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Development and test of a low cost portable soil apparent electrical conductivity sensor using a Beaglebone Black

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ABSTRACT. *The adoption of soil apparent electrical conductivity (ECa) sensors has increased in precision agricultural systems. The ECa sensors have low cost and generally the ECa values correlate well with soil chemical and physical attributes. The objective of this work was to develop a portable soil sensor for measuring soil apparent electrical conductivity that could be used in mountainous areas and in small farms. The developed system was based on the electrical resistivity method and uses an alternating current signal. The system measured the electrical conductivity by applying a square wave signal at a frequency defined by the user. The acquired data was georeferenced using a low cost GPS receiver. The sensor system was developed using a Beaglebone Black that is a low cost single board computer. A user interface was developed in C++ and a touch screen with a resolution of 800x480 pixels was used to display the results. This interface performed statistical analysis and the results were used to guide the user to identify more field locations to be sampled to increase mapping accuracy. The system was tested in a coffee plantation located in a mountainous area in Minas Gerais, Brazil. The system worked well in mapping the apparent soil electrical conductivity.*

Keywords. *Geostatistics, Precision agriculture, Spatial variability, Soil map, Soil sensor.*

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Introduction

Mapping soil attributes is an important step for managing precision agriculture systems. It can be used for prescribing fertilizers, lime and other amendments. The process of soil sampling and laboratory analysis has been used for determining soil attributes. The problem of this procedure is cost and time to process samples. Due to these problems, generally a sparse soil sampling is applied, resulting in a low accuracy of the generated soil attribute maps. One alternative is to use on-the-go soil sensors that present low cost and that have fast response. By using soil sensors, finer grid sampling process can be achieved, improving the spatial resolution of the generated maps.

Soil sensor do not measure the soil attributes directly. Soil sensors generally are based on electrical and electromagnetic, optical and radiometric, mechanical, acoustic, or pneumatic of electrochemical principles (Adamchuk et al., 2004). Therefore, the sensor signal should be correlated with soil attributes that have agronomic interest and the measured variable by the sensor should present a stable pattern of spatial variability over time.

One type of soil sensors that has been applied for mapping soil in precision agriculture systems measures soil apparent electrical conductivity. The signal generated by this type of sensor has correlation with many soil attributes (Adamchuk et al., 2004; Valente, et al. 2012; Sudduth, et al., 2005). The pattern of spatial variability of soil maps produced by this sensor is stable over time (Pedrera-Parrilla et al., 2017; Medeiros et al., 2016; Farahani & Buchleiter, 2004). Besides, the soil apparent electrical conductivity sensors are relatively simple to use and have a low price, especially the ones based on the electrical resistivity principle. One point still not explored when using the soil apparent electrical conductivity measured by the resistivity method is the effect of the frequency of the signal applied to the soil. Because soil is a heterogeneous material, applying signal with different frequencies may result in different soil apparent electrical conductivity maps. These different maps may correlate differently with the chemical and physical composition of the soil.

Besides the soil sensor, a system for mapping the soil apparent electrical conductivity should have a position sensor for data georeferencing. A graphical interface that makes easier the data acquisition by the user is also important. In this interface, it is important to have a navigation window to help the user to go thru the points where the measurements should be done. The sensor system can be pulled by a vehicle or can be a portable one. The systems pulled by vehicles allow a faster data acquisition. However, in mountainous areas, a system pulled by a vehicle generally cannot be used, for this purpose, a portable system is recommended.

To build a system for soil apparent electrical conductivity mapping, a single board computer can be used. It can be less expensive and provide good processing speed. One good option is the Beaglebone Black Board. This board allows input and output of digital and analog signals and is an open-source Linux computing platform. By using BeagleBone Black, complex applications using high-level software integrated with low-level electronic circuits can be developed (Molloy, 2014).

By using the Beaglebone Black Board, Queiroz, et al. (2016) developed a portable system for measuring the apparent soil electrical conductivity by the resistivity principle. The developed system integrated a sensor that measured the apparent soil electrical conductivity using a signal produced by an op-amp and a GNSS (Global Navigation Satellite System) to get the position of each point of measurement. The system produced an alternated electrical current with four different frequencies that could be selected by four switches operated manually by the user. A graphical interface was developed using C++ using the Qt 4.8.6 IDE (Integrated Development Environment). The system worked well, however the graphical interface was still difficult to be used by the user and the manual switches were not very practical. Therefore, the objective of this paper was to develop a new apparent soil electrical conductivity mapping system with improved capabilities from the previous prototype. The design incorporated the possibility of the user defining the signal frequency to be used without the necessity of using manual switches and improvements were made in the graphical interface easier to be used. By removing the manual switches, the cost of system was reduced by reducing the wiring and by eliminating the cost of the manual switches.

Material and Methods

Sensor development

The soil apparent electrical conductivity sensor was developed using the resistivity principle. Four equally spaced electrode probes were used. The distance between electrodes was set to 30 cm. A schematic view of the sensor system is shown in Figure 1.

