A VERSATILE ELECTRONIC INTERFACE FOR SOIL QUALITY

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ABSTRACT

Soil is the most vital component of today’s agricultural system. Monitoring soil quality can improve crop/fruit quality while minimizing unnecessary use of natural resources. Existing soil sensors can monitor basic soil parameters but usually the cost of the electronic interfaces required to run the sensors are more expensive than the sensors. Furthermore, sensors lack repeatability in their properties and their interfaces are not versatile enough to accommodate for that. The objective of the project was to design and assemble a versatile and low-cost, electronic interface for an existing soil-sensing array. The interface has been designed based on the operating principles of the sensors and the performance of the circuits has been simulated to meet the application’s specifications. The circuits have been assembled on a Printed Circuit Board (PCB) using discrete components and the PCB is powered through a USB or BNC connection.

Index Terms— Soil sensor, soil quality, sensor interface

1. INTRODUCTION

Mother nature has been feeding us since our arrival on planet earth. From herbs, to fruits, to vegetables, these are only very few of the foods we need to stay healthy. However, nowadays more and more people tend to face health problems, mainly because of their nutrition and the quality of the products they consume as part of their daily routine. Every food on our planet depends on soil quality, directly or indirectly. As a result, soil is considered as the world’s most vital “tool” for food and fiber production, hence playing a critical role on plant health and crop quality [1]–[4]. The increasing population of our age increases the need for nutrition from natural products, putting increasing pressure on the farmers. Farmers of the future want to monitor soil parameters as part of their effort to maximize their production efficiency and quality. Soil parameters such as water content, salinity, temperature, microorganism population, pH, concentrations of basic nutrients like nitrates and phosphates, are some of the most important indicators of soil quality [5], [6]. Phosphorus has been recently added to the list of critical materials of the European Commission and optimized use of such natural resources is becoming not only preferable, but mandatory [7].

The design of a sustainable soil quality monitoring system is a promising solution to the problem. The system will provide farmers with all the useful parameters, which are vital for the cultivation and monitoring of crops.

The aim, as a team of engineering students, was to design and implement a low-cost and smart sensing system for soil monitoring. The sensing system is based on a previously developed screen-printed, multisensor array [8]. The multisensor array can measure pH, temperature, dissolved oxygen and salinity whilst it should be able to provide data in real-time. The goal was to develop the instrumentation for the multisensor array in such a way that it can be smart enough to auto-calibrate and versatile enough to eliminate any sensor fabrication discrepancies in cases of sensor replacement. The system is of relatively low cost, ergonomic and simple enough so that every farmer can use it without any special knowledge or training.

After some research on the market, several soil sensing systems were found that can measure only one or two soil parameters, however, none of them offers direct soil measurements at low cost with the flexibility and versatility of the proposed system. In fact, there was no product available matching the application specifications.
Some farmers were contacted for more information about the parameters affecting soil quality and the answers involved the soil parameters that the array can measure. Soil pH can affect plant health and growth and subsequently, the quality of the crops. Different plant types flourish at different soil pH levels, allowing a faster nutrient absorption and growth. Furthermore, pathogens coming through soil can only develop at specific soil pH levels. Soil temperature defines the rate of nutrient absorption for each cultivation whilst ambient temperature affects water absorption from the soil. The supply of oxygen to the plant roots is achieved through the dissolved oxygen in water and the oxygen between soil particles. Oxygen is vital for plant growth and health as plant roots need it for proper respiration. Very low oxygen levels in the ground can result in anoxia, eventually killing the plant. Soil salinity is another vital parameter which will execute all the factors that affect the sensors’ accuracy, in a wide operating range.

The designed instrumentation includes a microcontroller, which will execute all the necessary calculations and extract the required information. The architecture of the instrumentation at the system level is shown below (Fig. 2).

![System Level Diagram](image)

Fig. 2: System Level

Each section of the instrumentation was studied independently while simulations were performed simultaneously. The various circuits are further discussed in detail in the following sections.

