

Soil Digitalization Using Micro-Sensors

Federico Fina¹, Massimo Piotto², Simone Contardi³, Fabio Leccese¹

¹*Dipartimento di Scienze, Università degli Studi Roma Tre, Rome (Italy), federico.fina@uniroma3.it*

²*Dipartimento di Ingegneria dell'Informazione, Università di Pisa, Pisa (Italy),
massimo.piotto@unipi.it*

³*Sensichips.srl, Aprilia (LT, Italy), simone.contardi@sensichips.com*

¹*Dipartimento di Scienze, Università degli Studi Roma Tre, Rome (Italy), leccese@uniroma3.it*

Abstract – In this paper, we propose a method of data collection from different sensors through a software developed by Sensichips srl, SLM-Studio, which can then be compared with MLP machine learning models trained through training data available on the Sensichips website. The measurements performed by the SCW water sensors, the SCA air sensors and the SCP multispectral sensor can be applied in different fields of precision agriculture ranging from irrigation water monitoring to the health status of plants and soils up to the monitoring of the chemical-physical conditions of the air.

Keywords - microsensors, machine learning, colorimetry, digitalization

I. INTRODUCTION

Precision agriculture [1] aims to develop techniques and technologies to be used in the agri-food sector to reduce both wastes associated with resource consumption and to develop methods to reduce the impact of crops on the environment and to obtain high quality products that can improve the quality/price ratio. To do that, it is important that cultivated fields have a series of tools to monitor the health of a plant, the ripening of a fruit and the possible onset of problems related to the presence of fungi, the health of the soil as well as its chemical-physical characteristics. In recent years, materials science and various engineering sciences have introduced various sensors into the agricultural market that can be installed in strategic points of the agricultural field or mounted on special drones [1]. The measurements taken by these sensors can then be transmitted via Wi-Fi [2], ZigBee [3-4] or Bluetooth [5] systems to a sort of central system that is consulted by the farmer, who can decide whether to intervene to reduce the possible onset of problems that can damage the quality and the harvest itself. In the future, these data could be an integral part of a single dataset in which it is possible to consult the possible problems of a plant or a vegetable as the chemical-physical conditions and the type of soil, the meteorological conditions and the state of health of the plant itself vary.

A soil is the most superficial layer of the earth's crust and extends from the surface, where there is almost exclusively

humus and organic matter, to a layer of rock, the bedrock, which has a low degree of fragmentation. Each layer of the soil is called a horizon and at the level of nomenclature is named by specific letters as shown in Fig. 1.

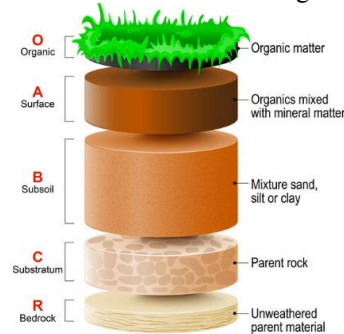


Fig. 1 Geological structure of a soil (Soil is the thin layer of material covering the earth's surface)

In nature there are different types of soil that are classified based on the granulometry through sieves that evaluate the percentage of sand, silt and clay present in each soil sample (Fig. 2). Each soil is also associated with a specific color that is associated both with the content of the grains present but above all based on their mineralogical content.

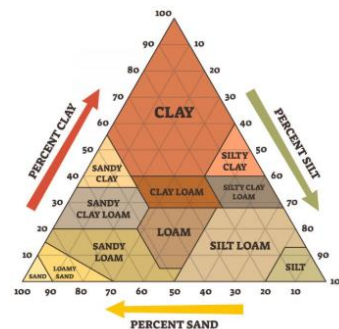


Fig. 2. Soil types classified according to the percentage content of clay, sand and silt (Soil is the thin layer of material covering the earth's surface).

In agricultural fields there are different types of sensors that incorporate different scientific technical knowledge such as geophysics, chemistry up to electronic and telecommunications engineering.

Geophysical sensors are mainly applied for monitoring the first horizons of the soil. At a theoretical level, geophysical sensors analyze two types of waves: electromagnetic waves (in the case of a GPR [6] or a three-wire probe connected to a VNA [7]) or an acoustic wave [8] (in the case of a seismometer). Seismometers, for example, in addition to having an interesting application for the study of site effects in different types of agricultural land [9-10], can also have interesting applications for soil moisture analysis as well as in the case of a permanent seismic station allow other research institutions to perform geophysical analyses such as seismic tomography [11]. Instead, with the use of GPR from the interaction of the waves with the dielectric properties of water, from the analysis of the reflected signal it is possible to analyze the water content of the soil and the soil horizon in which it is located [12-13].

