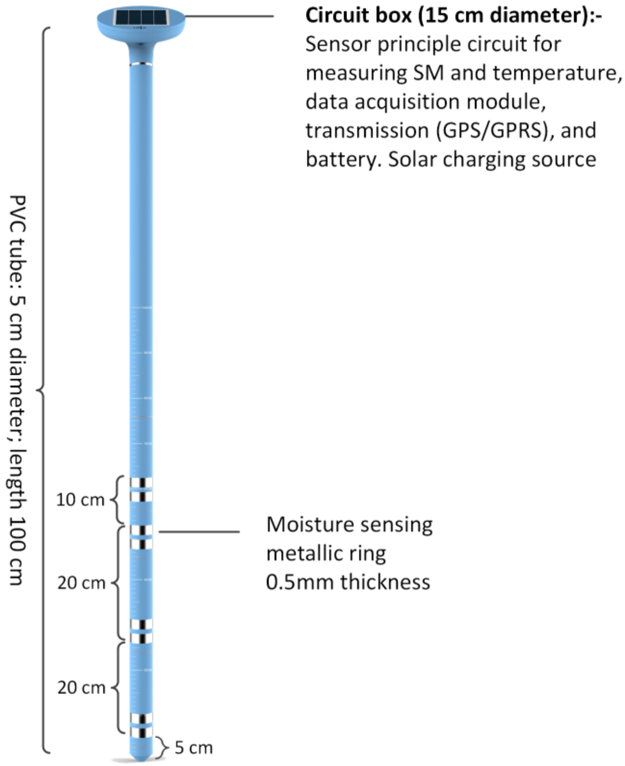

Figure 2. Practical figure.

FIGURE 3. The developed sensor was installed in an open field to measure the SM.

B. SENSOR MEASUREMENT PRINCIPLE

A multi-depth (4 depths) SM sensor was designed and developed in this study. This is a type of EM sensor that indirectly estimates the SM on the basis of the dielectric properties of soil. The permittivity of various media also varies as of water it is 80, dry soil ranges from 2.4 to 3.5, and for soil minerals, it ranges from 2.7 to 5.0. Therefore, the change in SM will influence the soil permittivity [26, 27]. The capacitance can be estimated by two methods. One is the traditional method that uses the frequency measurement technique. The frequency varies with capacitance, which is influenced by the permittivity of the medium [1]. The second method calculates the electrical impedance of the soil at a definite excitation frequency. The developed sensor functioned on 100MHz frequency [28-31]. Figure 4 describes the principle circuit for SM monitoring. It uses a double-resonance circuit and two resonance frequencies. The sensing probe (Cx representing capacitance) connected to C11 in parallel. Cx is related to the available SM contents. The capacitance decreased when the sensor was placed in air or in dry soil. The u2 amplitude would be slightly greater than u1. The first resonance is depended upon Cx which increases with the increase in SM. L1 and C11 resonate in series at a signal frequency of 100 MHz, and $|u_1| = |u_2|$ approximately. The Cx increases with the increase in SM and C11, L1 parallel with Cx detuned. The second resonance occurs when voltage at u1 increases whereas at u2 decreases with SM. Meanwhile, U1gradually approaches to equivalence, i.e. $|u_1| = |u_0|$. C7 resonate parallel with L1 which is connected in series to Cx and C11. The high-frequency signal can pass through C11, C12, and C13, but not the DC signal. Furthermore, the circuit has four protective resistors i.e. R3, R5, R6, and R7. They prevent breakdown due to over-voltage. Another resistor (R2) is installed to protect oscillator (I1) from excessive current damage when the circuit is in parallel resonance. The u1 and u2 are added to the detection circuit to detect the voltage amplitude at U1 and U2, respectively. Differential amplifier output U_{out} is expressed by equation (1):

$$U_{out} = k(U_1 - U_2) = K\Delta U \quad (1)$$

The change in Cx will change U_{out} due to the variation in soil permittivity. The double resonance circuit improves the sensitivity of the sensor. Therefore, when Cx has a small change (moisture = 0.1%) it will affect bothU1 and U2.