2. SYSTEM AND STRUCTURE

The main goal of the project was to provide a robust and reliable method to collect data from soil with low power-consumption and with the potential of dynamic regulation. The sensor array was fabricated using the low-cost, Thick-Film Technology having a lifetime of approximately 6 months. The sensors’ properties present fluctuations between each fabrication batch. Therefore, the instrumentation was designed to be capable of auto-adjusting the circuits in such a way to eliminate all the factors that affect the sensors’ accuracy, in a wide operating range.

2.1. Power Supply

Generally, one of the main goals was to create a low power-consumption system to enable its long-term use in the field. In case of using the sensing arrays in a high-density sensor network, high power consumption of the instrumentation will require power supply eliminating the use of batteries. In addition, lower power consumption implies smaller batteries and a smaller size of the system, something that allows soil monitoring without affecting any other agricultural practices.

The power supply circuit is capable of providing a DC voltage of ±5 V (dual rail voltage with a reference point 0 V). The system has two voltage regulators where one of them is dedicated to the microcontroller and the other to the rest of the circuits. The circuits that need ±5 V power supply are most of the time turned-off. The second regulator creates a continuous voltage that is inverted to approximately -7 V. These voltages are the supplies to the two operational amplifiers (OpAmp). One of these OpAmps is designed using an inverting topology where a positive gate input has a reference voltage at 1.8 V, which is provided from the voltage reference circuit with high accuracy. This signal is amplified through the inverting amplifier and as a result, the output of the OpAmp is 5 V. The 5 V output is imported into an inverting amplifier (second OpAmp) presenting unity gain, thus the signal is inverted to -5 V. The benefit of this design is that the two outputs are interdependent and have a common ground.

The main use of the power supply circuit is to supply power without variations to the Central Processing Unit (CPU) at the stable voltage of 5 V. In addition, the second voltage regulator, which is controlled from the CPU, is used to power-up the digital circuits and any other circuit that does not require bipolar voltage supply. The power supply circuits provide enough current so that the voltage drop is proportional to the load. For that reason, the supply must be turned off when not needed achieving a much lower power consumption. An extra circuit was developed with the aim to provide dual voltage supply to the analogue circuits. The output voltage is ±5 V.
2.2. Dissolved Oxygen Sensor

The dissolved oxygen sensor consists of 4 electrodes. A reference electrode, a working electrode, a counter electrode and a guard electrode. The positive input terminal of one of the OpAmps is set to 0.8 V and based on amplifier rules, the same voltage is applied on the negative input terminal. The output terminal of that amplifier is connected to the counter electrode. The negative input terminal of that OpAmp is also connected to the output terminal of another OpAmp, which is also connected to the negative input terminal of the same OpAmp. The positive input terminal of that OpAmp is connected to the reference electrode, which sits at 0.8 V. The negative input terminal of a 3rd OpAmp is connected to the working electrode that is set at 0 V by connecting the positive input terminal to the ground. The current through the working electrode is converted to voltage through a known resistor. The resistor used for the loop gain is programmable, giving the circuit the extra feature of adjusting sensitivity. The last block is an inverting amplifier, which is used to further amplify the output signal. The non-inverting input is connected to $V_{\text{ref}}$ of the circuit. The main challenge for this sensor was to make it dynamic. The output signal from the sensor will be controlled through the programmable resistor and as a result, the sensitivity of the sensing circuit can be adjusted.

2.3. Platinum Resistance Thermometer

The thermometer on the array is a platinum resistance thermometer (PRT). The equation for the resistance of the PRT is:

$$R_t = R_o(1 + \alpha T) \quad \text{Eqn. 1}$$

where $R_t$ is the resistance (Ω) at temperature $T$(°C), $\alpha$ is the temperature coefficient of resistance (Ω/°C). The operating temperature range of the thermometer was chosen to be -10°C and 50°C.