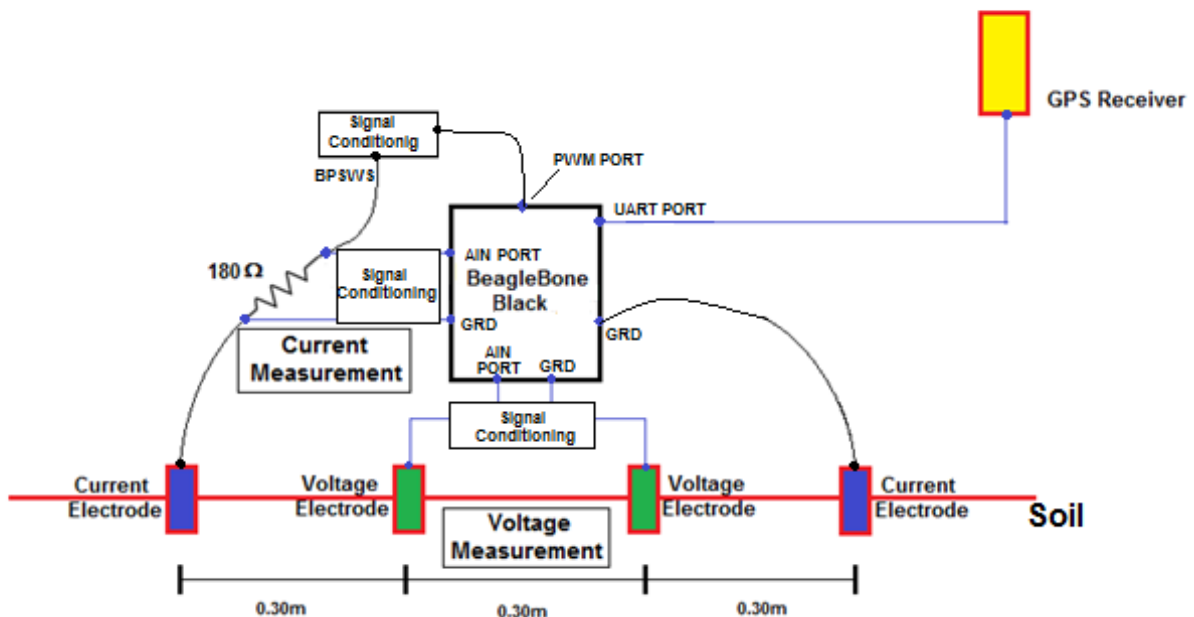


Figure 1 – Schematic view of the soil apparent electrical conductivity sensor system. GRD means ground, UART means universal asynchronous receiver/transmitter, AIN means analogic input and BPSWS means bipolar square wave signal.

The position sensor (Ultimate GPS sensor, Adafruit Technologies, NY) was connected to a UART (universal asynchronous receiver/transmitter) port. To generate the electrical signal to be applied to the current electrodes, a PWM (pulse-width modulation) output port (the EHRPWM2B port) was used. The PWM signal was passed thru a signal-conditioning module to transform the unipolar square wave signal to a bipolar square wave signal. A 180 Ω resistor was added for measuring the electrical current applied to the soil, and the electrical current was calculated based on the voltage drop across this resistor. The voltage differences across the 180 Ω resistor and the two voltage electrodes of the soil probe were measured using two analog ports of the Beaglebone Black, the ports AIN5 and AIN6, respectively. An LCD of 800x480 pixels resolution (model 4DCAPE-70T made by 4D Systems, Australia), was connected to the Beaglebone Black Board for displaying the results.

The circuit used for transforming the PWM signal to a bipolar square wave signal is shown in Figure 2. This circuit was simulated using the Multisim software version 14 from by National Instruments. The PWM port of Beaglebone Black produced a signal with an amplitude of 3.3 volts. By using this circuit, a -8.2 V to +8.2 V square wave signal was generated. The circuit used for measuring the voltage across the 180 Ω resistor and between the two inner electrodes of the sensor probe is shown in Figure 3. This circuit was also simulated in Multisim software before being built. The analog inputs of Beaglebone Black Board only measured signal between 0 and 1.8 volts.

Graphical interface

The graphical interface was programmed in C++ by using the Qt IDE version 4.8.6. The generated code was transferred to the Beaglebone Black Board and compiled using a qt4 tool available in Debian 8.2, that was the operating system running on Beaglebone Black. The main parts of the developed software are shown in Figure 4. The Blacklib C++ Library version 2.0 (an opensource code available at <http://blacklib.yigityuce.com/>) was used for generating the PMW signal, for reading the GPS sensor in the UART port and for reading the two analog signal. The graphical interface displayed a crop field in the screen so the user can choose the signal frequency for the electrical current signal to be applied to the soil probe. Depending on the soil attributes to be analyzed and the crop and soil conditions in the fields, it might have a frequency that works better.