Chemical sensors instead work mainly in monitoring the chemical-physical characteristics of agricultural soil. Temperature [15-16], pH [17] and humidity [18] sensors and conductivity meters [19] are available on the market as gas detectors [14]. The parameters just mentioned can be applied both in monitoring the water with which the fields are irrigated, and to monitor the horizon A of a soil and to monitor the atmospheric environment in which the crop is located. In recent years, the microelectronics industry is developing smart microsensors that can be applied to the world of precision agriculture and through machine learning techniques it is possible to reveal chemical anomalies of the soil or of the leaves themselves even before the effects are perceptible by the human eye [20-21].

The optical sensors available on the market exploit different forms of material radiation interaction such as reflectance [22], transmission [23] and fluorescence [24] of a given substance. This technique is applied through different portable spectrophotometers that work in different ranges of the electromagnetic spectrum: from UV, to VIS [24] up to NIR [25]. The different spectroscopic techniques help us to discriminate for example the presence of microfungi substances on the surface of a leaf as well as the health status of the plant [26]. Fluorescence, for example, is a technique that allows us to observe the water content of a leaf and therefore can provide interesting data on its hydration [27]. Another important type of optical sensors available on the market are colorimeters that can be applied in different fields such as: monitoring the health status of a leaf [28-29] or the color of a soil [30] which is also a diagnostic element of a soil.

II. METHODS

In this context, the company Sensichips srl ([Sensors - Sensichips - learning MICROSENSORS](#)), has developed several microsensors that can be applied in different agricultural fields by providing a data set that can be found

online on the site. These sensors can be applied for the monitoring of water and air pollutants that can be applied in different fields, including precision agriculture as well as for monitoring the colorimetry of a colored surface such as a leaf or soil.

A. SCA

SCA, Fig. 3, is a multi-sensor microsystem (MSM) for monitoring the presence of toxic chemicals (TICs), pollutants, volatile organic compounds (VOCs) and flammable gases in the air.

The SCA integrates temperature, relative humidity, ionic compounds, and metal oxide hotplate sensors. It uses temperature and voltage cycling combined with an electrical impedance spectrometer (EIS) to achieve better gas discrimination. The alternating current (AC) reading is less sensitive to drift, and the EIS allows the sensor's R/C equivalent circuit to be derived to decouple drifting components from gas response components, supporting drift mitigation algorithms. With its versatile analytical tools and integrated interdigitated electrodes, the SCA is also an excellent experimental board for novel sensing materials. Multiple SCAs can be installed on long cables for continuous monitoring of large areas.



Fig. 3. SCA sensor for air quality monitoring

In an agricultural land, the SCA can be installed in some strategic points in order to monitor the air quality and possibly the presence of pollutants harmful to the health of the plant. This sensor will be installed on special poles where it is possible to install a thermometer to monitor the air temperature, an anemometer and hygrometer to analyze the humidity currents and IR cameras facing the agricultural field that allow to monitor the surface temperature of the plant leaves and therefore its health status.

B. SCW

SCW, Fig. 4, is a multi-sensor microsystem (MSM) for monitoring the presence of toxic chemicals (TIC), pollutants, hydrocarbons and organics in water.

At the heart of SCW is SENSIPLUS, Sensichips' microsensor platform that can interrogate on-chip and off-chip sensors with its versatile and accurate Electrical Impedance Spectrometer (EIS) and potentiostat. EIS analyses exploit the RedOx dynamics of catalytic noble metals to aid in chemical discrimination and measurement of conductivity and permittivity spectra. The on-chip

potentiostat is used for a variety of different voltammetric or amperometric measurements and for real-time pollutant discrimination.

By flowing the electrodes with overvoltage, the device prevents or mitigates the formation of biofilm. SCW is a complete and multiparametric microsystem for water analysis.

Thanks to its versatile analytical instruments and the availability of integrated interdigital catalytic electrodes, SCW is also an excellent experimental microsystem for discriminative measurement techniques.



Fig. 4. SCW sensor for irrigation water quality monitoring

This sensor can be applied in different agricultural fields such as monitoring irrigation water and wastewater. In particular, in an agricultural land one can think of installing several SCWs near the irrigation system monitoring pH, temperature and contaminants and the same reasoning can be applied for wastewater. Furthermore, one could think of installing this sensor in different strategic points of the agricultural soil to monitor the nutrients that are dissolved from the soil in the irrigation water near the tree trunks.