One of the targets for this sensor was to be capable to auto-calibrate in cases of fabrication discrepancies in sensor’s properties. Eqn 1 is linear and dependent on $R_o$ and $\alpha$. Therefore, a minimum of two values is required to calculate $R_o$ and $\alpha$. Those values can be calculated if $R_t$ and $T$ are known at two points The basic idea for the thermometer calibration was to supply a known current through thermometer in order to heat it up and measure the voltage across it. The temperature of the sensor will be also monitored using the On-Board Reference Thermometer (LM73-Q1) in order to calculate the required constants. In case of sensor replacement, the user will only have to get the two sensors in contact for the system to auto-calibrate.

In normal operation, our circuit’s starting point is the reference voltage ($V_{\text{refTemp1}}$), which will be obtained from the calibration. This voltage will be applied to create a constant current (caused from $R_e$ resistance). This current will pass through the PTR for 1 millisecond, eliminating the chance of self-heating the sensor. As a result, at point “TempPin1”, a voltage will be generated and the output voltage from PRT will be amplified. It is vital to amplify the signal and create some offset so that the temperature measurement range is controlled. Using a programmable resistor $R_{\text{res prog}}$, the gain is maximized setting the limit of the output voltage between 0.5 V and 4.5 V.

The equation extracted from the circuit is:

$$V_{\text{outTemp}} = \left(\frac{R_g}{R_{\text{offset}}} V_{\text{offset Temp}} \right) - \left(\frac{R_g}{R_{\text{res prog}}} V_{\text{ref Temp1}} \right) \cdot \frac{R_o}{R_e} \cdot aT \quad \text{Eqn. 2}$$

The main challenge was the adjustability of the circuit. The thermometer should be able to auto-calibrate. The main aim was to synchronize the surface mount thermometer in conjunction with the controller and the programmable resistor used for adjusting the gain, so that the PRT obtains a wide
range of values that match the application’s temperature range. In this way, any fabrication discrepancies of the sensor are eliminated and the system is versatile enough to match a variety of sensors of the same category. An indicative amount of time required to heat up the thermometer is given by the equation:

\[ t = \frac{cV}{q} \Delta T \]  
Eqn. 3

The equations which are constant and set by the CPU are the following and they depend on the characteristics of the sensor.

\[ V_{refTemp1} = \frac{slopeSuggested \times R_c}{R_o} \]  
Eqn. 4

\[ V_{offset} = \frac{R_{offset}}{R_g} V_{\min} + \frac{R_g}{R_{resprog}} \left\{ -V_{refTemp1} \frac{R_e}{R_c} (1 + aT_{min}) \right\} \]  
Eqn. 5

\[ R_{resprog} = \frac{R_g}{\left\{ \left( \frac{V_{out max} - V_{out min}}{T_{max} - T_{min}} \right) / slopeSuggested \right\} \} \]  
Eqn. 6

2.4. pH Sensor

The pH sensor is a potentiometric sensor using a Silver/Silver Chloride (Ag/AgCl) Reference Electrode (RE) and an Ion-Selective-Electrode (ISE) based on Ruthenium (II) Oxide. The sensor’s potential is given by the Nernst’s equation:

\[ E = E^o - \frac{2303 R T}{n F} \times \text{pH} \]  
Eqn. 7

where R is the universal gas constant (J/mol K), T the temperature (K), F the Faraday constant (C/mol) and n the number of electrons transferred during the cell reaction.

It is very important to calibrate the pH sensor in order to increase its accuracy. The calibration will help define \( E^o \) and n, which varies from one sensor to another. In addition, the output (potential (E)) is temperature dependent. Therefore, the calibration will also consider temperature, for higher accuracy.