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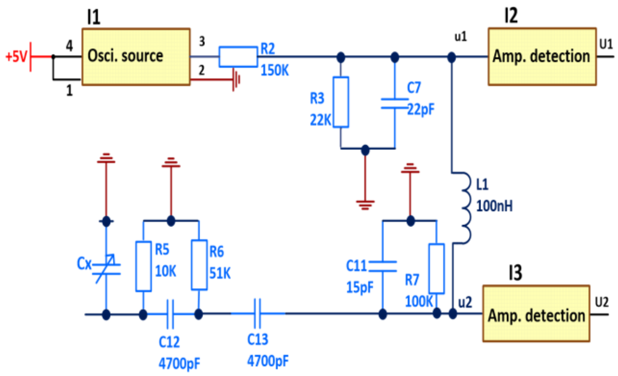

FIGURE 4. SM detection principle circuit.

C. TIME DIVISION MULTIPLEX (TDM) DETECTION TECHNIQUE

TDM is an authentic approach having better performance than conventional methods. Furthermore, it provides ease of error detection and correction [32, 33]. The TDM technique was used to develop a single detection circuit to measure SM in the vertical profile. This single detection circuit could measure the SM from specified depths one by one. TDM gates were used to select the measuring depth at a time interval of 50 milliseconds. The prevailing multi-depth moisture monitoring sensors use a couple of sensing loops and multiple detection circuits for each depth, which causes complex circuitry paraphernalia [8, 15]. Furthermore, the mutual interferences might be generated by the integration of multiple detection circuits that could affect the sensor efficiency [4]. The TDM multi-depth selection chip is shown in figure 5. The layout of TDM and available multiple detection circuits based sensor is shown in figure 6(a) and (b) respectively. The TDM sensor is simple and easy to install, and it detects SM at 4 different soil depths simultaneously rather than using 4 individual sensors at the same time or a sensor having multiple circuits for each depth.

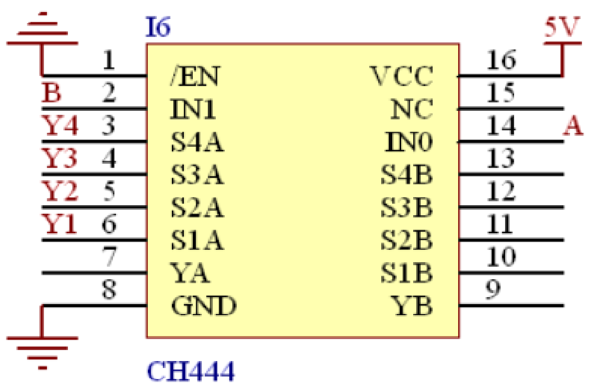

FIGURE 5. TDM multi-depth selection chip.

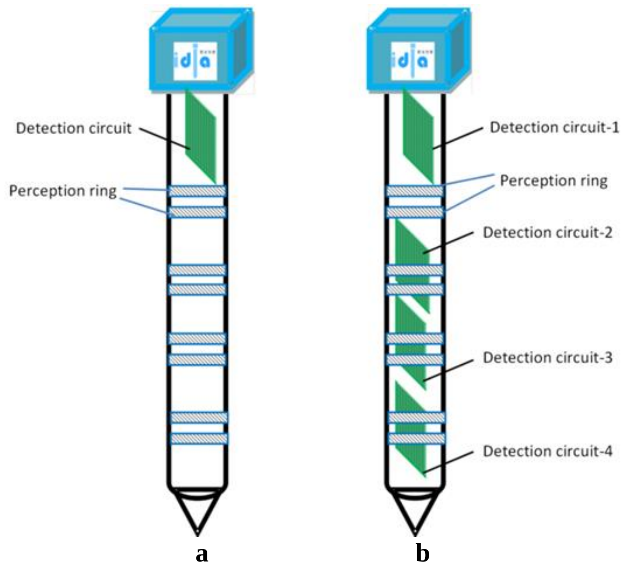

FIGURE 6, **The internal layout of two access tubes, (a) TDM based multi-depth SM monitoring sensor layout; (b) available multi-depths SM sensors layout.**