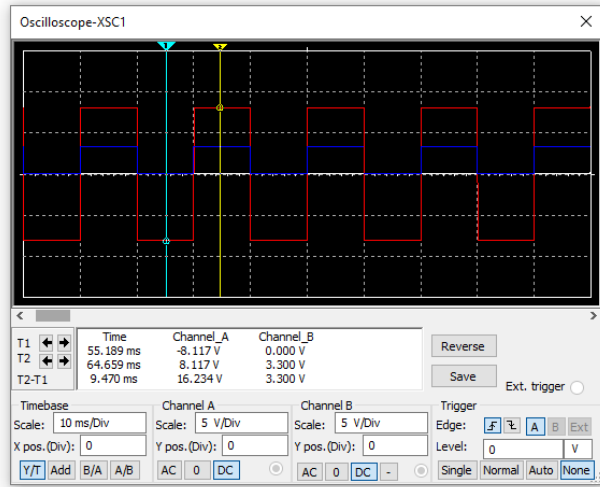
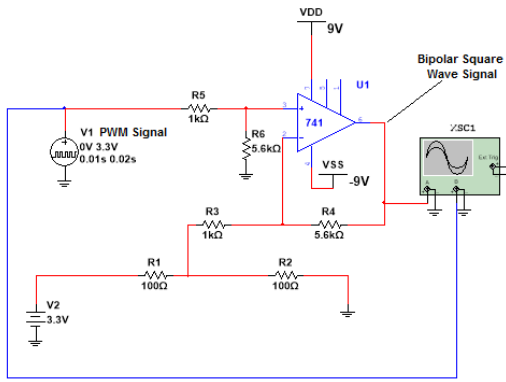
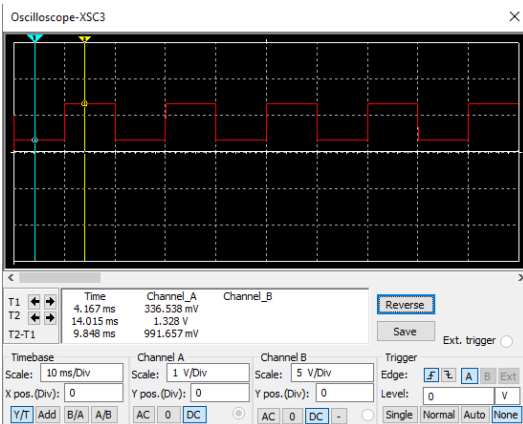
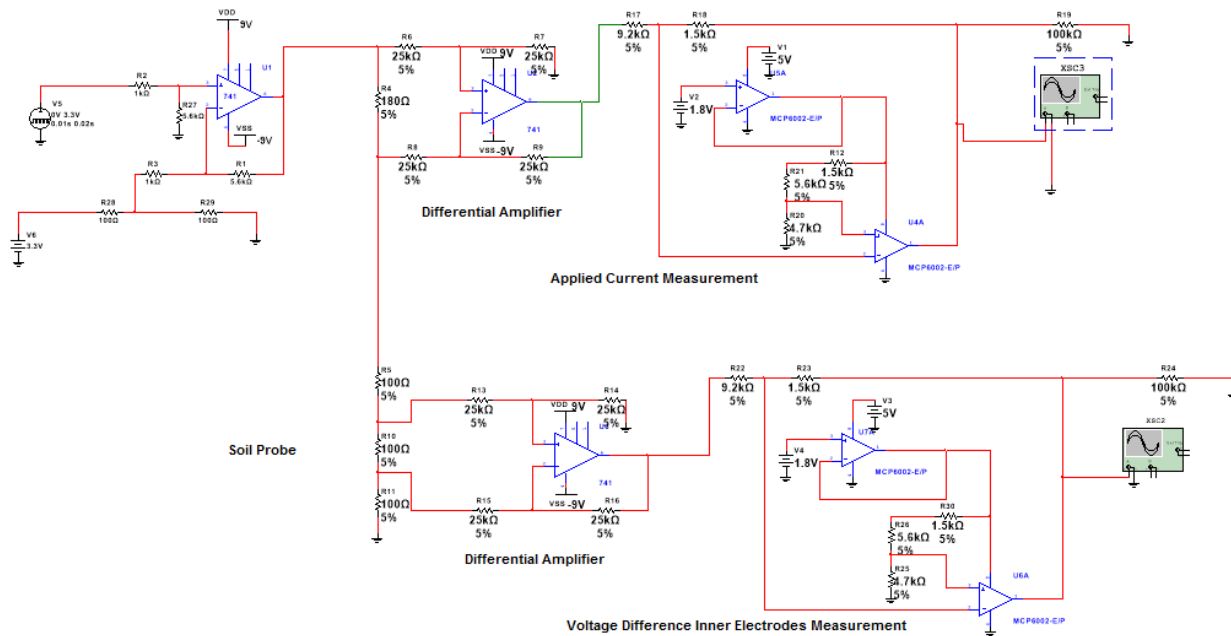
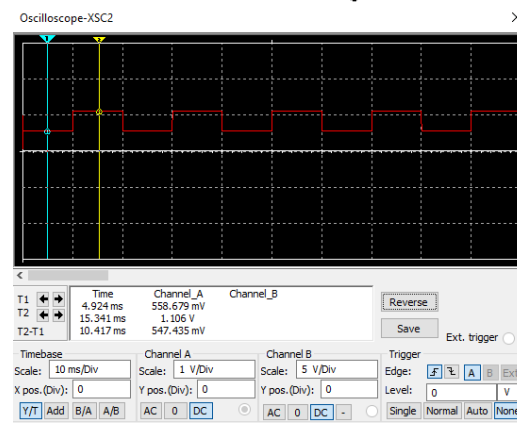