Potentiometric sensors are based on the principle of no current flowing through the electrodes. In cases where the impedance of the medium between the electrodes is high, a much higher input impedance is required by the instrumentation to obtain reliable measurements. That was achieved by setting as input a signal coming from a voltage follower. The next critical point was to amplify the signal. An inverting amplifier and a programmable resistor (ResProgPh) was used to control the gain. As a result, the range of measurements has expanded and the sensor has become more sensitive and dynamic.
The equation extracted from the circuit above is:

\[
V_{\text{out}pH} = \left( \frac{R_{\text{ref}pH}}{R_{\text{f}pH}} V_{\text{ref}pH} + \frac{R_{g\text{ph}}}{R_{\text{es}\text{Prog}pH}} E^0 \right) - \left( \frac{2.303 R T}{n F} \frac{R_{g\text{ph}}}{R_{\text{es}\text{Prog}pH}} pH \right)
\]

Eqn. 8

\[V_{\text{ref}pH} = \left( V_{\text{out} \max} - \frac{R_{\text{ref}pH}}{R_{\text{es}\text{Prog}pH}} E^0 \right)
\]

Eqn. 9

\[V_{\text{out}} = \left( V_{\text{ref}pH} + \frac{R_{g\text{ph}}}{R_{\text{es}\text{Prog}pH}} E^0 \right) - \left( \frac{2.303 R T}{n F} \frac{R_{g\text{ph}}}{R_{\text{es}\text{Prog}pH}} pH \right)
\]

Eqn. 10

The size of the programmable resistor is defined by the equation:

\[R_{\text{es}\text{Prog}pH} = \frac{2.303 R T}{n F} \frac{R_{g\text{ph}}}{V_{\text{out} \max} - V_{\text{out} \min} pH_{\max}}
\]

Eqn. 11

2.5. Electrical Conductivity Sensor

The conductivity sensor is based on the classical four-electrode method where a known current is passed between the two outer electrodes and the voltage is measured between the inner two. The designed circuit applies a sinusoidal current with the use of a current source. It is important to eliminate any DC offset in the sensor otherwise, the electrodes will get polarized. The conductivity sensor measures conductance and converts it into conductivity using the known cell constant of the cell. Conductance is defined as the reciprocal of resistance. A circuit incorporating a current source that can measure voltage was designed. The theory of the Wien-bridge oscillator was implemented. An oscillation frequency of 1 kHz \((f_0=1/[2\pi RC])\) was chosen because impedance at low frequencies depends mainly on resistance and less on capacitance or inductance. The signal was then conditioned using a voltage divider and a high-pass filter blocking any DC offsets. Then, the signal is inserted in a voltage follower to ensure that the current is load independent. The voltage signal is converted to current through \(R_c\), which is a programmable resistor. The conductivity range has been expanded to 1-4000 \(\mu S/cm\). The microcontroller sets the resistance of the programmable resistor in such a way to control the current. Finally, the voltage measured between the two inner electrodes is proportional to the conductivity.

The value of the programmable resistor is controlled from the microcontroller depending on the magnitude of the output voltage. The system starts with low values of programmable resistance. If the output voltage is higher than 4 volts, then the resistance increases, thus the voltage will decrease. This process will be repeated until the voltage output is between 2 V to 4 V, which will increase the accuracy of the measurements.

The resistance of the circuit is given by:
\[ R = \rho \frac{L}{A} \quad \text{Eqn. 12} \]

The two voltage electrodes will measure voltage through the use of an instrumentation amplifier (INA826). Also, the OpAmp AD8571 has a very low offset voltage in the range of 1 μV to ensure that the DC polarization on the sensor is eliminated. The equation produced from the circuit is:

\[ V_{\text{out,conductivity}} = \frac{V_{\text{in,con}} - Z_{\text{soil}}}{R_{\text{progress}}} \quad \text{Eqn. 13} \]

An additional feature of the above circuit is the ability to check if the produced waveform is a sinewave. This action is performed by a function that turns the waveform into a Fourier series representation and compares the data structure with a pre-programmed data structure, which decides if the waveform is correct or not.