III. SOIL SAMPLING AND PREPARATION

SM monitoring is essential for scheduling water balance and irrigation events. Soil samples were taken at uniform depth from three topographical regions of China; Beijing (39°90‘N, 116°39‘E), Hebei (39°47‘N, 115°85‘E), and Yunnan (25°03‘N, 102°71‘E). The collected soil samples textural composition is given in table 1.

TABLE 1
THE TEXTURE OF THE SOIL SAMPLES COLLECTED FROM DIFFERENT EXPERIMENTAL LOCATIONS

Location	Sand (%)	Silt (%)	Clay (%)	Soil type
Beijing	68	25	7	Sandy loam
Yunnan	30	15	55	Clayey loam
Hebei	60	10	30	Sandy clay loam

A. SENSOR CALIBRATION EXPERIMENT

A systemized calibration procedure was adopted to calibrate the sensor [34]. Soil samples were crushed dried and sieved (1mm × 1mm size). In order to measure original moisture contents, the soil samples were oven-dried at a temperature of 105 ℃ for 48 hours. They were then cooled down at room temperature, shifted layer by layer to PVC containers of 18×18×18 cm dimensions, and compacted by hammering. The sensor, composed of four perception rings, was installed in a container and readings were recorded at 15 minutes intervals [34]. During the calibration process, the containers were irrigated from the top by drip emitters. Soil samples were taken out by inserting a push probe (with inside and outside diameter of 36 and 39 mm, respectively) near the installed sensors to calculate actual moisture contents and gaps were filled by the equivalent soil and compacted. The same calibration procedure was repeated for all the collected soil samples. The calibration functions were obtained by fitting the estimated and pooled data using polynomial (3rd order) equations [35]. The pooled data were acquired by averaging the sensor output voltage, and volumetric water contents (VWC) of all soil samples. The R^2 and RMSE values of the data were calculated. However, the field-specific calibrations are recommended when the sensor is used in the field, especially where the SM contents are high.

IV. PERFORMANCE TESTS

Three sets of experiments were carried out to examine the performance of the developed sensor. The experiments were conducted both in the laboratory and open field conditions. The sensor's sensitivity, TDM detection consistency, stability, error rate; transmission accuracy was tested. Soil samples were taken out by inserting a push probe near the installed sensors, and actual SM values were calculated by oven drying method (mentioned earlier). The sensor measured SM values were compared with actual SM values of soil samples after employing oven drying method.