Figure 2 – The circuit used for transforming the pulse-width modulation signal into a bipolar square wave signal.



Current Measurement



Difference of Voltage Measurement

Figure 3 – The circuit used for measuring electrical current and voltage difference between the inner electrodes of the sensor.

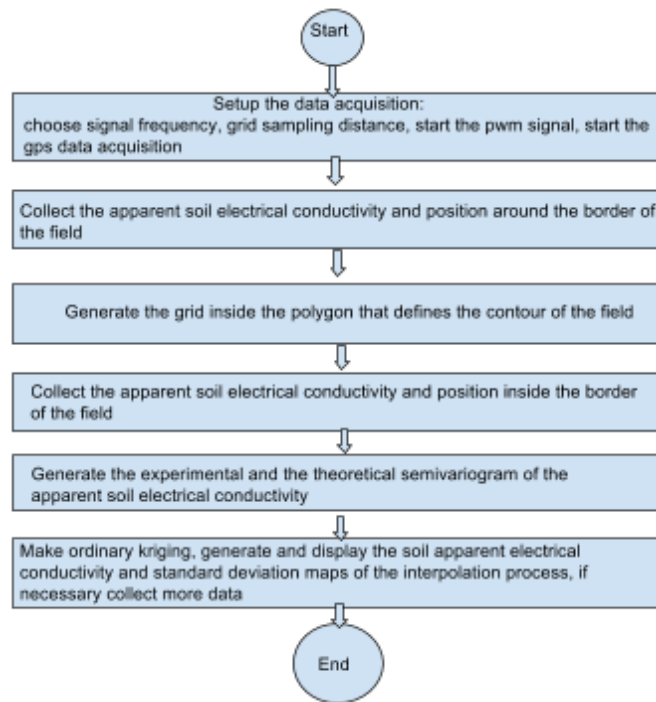


Figure 4 – General flowchart of the software for the graphical interface

The graphical interface allowed the user to choose between two sampling strategies. The first one was a uniform sampling grid with the distance among points provided by the user. The second one was a smart sampling grid. If the user chose this strategy, the program compared the last acquired value with the average value. In addition, the program calculated the rate of change of the soil apparent electrical conductivity. If the measured value of the soil apparent electrical conductivity was closer to the maximum or to the minimum value, or if the rate of change of the soil apparent electrical conductivity was high, the software recommended the user to sample using a finer grid. The navigation window of the graphical interface showed the user where to sample to achieve that finer grid.

A set of functions was written to perform the ordinary kriging. The idea was to perform an initial geostatistical analysis while in the field, so the user could check where he/she might have a problem in map generation. The program calculated the experimental semivariogram. The active lag distance was set to 60% of the maximum distance between all pair of points. This active lag distance was divided in 20 lag distances using a uniform interval. The semivariance for each point of the semivariogram was calculated based on Equation (1).

$$\gamma = \frac{1}{2N} \sum_{i=1}^N (Z_i - Z_{i+h})^2 \quad (1)$$

where γ is the semivariance (mS^2/m^2); N is the number of pair of points with the lag distance h ; Z_i is the value of the soil apparent electrical conductivity measured at i position (mS/m); Z_{i+h} is the value of the soil apparent electrical conductivity measured at a position with a distance of h from the i position (mS/m).

The program fitted three theoretical semivariogram models, the exponential, the spherical and the Gaussian models. To do that, the program used the minimization of the sum of squared errors. To calculate the nugget effect, the range and the sill for each model, the univariate search method (Chapra & Canale, 2015) was used. The model that resulted in the minimum sum of squared errors was used in the ordinary kriging interpolation process. The ordinary kriging was performed using the method described by Isaaks & Srivastava (1989). For each point, the soil apparent electrical conductivity and the corresponding standard deviation were calculated. The interpolation process started using the 16 data points that were closest to the interpolation point. If any of the weights to be applied to the neighbor points were negative, the program reduced the number of neighbors until no negative weights were found. At the end of the process, the user interface displayed the standard deviation map. The points where the standard deviation were higher imply that there was more uncertainty in the estimation process. The user could go to these places in the field to collect more data.

