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Toward soil smart sensing in v3.0 agriculture: a new original single-shape design for a capacitive moisture and salinity sensor

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Abstract: To rationalise the amount of water needed to irrigate cultivated fields, modern agriculture imposes the need for better knowledge of the soil moisture content. In this context, since current technological solutions do not correspond to criteria of cost or use, this paper presents a design for a new original capacitive bi-functional sensor to measure soil moisture and salinity. In this paper, we outline all the stages of the design, from simulation to finished elements of the optimal design to deployment in the fields, taking into consideration the constraints of mechanical integration necessary for its industrialisation. Measurement electronics have been developed on the basis of an electric model of the sensor in order to obtain double measurement. Then, an on-site (field lot) measurement program was carried out to validate the good performance of the system in real time. Finally, this performance was matched with that of leading industrial sensors on the market. This work clearly demonstrates that, after deployment of the sensors, the overall system makes it possible to obtain a precise image of the hydric condition of cultivated soil, with the best response time.

Keywords: smart sensing; connected agriculture; capacitive bi-sensor; soil moisture and salinity.

1. Introduction

In modern and ecological agriculture, knowledge of the hydric condition of the soil has become an economic factor of major importance for the supply of water to crops. Accordingly, knowledge of moisture content and salinity is essential to the development of new irrigation systems. To meet this need, one of the most widely employed methods of measurement is the use of tensiometers [1]. Yet, this type of sensor has two main drawbacks: a response time of several hours, during which water is being supplied [2], as well as a phenomenon known as uncoupling [3]. These failings make it problematic to check the quantity of water supplied naturally (rain) or artificially (irrigation). Not only is it impossible to check the soil in real time, but, while these sensors are very sensitive, they often cease to work when the soil is too wet or too dry. In the latter event, it becomes necessary to reinstall sensors, which can be prejudicial to large farm operations.

Consequently, new capacitive measuring technology has been developed to modernise future agricultural installations. It is this capacitive measuring principle that we have selected to measure the level of moisture in the soil [4-6]. The main advantage of this type of sensor is that it possesses a response time of less than a minute, which gives it the ability to monitor the hydric condition of the soil in close to real time [7]. Existing solutions [8-10] include sensors based on a small-sized (<1 mm) detection cell), which limits the volume of soil that can be tested. On the other hand, their complex structures [11-13] do not make them easy to use and require some time, several months, to restructure the soil, which can be damaging to farmers.

44 Since alternative technologies to measure moisture do exist, let us examine the radiofrequency
 45 method [14-15]. This approach does not allow for a double measurement to evaluate soil salinity at
 46 the same time. To respond to this need, our solution exploits the capacitive properties of a sensor
 47 structure because it makes it possible to measure salinity as well as moisture [16-17]. Indeed, subject
 48 to a certain range of frequencies, soil capacity depends not only on moisture but also on its ionic
 49 composition [18]. Thus, by taking one moisture measurement followed by a measurement of
 50 moisture/salinity combined, the same sensor can obtain the two parameters.

51 To allow measurement on the scale of a large agricultural operation, multiplication of
 52 measurement points makes it possible to reach areas that are sufficiently representative of the soil's
 53 hydric condition. Several systems already have been created, but either their cost largely limits their
 54 deployment [19] or the existing system is technologically limited for large-scale use [20].

55 So, in response to these technological barriers, our innovation is based on the design of a new
 56 generation of affordable capacitive sensors that are compatible with the demands of deployment
 57 on a large scale. Section 2 presents an elementary design of the sensor and its optimization. Section
 58 3 presents a modification of the shape factor of the electrodes to optimise measurement parameters.
 59 Section 4 describes the electric model of the sensor, while section 5 presents the design of on-board
 60 electronics for the associated measurement. Finally, section 6 outlines results of on-site performance
 61 tests on actual agricultural operations.

62 2. First approach and optimization

63 Initially, design of the transducer is based on the same principle as a condenser. The structure
 64 rests on two electrodes separated by a dielectric image of the soil. A cylindrical shape is preferred
 65 for this type of transducer to facilitate insertion into the soil. Copper electrodes are fixed to the
 66 cylinder as shown in Figure 1. Since the thickness of the electrodes is less than 1/10 mm, inter
 67 electrode $C_{\text{electrodes}}$ capacity is negligible.