A. TIME DIVISION MULTIPLEXING BASED CIRCUIT LABORATORY TESTS

A systematic process was followed to examine the measurement consistency and sensitivity of the TDM based detection circuit. The detection consistency of the TDM based circuit was tested and compared with the available detection circuits, which we developed ourselves. Nine samples (18Kg each) of Beijing soil with different moisture contents were prepared by oven drying as shown in table 2. The samples were loaded into a PVC container and pooled output calibrated TDM and available sensors were installed. The output voltages of both sensors were recorded at the 15 min interval, and polynomial (3rd order) [35] analysis was investigated to calculate R^2 and RMSE values. In addition, the TDM based sensor measured moisture contents were compared with the laboratory measured VWC. The linear fit analysis was investigated and R^2 and RMSE values were calculated, respectively. Moreover, the sensitivity of the developed sensor was tested in the micro-control irrigation system. This is a new type of water-saving technology, where the water infiltrates slowly. The experiment was carried out from December 2017 to the mid of January 2018. The experiment was conducted in a Plexiglas box of 10 mm thickness and 60×60×60 cm dimensions. First of all, Plexiglas box, inner walls were treated with Vaseline to minimize any preferential flow along the walls. The sieved and oven dried Beijing soil was filled into the box. Two TDM based sensors (pooled output calibrated) were installed in the soil filled box at six different depths (5, 10, 20, 30, 40, and 50 cm) to measure the moisture contents all day long at 1hour intervals. The soil filled box was sealed with a plastic sheet to prevent evaporation. The first sensor was installed at 5, 20, and 40 cm, whereas the second one was installed at 10, 30, and 50 cm depths, having 10 cm horizontal distance between them. In the center of the soil filled box, a microfluidic porous 52 cm long tube was installed at 50 cm depth from the top. Two systematic openings were made on two side walls of the box. The porous tube installed at 50 cm depth was connected with a water reservoir (Markov bottle with 5 mm wall thickness) through a PVC pipe of 160cm length [24]. The wetting patterns could easily be monitored from the glass walls. The wetting patterns were numerically simulated by using HYDRUS-2D. The simulated SM values were compared with the sensor measured moisture values to examine the monitoring sensitivity of the developed sensor. The experimental layout (water reservoir connection and locations of SM sensors) is shown in figure 7.

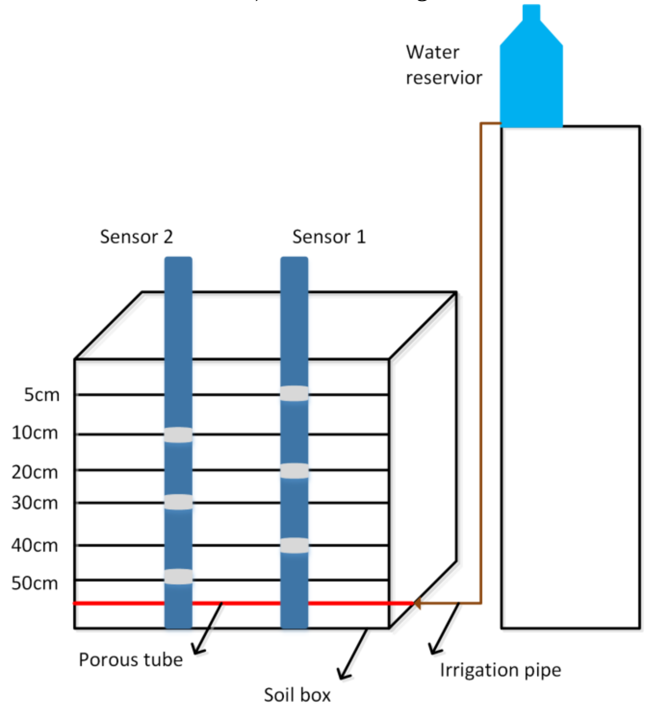

FIGURE 7, The experimental layout of sensitivity test with connected water reservoir and locations of SM sensors

TABLE 2

THE RELATIVE MOISTURE CONTENT OF SOIL SAMPLES COLLECTED FROM BEIJING AREA

Soil sample number	Volumetric moisture (cm3.cm-3)
1	0
2	9.6
3	14.5
4	20.0
5	25.0
6	28.0
7	32.1
8	36.3
9	43.0

1. HYDRUS SIMULATION

Since one porous tube was used in the experiment, the water movement and its infiltration processes could be taken as symmetrical, assuming that the soil was uniform, and neglecting the evaporation, as the soil box was covered with a plastic sheet. The following Richards equation (2) was used [23, 24].