In Figure 5, a screen capture of the user interface and a complete view of the sensing system are shown. Just one person was required to operate the developed system. When the system was turned on, the user had to proceed with the setup

configuration that consisted of defining the distance between points of the grid, the frequency of the electrical current to be applied to the soil and what type of sampling strategy was going to be used. After the setup configuration, the system was ready to be used. The user had to start the data collection around the boundary of the field. So, the system could create the grid inside the boundary of the field. The system displayed the distance to the next point and the GPS status. When the user was ready to collect the data, it was necessary to press the “Save Coordinates and ECa” button, and the system showed the apparent electrical conductivity value and the number of the point that had just been read. Also, the system presented the “Value Index” and the “RC Index”. The Value Index showed how far the data that has just been measured was from the mean value. Negative indices meant that the value was less than the mean value minus one standard deviation. Positive values meant that the value was greater than the mean plus one standard deviation. In addition, zero value meant that the value was between the mean minus one standard deviation and the mean plus one standard deviation. The RC Index did the same, just changing the soil apparent electrical conductivity values to the rate of change of the soil apparent electrical conductivity values. When the user finished collecting the contour point, it was necessary to press the “Contour Done” button. After that, the system generated the grid where the user should collect the data. When the user finished the data acquisition, it was necessary to press the “Data Acquisition Ended” button. Then, the system run the geostatistic analysis by generating a semivariogram and proceeding with the ordinary kriging interpolation. The “conductivity map” and “error map” buttons can be used by the user to display the soil apparent electrical conductivity map and the standard deviation map, respectively, for the kriging interpolation.

The soil apparent electrical conductivity mapping system was tested in two conditions. First laboratory tests were done to check if the system was providing the designed signal and if the system were measuring the voltage difference in the inner electrodes. In these tests, three 180 Ω resistors were connected between the four electrode probes. As the soil apparent electrical conductivity is given by Equation (2), for a distance of 0.30 m between electrodes, the equivalent electrical conductivity is 2.95 mS/m.

$$EC_a = \frac{i}{2\pi a \Delta V} \quad (2)$$

where EC_a is the soil apparent electrical conductivity, in $S\ m^{-1}$; i is the applied electrical current, in A; a is the distance between electrodes, in m; and ΔV is the potential difference in the inner electrodes. The testes were done applying electrical current with the following frequencies: 10 Hz, 20 Hz, 30 Hz and 40 Hz. The second set of tests were performed in outdoor soil conditions. Tests were done to verify the signals read by the analog input ports of the Beaglebone Black and for producing a soil electrical conductivity map in a coffee field (Figure 6).