C. SCP

The SCP multispectral sensor, Fig. 5, features 12 LEDs covering most of the VIS to NIR spectrum, Fig. 6, and a SFH-2201 photodiode as a detector. The sensor operation is based on the emission of a discrete frequency modulated signal by each single LED on the SCP that is reflected by a colored target such as a leaf or a soil sample and then analyzed by a photodiode that converts it into a current signal. Each LED sensor will be associated with two currents analyzed by the photodiode, one IN-PHASE and one 90° phase-shifted QUADRATURE.

Any LED can be used for light emission and any other LED or photodiode can be used for measurement. Light emission and measurement can be performed with a lock-in amplifier modulation at a user-programmable frequency, both in-phase and quadrature components can be acquired. The use of the lock-in technique helps to reduce ambient light interference on the measurement. This sensor can be thought of as an integrated part of a drone that can ideally fly at a height of about 2.0 m from the ground monitoring the colorimetry of the latter, this

data can provide information on the type of soil and any water shortage.

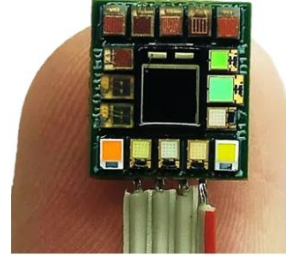


Fig 5. SCP multispectral sensor for monitoring plant and soil colorimetry

Furthermore, the spectral analyses from the drone can also be applied to the analysis of leaves from which the possible onset of diseases as well as a lack of nutrients and water can be analyzed.

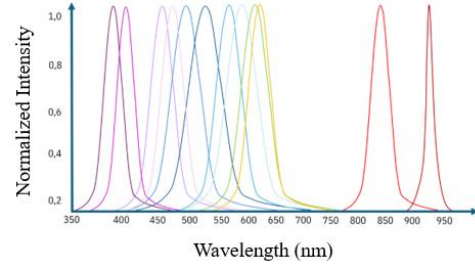


Fig. 6. Emission spectrum of the 12 LEDs present on the SCP multispectral sensor. As can be observed, they cover a large part of the VIS (10 LEDs) and a part of the NIR between 800 nm and 950 nm.

III. MEASUREMENTS

The measurements were performed using the software developed by Sensichips, SLM-Studio, which allows data to be collected from different sensors in a single device. This communicates with the various sensors via a Wi-Fi or ZigBee system that collects the measurements from the various sensors and communicates them to the PC in which the SLM-Studio software is present for data analysis. The measurements are driven through different measurement batches, which provide an alternating current, modulated in frequency, as inputs to the sensor and the collected data is inserted into a Zip folder containing an Excel file with the data.

IV. POST PROCESSING

The data analysis phase is performed through SLM-Studio which provides the possibility of training the various substances through three possible machine learning techniques developed directly by Sensichips in the case of the μ DSP model and preloaded by the IT company UEKA in the case of the MLP and KNN models. At the end of the neural network training phase, SLM-Studio allows you to analyze the average accuracy of the

newly created model as well as the confusion matrix with the accuracies and standard deviations associated with the individual substances for which the model was trained. On the website, you can also consult the test data carried out with SLM-Studio in different experimental conditions that replicate the same training conditions and some small changes to the experimental setup.

V. CONCLUSIONS

The sensors described can be an integral part of an agricultural land where different chemical-physical properties of both the soil and the plants present can be monitored. This system can communicate the various data to SLM-Studio via microcontrollers that communicate with each other with a Wi-Fi or ZigBee system. The dataset available online on the Sensichips website can allow the creation of machine learning models with accuracies greater than 90% that allow the comparison of the raw data of the sensor with the training data available online. From this comparison it will therefore be possible to reveal any anomalies in the soil or plants, providing the farmer with important data on the possible timing of intervention to avoid damage to the plant and minimize losses to the harvest.

VI. ACKNOWLEDGMENT

This work was co-funded by the European Union Horizon Europe program with the project URBAN M20 (GA 101180710).