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}[K(\theta)\frac{\partial\psi_m}{\partial x}]+\frac{\partial}{\partial y}[K(\theta)\frac{\partial\psi_m}{\partial y}]+\frac{\partial}{\partial z}[K(\theta)\frac{\partial\psi_m}{\partial z}]+\frac{\partial K(\theta)}{\partial z} \quad (2)$$

Where $\theta(cm^3.cm^{-3})$ represents the VWC, t is the time, x describes the horizontal coordinate, z is the vertical coordinate assumed to be positive, h (cm) is the pressure head, $k(cmd^{-1})$ is the unsaturated hydraulic conductivity. The hydraulic conductivity and soil water retention were determined through the HYDRUS-2D software using Van Genuchten (1980) analytical equations (3) and (4).

$$\theta=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{\left[1+|\alpha h|^n\right]^m} & h<0\\ \theta_s & h>0\end{cases} \quad (3)$$

$$K(\theta)=K_sS_e^{\lambda}\left[1-\left(1-s_e^{1/m}\right)^m\right]^2 \quad (4)$$

Where S_e is the relative saturation; K_s is the saturated hydraulic conductivity, θ_r and θ_s represent the residual and saturated water contents $(cm^3.cm^{-3})$, respectively, α is related to the air entry, and m represents Van Genuchten-Mualem shape parameters. The pressure head was taken constant during the simulations. During the irrigation, the flux was set to zero, and "free drainage boundary condition" was set as bottom boundary. The surface boundary condition was also assigned with zero flux. The water flow was numerically controlled, and the surface evaporation was negligible due to plastic sheet cover. All numerical simulations were carried out with similar initial and boundary conditions to simulate the situations closer to the real environment, an "atmospheric boundary condition" was set when the simulation duration was 120 h. Daily variations of evaporation were ignored. The atmospheric upper boundary condition is defined by the potential evaporation and potential transpiration.

B. OPEN FIELD EXPERIMENT

This experiment was carried out in an open field of Jiaxing city (30°45'N, 120°45'E) having heterogeneous moisture conditions. A pooled output calibrated sensor was installed, and SM was measured at 10, 20, 40, and 60 cm depths all day long at hourly intervals from May to June 2018. During the experiment, the field was irrigated with canal water. Although the soil in the research site was uniform loamy, to reduce estimation error due to variations in soil texture and bulk density, soil samples were collected from the vicinity of the installed sensors.

V. RESULTS AND DISCUSSION

A. SENSOR CALIBRATION

The calibration experiments were conducted with different soil samples (Hebei, Beijing, Yunnan) and pooled data. The sensor measured voltage and SM contents were fitted using polynomial (3rd order) equation. Figure 8 shows the calibration curves and the corresponding equations are shown in table 3. Where x was the output voltage (mV) and y was the SM contents. The R^2 values ranged from 0.97 to 0.99 and RMSE was ranging from 0.72 to 2.01. The variations in the results were due to the soil types [25].

TABLE 3
SOIL MOISTURE SENSOR CALIBRATION POLYNOMIAL (3RD ORDER) EQUATIONS

Polynomial (3rd order) plot	Equation	R2	RMSE
Pooled output	y =-177.24x3+ 197.04x2 -1.48x-0.04	0.99	0.72
Hebei soil	y =-83.99x3 + 125.45x2 -0.17x +0.02	0.98	1.89
Beijing soil	y = -206.55x3+ 231.81x2 -8.38x +0.11	0.99	0.97
Yunnan soil	y = -64.57x3+ 45.48x2 + 52.38x -0.79	0.97	2.01