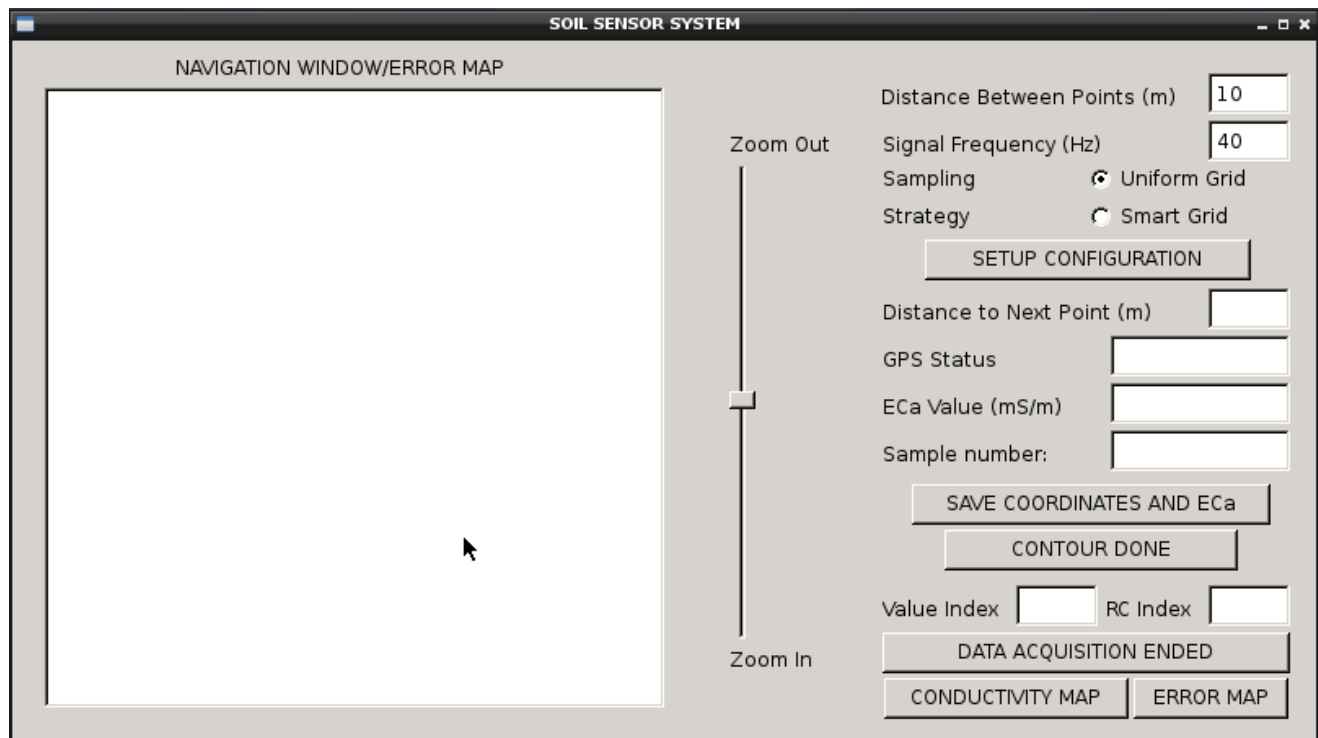


Figure 5 – Print screen of the graphical interface of the soil apparent electrical conductivity mapping system.



Figure 6 – Data acquisition in a coffee field.

Results and Discussion

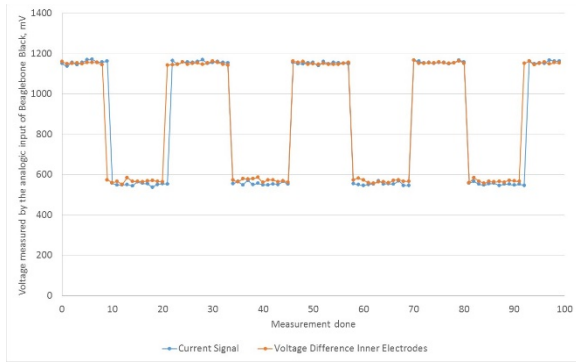
Laboratory tests

Figure 7 shows the signal measured using the analog input ports of the Beaglebone Black Board when the $180\ \Omega$ resistors were connected between the four electrode probes. It can be seen that the amplitude of the signal was not influenced by the frequency of the applied current. In the four tests performed, the equivalent soil apparent electrical conductivity was $3.00\ \text{mS/m}$ and the expected value as $2.95\ \text{mS/m}$, therefore the developed system presented an error of 1.7% in the determination of the equivalent soil conductivity. By analyzing the range of the voltage in the analog input ports of the Beaglebone Black, it could be seen that the signal was far from the limits of the port (a minimum of $0\ \text{V}$ and a maximum of $1.8\ \text{V}$). The $180\ \Omega$ resistors simulated a soil with low apparent electrical conductivity. After running tests in a large variety of soils, we will be able to redesign the signal processing circuit of the system to get a better resolution of the system. The system as it is guarantees that the voltage applied to the Beaglebone Black analog port will not be over its limit.

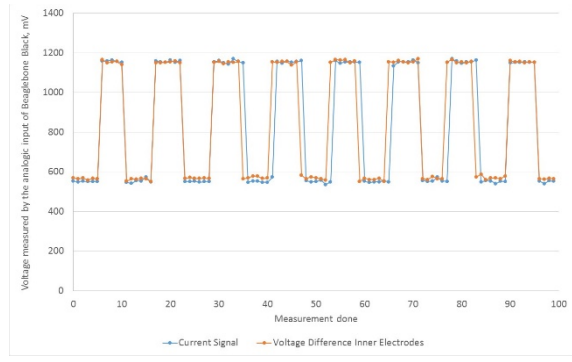
Field tests

Figure 8 shows the signal measured when performing the tests in field conditions. It can be seen that the signal for the electrical conductivity and the voltage difference between the probe inner electrodes were stable. The Figures show a delay in the signal of the voltage difference in the inner electrodes, and this is because the graphical interface first read the current signal then it measured the signal of voltage difference between the inner electrodes.

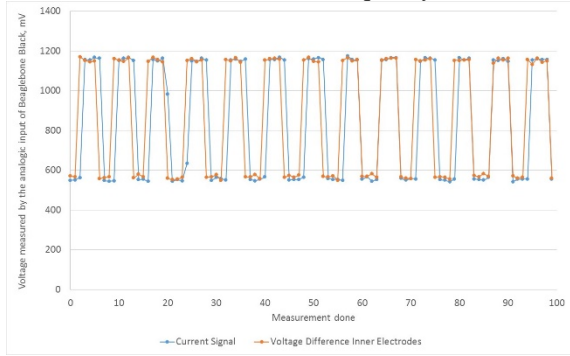
Figure 9 shows the soil apparent electrical conductivity map and the standard deviation map obtained using the developed system. The data acquisition was performed using a $10\ \text{Hz}$ signal in a coffee field. A total of 211 data points were acquired. The red color in the maps is the higher values and the lower values are in blue. The area showed moderate spatial dependence with a ratio nugget effect to sill equals to 0.58. The maximum interpolated value was $45.1\ \text{mS/m}$ and the minimum value was $5.4\ \text{mS/m}$. The standard deviation associated to the ordinary kriging was high and it did not change much, with a minimum of $23.6\ \text{mS/m}$ to a maximum of $26.2\ \text{mS/m}$.