2.6. Interference Elimination

Another important feature of the instrumentation was to ensure the isolation of each sensor in order to eliminate any interferences between them. All sensors are integrated on the same array making them prone to interference. Due to the fact that all sensors will be inserted in the same medium, a circuit might be formed that includes some electrode from one sensor and some electrodes from another. Consequently, the measurements will be misleading or this interference can even destroy the sensors.

One solution to the problem was an isolated supply voltage for each circuit but this is an expensive solution. Hence, the use of relays was chosen for the circuits. Relays provide a mechanical way for opening a circuit. The most important feature of relays is their ability to fully disconnect from the rest of the circuit. The possibility to use MOSFETs was explored, however the ground could not be disconnected due to the bulk effect. All the sensor connections to the circuit are through relays. The relays turn-on for a limited amount of time when the controller decides to, so power consumption of the system is significantly decreased.

2.7. MicroController

The use of a microcontroller was decided because it can make the instrumentation simple and more dynamic. In addition, the controller can make the calibration process automatic while storing important values. As a result, the performance of each sensor is optimized.

The AT-Mega32U4 microcontroller was chosen over the others for various reasons. It has a built in FTDI chip that allows it to connect directly to a USB port of any PC or laptop. It is very cheap because it has one of the chips used in the known Arduino MCU boards and hence, it is easier to program and debug using the Arduino IDE. It has 10 Analogue I/O and 13 digital I/O with a clock frequency of 16 MHz, which fits perfectly with the needs of this application. Furthermore, the MCU is power efficient and consumes only 27 mA at maximum speed. The requirements of the application exceed some of the controller’s specifications, so two DACs and one ADC were added. A controller containing DAC and more bits was also found but the price was not affordable and the design was more complex.

The resolution of the chosen DAC is 16 bits to provide accuracy of less than 1 mV. The controller itself includes an ADC with a resolution of 5 mV (12 bits), therefore, an extra ADC was used to improve the resolution to less than 1 mV. The ADC chosen has a limited number of inputs and therefore, a multiplexer with a ratio of 8:1 was used. Furthermore, the same component was used as a demultiplexer for the same reasons.

On the previous circuits multiplexers and demultiplexers act as signal controllers allowing the manipulation of the desired signal at the exit or the input. For this specific case, the usage of analogue devices was inevitable as the signals received from the sensors are analogue. An advantage of the current architecture is that it saves pins from the processor when there is no need for simultaneous signal processing. The system requires reading 5 signals so the control signal consists of 3 bits. The systems for the manipulation of a sensor are serial and as result the

<table>
<thead>
<tr>
<th>Signal Names</th>
<th>Uses</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN_Source</td>
<td>Active all power sources (expect μC)</td>
<td>0 off 1 on</td>
</tr>
<tr>
<td>SsigD[0..2]</td>
<td>Control all circuit which will work for specific time, for read /write.</td>
<td>000 for Temperature 001 for pH 010 for DO2 011 conductivity Vout 111 conductivity Vin (generally conductivity is X11)</td>
</tr>
<tr>
<td>En_relay</td>
<td>Close circuit between circuit and sensor. Some system needs to work for limit time.</td>
<td>0 active mode</td>
</tr>
</tbody>
</table>

Table 1: Signal names & meanings
Signals supporting the operation and come from the multiplexers are acting simultaneously. The summary table indicates all the functions and how they are grouped. Since relays were used and they require quite high currents, the idea of connecting them directly on the processor was impossible due to the processor’s incapability to provide the suitable amount of current. For that reason, MOSFETs have been inserted, which act as electronic switches. The current relays are triggered for a minimum amount of time and thus the relay enable signal was added. In a nutshell, the microcontroller acts as the main brainpower for the dynamic behavior of the circuit. This involves the calibration for the thermocouple, the control of the programmable resistors, the control and evaluation of the sinewave of the conductivity sensor and any other control signals that drive the sensors.