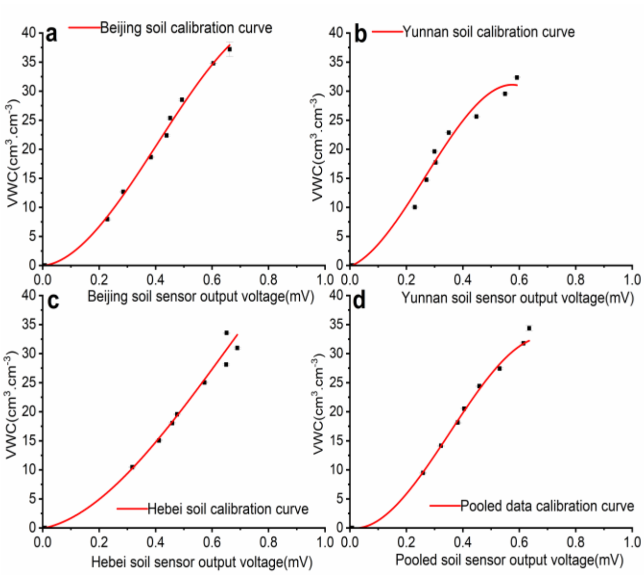

FIGURE 8, TDM based sensor calibration curves of soil moisture from soil samples of different geographical locations.

B. PERFORMANCE TESTS MEASUREMENT RESULTS

Three different tests were conducted both in the laboratory and open field to examine the sensor's consistency; sensitivity and adaptability with the system, error rate, and transmission accuracy were tested.

1) LABORATORY TESTS MEASUREMENT RESULTS

The monitoring consistency of both the sensors was compared. TDM and independent detection circuit based sensors (pooled output calibrated) were installed in containers to measure SM simultaneously. The recorded output voltages of both sensors were linearly fitted. Figure 9 shows polynomial (3rd order) curves, and the corresponding values are shown in table 4. The independent moisture detection circuit R^2 values ranged from 0.96 to 0.98, and RMSE values from 2.51 to 3.91. The TDM moisture detection circuit R^2 value was 0.99, and RMSE was 1.31. Furthermore, TDM based sensor measured moisture contents at 10, 20, 40, and 60 cm depths were linearly fitted and compared with actual VWC as depicted in figure 10. Where x axis was the actual VWC and y axis was measured moisture contents. The R^2 value was 0.98, and the RMSE value was 2.33 that corresponds to SM.

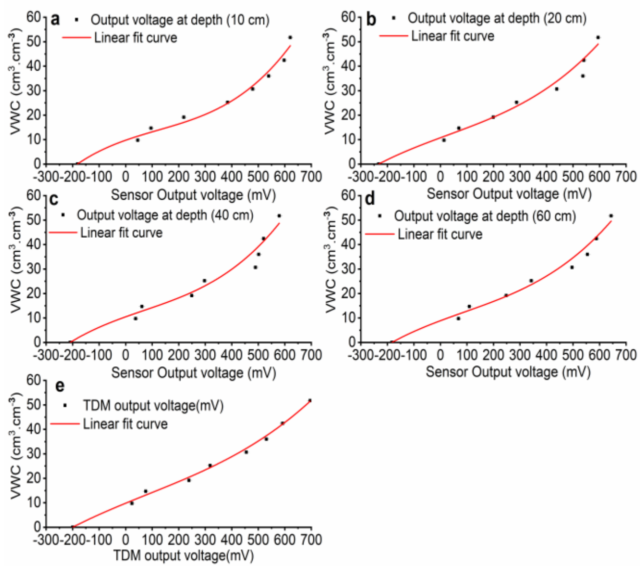

FIGURE 9, TDM based and independent detection circuit sensor consistency comparison test results.

TABLE 4
TDM AND INDEPENDENT DETECTION CIRCUITS' CONSISTENCY TESTS POLYNOMIAL (3RD ORDER) RESULTS

Polynomial (3rd order) plot	R2	RMSE
Depth (10cm)	0.98	2.51
Depth (20cm)	0.97	3.39
Depth (40cm)	0.96	3.91
Depth (60cm)	0.98	2.51
TDM	0.99	1.31