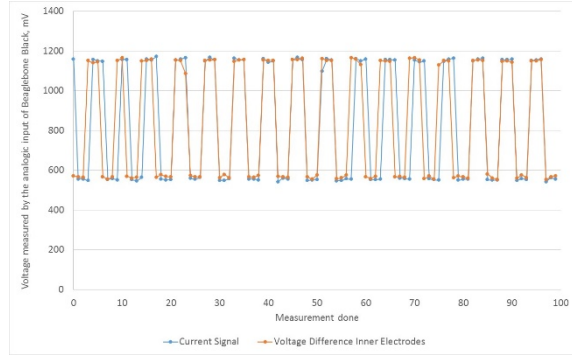
(a) 10 Hz Frequency Test



(b) 20 Hz Frequency Test

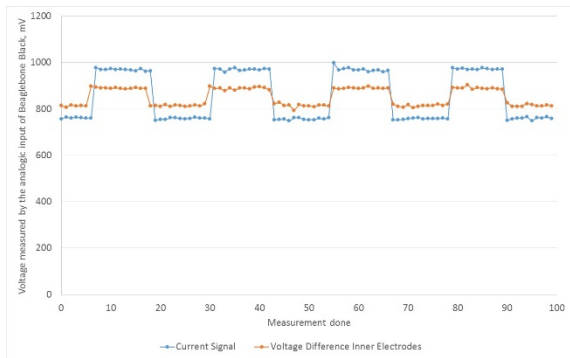


(c) 30 Hz Frequency Test

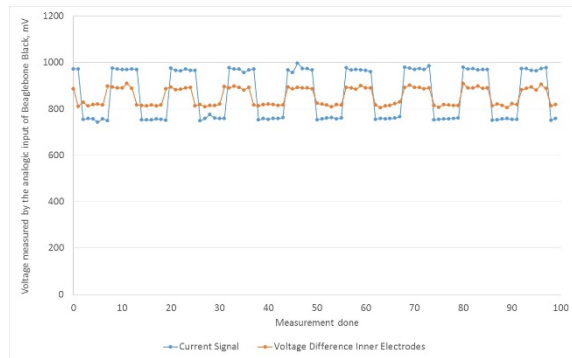


(d) 40 Hz Frequency Test

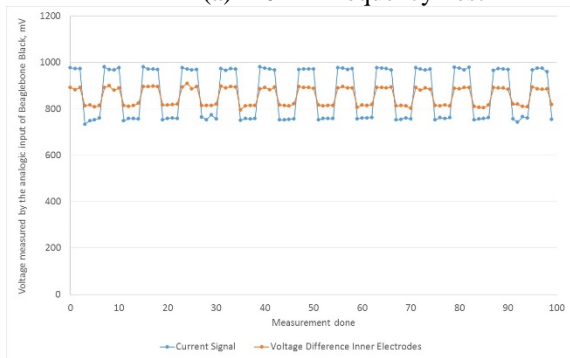
Figure 7 – Signal measured by the analog input for the four tests performed in a laboratory. (The legend is not very visible. Maybe you can add the description here.)