REFERENCES

- [1] F. Fina, F. Leccese, "The LED's spectrophotometry in precision agriculture: A brief survey", *Acta IMEKO*, vol. 14 (2025) no. 1, pp. 1-15. DOI: 10.21014/actaimeko.v14i1.1970
- [2] P. Musa, H. Sugeru, E. Prasetyo, "Wireless Sensor Networks for Precision Agriculture: A Review of NPK Sensor Implementations", *Sensors*, 2023, doi: <https://doi.org/10.3390/s24010051>
- [3] F. Leccese, "Remote-Control System of High Efficiency and Intelligent Street Lighting Using a ZigBee Network of Devices and Sensors," in *IEEE Transactions on Power Delivery*, vol. 28, no. 1, pp. 21-28, Jan. 2013, doi: 10.1109/TPWRD.2012.2212215.
- [4] F. Leccese, "A New Remote and Automated Control System for the Vineyard Hail Protection Based on ZigBee Sensors, Raspberry-Pi Electronic Card and WiMAX", *Journal of Agricultural Science and Technology*, 2023, B. 3. 853-864.
- [5] W. Bian, Y. Liu, Y. Wu, "A Bluetooth-Based Automated Agricultural Machinery Positioning System", *Electronics*, 13 (24), 4902, (2024), DOI:<https://doi.org/10.3390/electronics13244902>
- [6] K. Zajícová, T. Chuman, "Application of ground penetrating radar methods in soil studies: A review", *Geoderma*, Volume 343, 2019, Pages 116-129, ISSN 0016-7061, DOI: <https://doi.org/10.1016/j.geoderma.2019.02.024>.
- [7] D. Moret-Fernández, F. Lera, B. Latorre, J. Tormo, J. Revilla, "Testing of a commercial vector network analyzer as low-cost TDR device to measure soil moisture and electrical conductivity", *CATENA*, Volume 218, 2022, 106540, ISSN 0341-8162, DOI: <https://doi.org/10.1016/j.catena.2022.106540>.
- [8] F. Adamo, F. Attivissimo, L. Fabbiano, N. Giaquinto, M. Spadavecchia, "Soil moisture assessment by means of compressional and shear wave velocities: Theoretical analysis and experimental setup, Measurement", Volume 43, Issue 3, 2010, Pages 344-352, ISSN 0263-2241, DOI: <https://doi.org/10.1016/j.measurement.2009.11.007>.
- [9] M. Pischietta, F. Linsalata, A. Mercuri, F. Salvini, F. Fina, G. Cultrera, L. Minarelli, G. Di Giulio, "Rock-site amplification on topography at Introdacqua, Central Italy: a rock-fracturing effect?", *Acta Geophys*, (2025), DOI: <https://doi.org/10.1007/s11600-024-01515-z>
- [10] M. Pischietta, A. Mercuri, F. Fina, F. Salvini, L. Minarelli, G. Cultrera, G. Di Giulio, "Passive seismic survey across the fault-zone of Introdacqua, central Italy: the subsurface geological structure role on the site amplification pattern", *EGU General Assembly 2024*, Vienna, Austria, 14–19 Apr 2024, EGU24-18014, <https://doi.org/10.5194/egusphere-egu24-18014>, 2024.
- [11] H. Berger Roisenberg, F. Magrini, I. Molinari, L. Boschi, F. Cammarano, "Rayleigh wave attenuation and phase velocity maps of the greater Alpine region from ambient noise", *Sci Rep* 14, 29164, (2024), DOI: <https://doi.org/10.1038/s41598-024-80729-z>
- [12] K. Grote, S. Hubbard, Y. Rubin, "Field-scale estimation of volumetric water content using ground-penetrating radar ground wave techniques: Water Resources Research", Volume 39, (2023), DOI: <http://doi.org/10.1029/2003WR0245>
- [13] E. Pettinelli, A. Di Matteo, S. E. Beaubien, E. Mattei, S. E. Lauro, A. Galli, G. Vannaroni, "A controlled experiment to investigate the correlation between early-time signal attributes of ground-coupled radar and soil dielectric properties", *Journal of Applied Geophysics*, Volume 101, 2014, Pages 68-76, ISSN 0926-9851, DOI: <https://doi.org/10.1016/j.jappgeo.2013.11.012>.
- [14] P. Tuccimei, M. Soligo, "Correcting for Interference in Soil Radon Flux Measurements." *Radiation Measurements* 43, no. 1 (2008): 102–5. DOI: <https://doi.org/10.1016/J.RADMEAS.2007.05.056>
- [15] A. Almaw, "Soil temperature Sensors in Agriculture and the role of Nanomaterials in Temperature Sensors Preparation", (2018)
- [16] Y. K. Kushwaha, R. K. Panigrahi, A. Pandey,