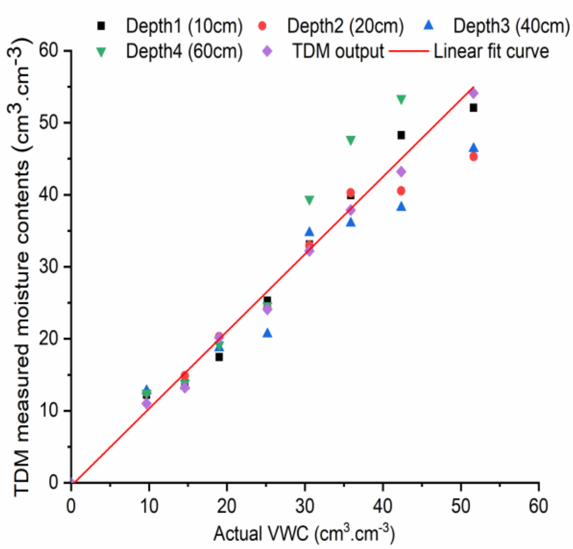

FIGURE 10 A comparisons between the TDM based sensor measured moisture content with actual VWC.

The results showed that the maximum R^2 value of the present circuits was less than the TDM R^2 value. The

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minimum RMSE value was also greater than the TDM RMSE value. The available sensor used independent detection circuits for each depth, which had inconsistent components. Therefore, the output was influenced by the mutual interference of circuits and circuitry paraphernalia, whereas the TDM sensor had a single detection circuit and had a negligible effect of mutual interference of internal circuit and circuitry paraphernalia. Thus, TDM sensor measurements were more precise. The results determined that the TDM technique based detection circuit's design and fewer components further improved the sensor measurement accuracy and consistency. Moreover, it was easy to handle and reduced the sensor manufacturing cost as well. Furthermore, the sensitivity of the developed sensor was investigated in a micro-control irrigation system. For convenience, the sensor measured moisture contents data were simplified to daily intervals, by averaging the 24 hourly taken moisture contents readings. A direct comparison between the HYDRUS-2D simulated moisture contents and sensor measured moisture contents in the soil box at different depths is presented in figure 11(a) and (b).

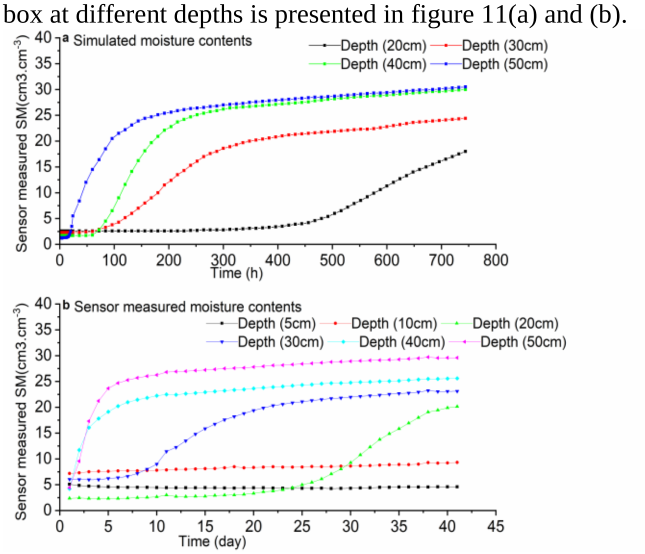

FIGURE 11, Sensitivity test results, a direct comparison of HYDRUS simulated moisture contents (a) with sensors measured moisture contents (b) in a soil box.

The sensor measured moisture contents were in close agreement with simulated moisture patterns [36, 37]. The measured moisture contents were simulated only for four major depths, i.e. 20, 30, 40 and 50 cm because the sensor at 5 and 10 cm depths showed similar results during the study. They showed a negligible change; because the capillary (upward) moisture movement was very slow due to gravity, whereas, at 20, 30, 40 and 50 cm depths, the sensor monitored the major wetting patterns, as shown in figure 11(b) [38]. The moisture contents at 40 and 50 cm depths showed significant change with the time. On day 5, a major increase in moisture contents was noted at 50 cm depth, because there was a shorter distance from the porous tube, and the dielectric sensors are biased towards high moisture magnitudes [39]. After the 15th and 30th day, the moisture contents at 30 and 20 cm depths showed smaller deviations. As the distance from the porous tube increased, the upward water contents decreased due to slow upward infiltration. The results revealed that after the 40th day, the wetting patterns at 30, 40 and 50 cm depths were relatively stable, as the soil was saturated [24].