### 3. PCB Design & Population

The PCB was designed on Altium Designer® software and was manufactured by EuroCircuits Ltd. All of the above circuits were designed initially as a schematic with specific components and sizes. Although the simulation results were satisfactory, when designing a real PCB, several other factors need to be taken into account such as current leakages, decoupling capacitors and connectors. The final outcome is a PCB containing all of the above. Once those modifications were completed in the schematic of the PCB, the footprints from each component were obtained by their manufacturer and the PCB was fully designed (Fig. 9).

#### Table 2: Summary Table

<table>
<thead>
<tr>
<th>Circuit</th>
<th>V supply</th>
<th>I supply</th>
<th>Work Time</th>
<th>Range</th>
<th>Vout</th>
<th>Expected Cost (€)</th>
<th>Detection method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>8.5v to 18v</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+5v, ±5v</td>
<td>12.65</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>±5v</td>
<td>34.5 mA</td>
<td>1-2ms</td>
<td>-10°C to 50°C</td>
<td>0.5v (10°C) to 4.5v (50°C)</td>
<td>9.5</td>
<td>Platinum Resistance Thermometer</td>
</tr>
<tr>
<td>pH</td>
<td>±5v</td>
<td>28.5 mA</td>
<td>5s</td>
<td>2-12 ph</td>
<td>0.5v (2 pH) to 4.5v (12 pH)</td>
<td>15</td>
<td>Potentiometric</td>
</tr>
<tr>
<td>Conductivity</td>
<td>±5v</td>
<td>68 mA</td>
<td>0.5s</td>
<td>1-4000 Ω</td>
<td>0.25v to 4v</td>
<td>13</td>
<td>4 Electrode Method</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>±5v</td>
<td>56.7 mA</td>
<td>1s</td>
<td>-</td>
<td>-</td>
<td>9</td>
<td>Clark Cell – 3 Electrode method</td>
</tr>
<tr>
<td>Controller-DAC-ADC</td>
<td>+5v</td>
<td>27 mA</td>
<td>15-20s</td>
<td>-</td>
<td>-</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>Sleep mode: 75uW</td>
<td>Active mode: ≈1.074W</td>
<td>This system turns on for 20sec every 30 minutes, as result if we will choose a battery with capacity 1.3Ah (14.8v) then our battery autonomy is around 65 days</td>
<td></td>
<td></td>
<td>74.15</td>
<td>-</td>
</tr>
</tbody>
</table>

The PCB was designed and fabricated using two layers. However, all the components were mounted on a single side. The PCB dimensions are 102 mm x 105 mm. The size of the PCB was another challenge. For soil applications, the PCB should be small enough not to interfere with other agricultural practices but at the same time it must be of low cost implying that the number of metal layers has to be as low as possible. Finally, the components to be used on the PCB have to be of certain size to allow an easier and reliable PCB population. The populated PCB is shown in Fig. 10 below.
The algorithms and code used to control and operate the CPU have been prepared and are currently being tested to ensure that the PCB will perform in full capacity.

4. CONCLUSIONS

The project outcome is a versatile and low-cost electronic interface for soil sensors. This interface provides soil information to the farmer so that the farmer can immediately respond to any resource needs for the plants. This increases productivity and decreases operating costs for the farmer while maintaining high quality products. The system provides the instrumentation for many sensors and its operation is simple, allowing anyone without any special knowledge to use it. The instrumentation has the flexibility to dynamically auto-adjust the circuits making it more versatile by measuring all the important factors affecting its performance at a low price and with a low power consumption.

The main point of the competition was to inspire high school students to pursue a degree in electrical engineering and the design of circuits and systems. Therefore, the team has taught the high school member of the team how to use various simulation and PCB design programs, whilst also understanding simulation results and finding ways to solve them. Finally, he has learned how to populate PCBs using discrete components, which brought him in touch with engineering, giving him a taste of how an engineer approaches and solves real-life problems.

5. REFERENCES