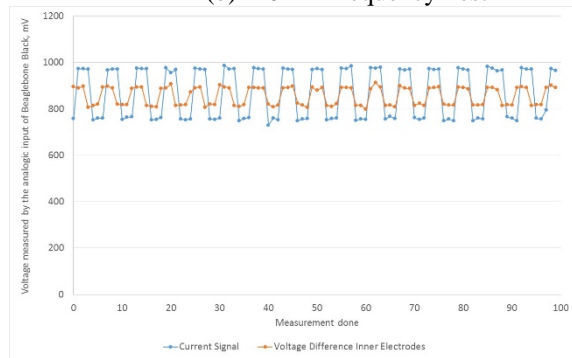
(a) 10 Hz Frequency Test



(b) 20 Hz Frequency Test

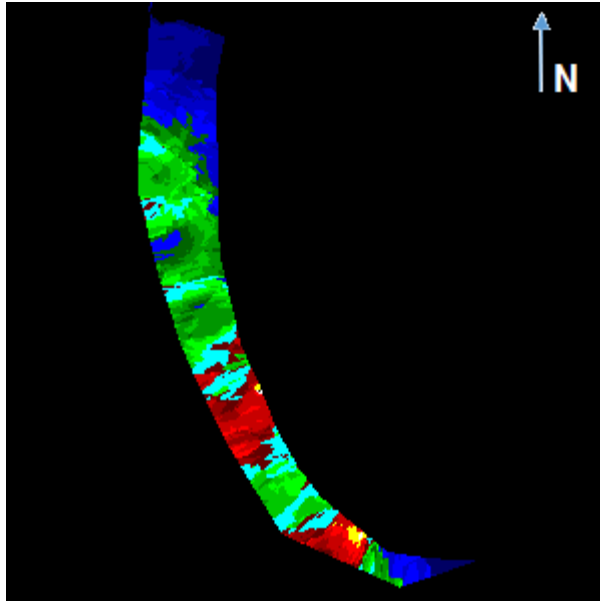


(c) 30 Hz Frequency Test

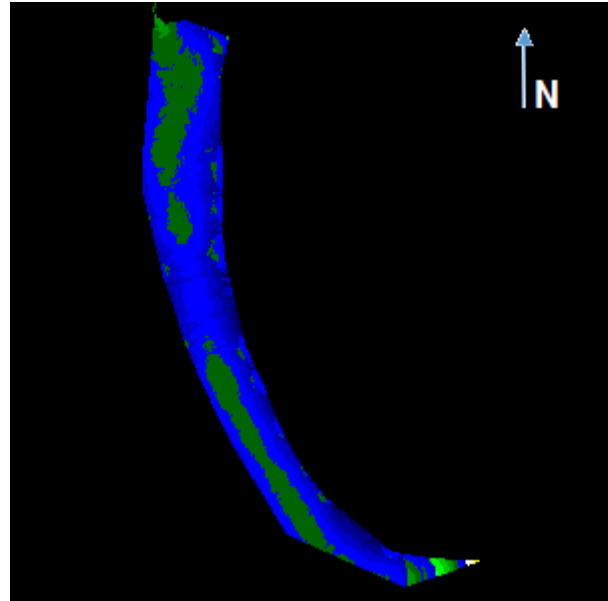


(d) 40 Hz Frequency Test

Figure 8 – Signal measured by the analog input for the four tests performed in field conditions.



(a) Map of soil apparent electrical conductivity, blue represents the lower values, green represents intermediary values, and red represents higher values



(b) Standard deviation map of soil apparent electrical conductivity, blue represents the lower values, green represents intermediate values, and red represents higher values.

Figure 9 – Soil apparent electrical conductivity and standard deviation map of a test of the developed system performed in a coffee field.

Conclusions

A soil sensor system for measuring soil apparent electrical conductivity was created using a BeagleBone Black board. The main features of the created soil sensing system was that it could measure the electrical conductivity using any frequency defined by the user and that a user interface was created to guide the user during the data collection. The user can use two different strategies: a uniform grid and a smart grid. The smart grid analyzes the value of the variable being measured and the rate of change of the variable. Tests performed in laboratory and field conditions showed that the developed system performed well.

Acknowledgments

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References

- Adamchuk, V. I., Hummel, J. W., Morgan, M. T., & Upadhyaya, S. K. (2004). On-the-go soil sensors for precision agriculture. *Computers and Electronics in Agriculture*, 44(1), 71-91.
- Chapra, S. C., & Canale, R. P. (2015). *Numerical methods for engineers*. 7th edition. New York: McGraw-Hill.
- Farahani, H. J., & Buchleiter, G. W. (2004). Temporal stability of soil electrical conductivity in irrigated sandy fields in Colorado. *Transactions of the ASAE*, 47(1), 79-90.
- Isaaks, E. H. & Srivastava, R. M. (1989). *An introduction to applied geostatistics*. Oxford University Press. New York.

- Medeiros, W. N., Queiroz, D. M., Valente, D. S. M., de Carvalho Pinto, F. D. A., & Melo, C. A. D. (2016). The temporal stability of the variability in apparent soil electrical conductivity. *Bioscience Journal*, 32(1), 150-159.
- Molloy, D. (2014). *Exploring BeagleBone: Tools and Techniques for Building with Embedded Linux*. John Wiley & Sons.
- Pedreira-Parrilla, A., Pachepsky, Y. A., Taguas, E. V., Martos-Rosillo, S., Giráldez, J. V., & Vanderlinden, K. (2017). Concurrent temporal stability of the apparent electrical conductivity and soil water content. *Journal of Hydrology*, 544, 319-326.
- Queiroz, D. M., Lee, W. S., & Schueller, J. K. (2016). Development of a portable soil sensor system using BeagleBone Black. In 2016 ASABE Annual International Meeting (paper #162447581). American Society of Agricultural and Biological Engineers.
- Sudduth, K. A., Kitchen, N. R., Wiebold, W. J., Batchelor, W. D., Bollero, G. A., Bullock, D. G., ... & Thelen, K. D. (2005). Relating apparent electrical conductivity to soil properties across the north-central USA. *Computers and Electronics in Agriculture*, 46(1), 263-283.
- Valente, D. S. M., Queiroz, D. M., Pinto, F. D. A. D. C., Santos, N. T., & Santos, F. L. (2012). The relationship between apparent soil electrical conductivity and soil properties. *Revista Ciência Agronômica*, 43(4), 683-690.