2) OPEN FIELD EXPERIMENT MEASUREMENT RESULTS

Figure 12 shows some moisture profiles measured by the developed sensor at 10, 20, 40, 60 cm soil depths. The sensor captured major SM patterns at all depths. The measurements were plausible, and the different depths with their specific moisture contents were clearly recognizable. The recorded moisture profile exhibited dynamic variations near soil surface due to environmental conditions but was stable deeper in the soil. The measured SM values at 10 and 20 cm depths showed bigger fluctuations than the lower depths. This is acceptable because shallow soils lose moisture contents easily and cannot retain as much water as those at deeper levels. The variations in SM measurements were due to irrigation because the EM field potentially penetrates into wet zones. Therefore, any change in the moisture profile would affect the sensor readings [39-42]. However, at 40 and 60 cm depths sensor's performance was stable compared to the upper points. The small deviations in sensor measurements could be attributed to the complex movement of SM in the vertical profile [28, 43-45].

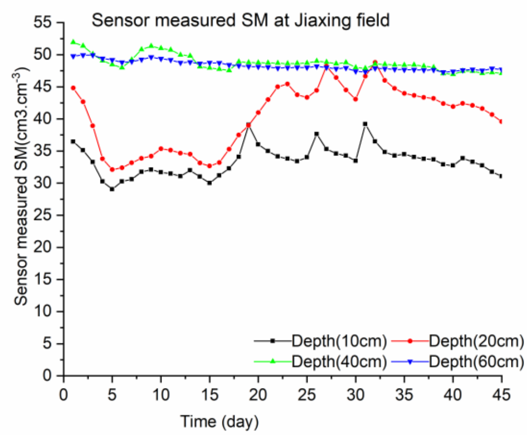

FIGURE 12, Multi-depth soil moisture contents measurements in open field at Jiaxing.

The results depicted that the sensor performed efficiently during the study period. Its findings were corroborated by our experiences and the temporal variations in moisture contents. They had a close agreement with simulations and reference findings. However, at some points, the measured moisture contents showed slight variations, which might be due to the field conditions [21, 41, 46]. The experiments result illustrated that the developed sensor could capture the major magnitude of SM in vertical profile in different terrain conditions. Moreover, an un-calibrated sensor can be

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used for irrigation purposes but it limits the accuracy of research work [47].

VI. CONCLUSIONS

The paper presents the design and development of a new, low-cost and multi-depth SM sensor, based on TDM approach. The sensor was calibrated with three soil samples whilst pooled data calibrated sensor exhibited good results. The sensor performance was thoroughly examined in laboratory as well as *in situ*. The following conclusions were reached.

(1) Due to the less circuitry paraphernalia, the developed sensor was so versatile in performance that it was negligibly affected by instrument's internal variability, circuit temperature dependencies, and soil electrical properties Moreover, our sensor is more economical than all the other prevailing ones, as it has one detection circuit (instead of several) that reduces cost and power consumption. Furthermore, the sensor tubing is done with strong PVC material that makes it durable and reliable.

(2) The sensitivity of the sensor was examined in a micro-control irrigation system and the test results indicated that the sensor measurements were in close agreement with HYDRUS-2D simulations. The laboratory and *in situ* experiments results were also plausible and the sensor performed equally well during the whole study period.

(3) The four months' results showed that the sensor could work consistently with 2100mAh/3.6V battery. Nevertheless, the sensor is equipped with photovoltaic cell for charging the sensor battery for as long as it is needed. It was advantageous for continuous and precise SM estimations in different soil horizons, and sensitive enough for arid and high moisture conditions. However, it would be logical to recalibrate the sensor under actual field conditions.

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