- "Performance analysis of capacitive soil moisture, temperature sensors and their applications at farmer's field", *Environ Monit Assess* **196**, 793 (2024). DOI: <https://doi.org/10.1007/s10661-024-12946-y>
- [17] M. Nadporozhskaya, N. Kovsh, R. Paolesse, L. Lvova, "Recent Advances in Chemical Sensors for Soil Analysis: A Review", *Chemosensors* **2022**, *10*, 35. DOI: <https://doi.org/10.3390/chemosensors10010035>
- [18] U. B. Mahadevaswamy, N. Meghana, "Design and Development of Soil Moisture Sensor", *International Journal of Innovative Technology and Exploring Engineering (IJITEE)* ISSN: 2278-3075 (Online), Volume-10 Issue-4, February 2021, DOI: <https://doi.org/10.35940/ijitee.D8438.021042>
- [19] M. Mattia, G. Mondati, R. Mazza, C. Rosa, C. Di Salvo, P. Tuccimei, "Groundwater–River Water Interaction in an Urban Setting (Rome, Italy) Using a Multi-Method Approach (Hydrogeological and Radon Analyses)", *Water*, *17* (10), 1555, (2025), DOI: <https://doi.org/10.3390/w17101555>
- [20] M. Vitelli, G. Cerro, L. Gerevini, G. Miele, A. Ria, M. Molinara, "SENSIPLUS-LM: A Low-Cost EIS-Enabled Microchip Enhanced with an Open-Source Tiny Machine Learning Toolchain", *Computers*. *12*. 23. DOI: <https://doi.org/10.3390/computers12020023>
- [21] A. Ria, M. Cicalini, G. Manfredini, A. Catania, M. Piotto, P. Bruschi, "The SENSIPLUS: A Single-Chip Fully Programmable Sensor Interface", In: Saponara, S., De Gloria, A. (eds) *Applications in Electronics Pervading Industry, Environment and Society ApplePies 2021. Lecture Notes in Electrical Engineering*, vol 866. Springer, (2022), DOI: https://doi.org/10.1007/978-3-030-95498-7_36
- [22] M. Leccisi, M. Greco, G. Schirripa Spagnolo, E. De Francesco, F. Leccese, "Low Cost Multispectral Sensor for Monitoring Vine Leaf Density," *2024 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)*, Padua, Italy, 2024, pp. 86-91, doi: <https://doi.org/10.1109/MetroAgriFor63043.2024.10948775>.
- [23] M. Greco, E. Giovenale, F. Leccese, A. Doria, "A Discrimination of Healthy and Rotten Hazelnuts Using a THz Imaging Scanner", 229-233, (2022), DOI: <https://doi.org/10.1109/MetroAgriFor55389.2022.9964672>.
- [24] M. Greco, G. Schirripa Spagnolo, A. Lai, F. Bonfigli, E. Giovenale, F. Leccese, "Detection of Powdery Mildew Disease on Hazelnut Leaves by UV/VIS Fluorescence", (2024), 92-96, DOI: <https://doi.org/10.1109/MetroAgriFor63043.2024.10948845>.
- [25] C.A. Santos, M. Lopo, R. N. M. J. Páscoa, J. A. Lopes. "A Review on the Applications of Portable Near-Infrared Spectrometers in the Agro-Food Industry." *Applied Spectroscopy* *67*, no. 11 (2013): 1215–33. doi:<https://doi.org/10.1366/13-07228>.
- [26] A. K. Mahlein, B. Arnal, G. Jayme, KS Chiang, E. M. Del Ponte, CH Bock, "From Detection to Protection: The Role of Optical Sensors, Robots, and Artificial Intelligence in Modern Plant Disease Management, Phytopathology", Vol 114, 1733-1741, 2024, DOI: <https://doi.org/10.1094/PHYTO-01-24-0009-PER>
- [27] Y. Qm, W. Zhang, "Estimation of Leaf Water Content of Different Leaves from Different Species Using Hyperspectral Reflectance Data", *Annals of Agricultural Sciences*, Vol 7, 1111-2022, (2024), DOI:<https://doi.org/10.26420/annagricropsci.2021.1111>.
- [28] K. Zhang, W. Li, H. Li, Y. Luo, Z. Li, X. Wang, X. Chen, "A Leaf-Patchable Reflectance Meter for In Situ Continuous Monitoring of Chlorophyll Content", *Adv. Sci.* 2023, *10*, 2305552. DOI: <https://doi.org/10.1002/advs.202305552>
- [29] I. Kasajima, "Measuring plant colors", *Plant Biotechnology*, (2019), Vol 36, DOI: <https://doi.org/10.5511/plantbiotechnology.19.0322a>.
- [30] N. Kirillova, T. Sileva, Colorimetric analysis of soils using digital cameras. *Moscow University Soil Science Bulletin*, Vol 72, 13-20, (2017) DOI: <https://doi.org/10.3103/S0147687417010045>