68
 69 **Figure 1.** Sensor shape, first design

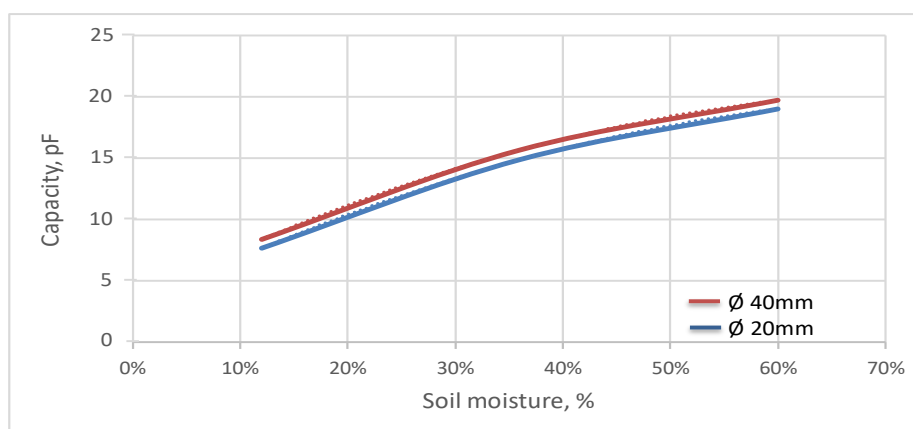
70 For practical reasons and for reasons of mechanical solidity, a 40mm diameter is selected to
 71 demonstrate the feasibility of the initial transducer. Advantages are:

- 72 • ease of insertion into the soil. An auger with a standard diameter is used to make a pre-
 73 hole.
- 74 • soil is minimally de-structured around the sensor to avoid skewing measurements.

75 Electrodes and inter-electrodes must be large enough to ensure connectivity and minimise
 76 parasitic capacity between electrodes. To permit soil moisture detection of 10% with a planar
 77 surface capacity of 25pF, analytical calculations point to 40 mm electrodes spaced 10 mm apart.

78 First, the electrodes surface must be limited to lower the cost of fabrication. The objective is to
 79 reduce the diameter of the transducer while preserving the dimensions' homothetic relationship in
 80 order to minimally affect the ultimate capacity of the transducer. Work to re-dimension the

81 transducer makes it possible to obtain a 20mm diameter on electrodes with a width of 30mm, spaced
 82 8mm apart. Figure 2 shows the evolution of capacities as a function of mass soil moisture for a
 83 diameter of 20mm as opposed to a diameter of 40mm.



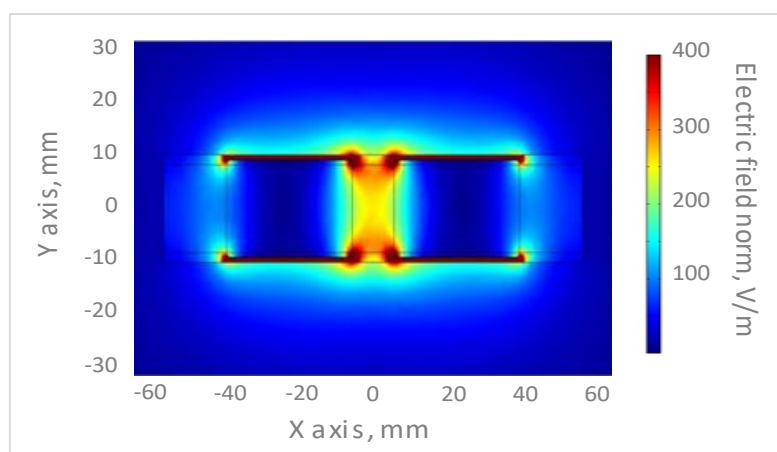
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Figure 2. Cylindrical sensor capacity as a function of soil moisture

86 Curves show that the 20mm transducer has the same characteristics as the transducer with a
 87 40mm diameter, with a sensitivity of $0.26\text{pF}\cdot\%^{-1}$, a variation of 12.6pF subsequent to a 48% change
 88 in moisture.

89 Beyond the sensitivity of the sensor, it is necessary to estimate the volume of soil probed. In
 90 order to conduct this study, COMSOL modelling of the final elements was carried out. The volume
 91 of soil probed is quantified on the basis of the density of the electric field generated (Figure 3).

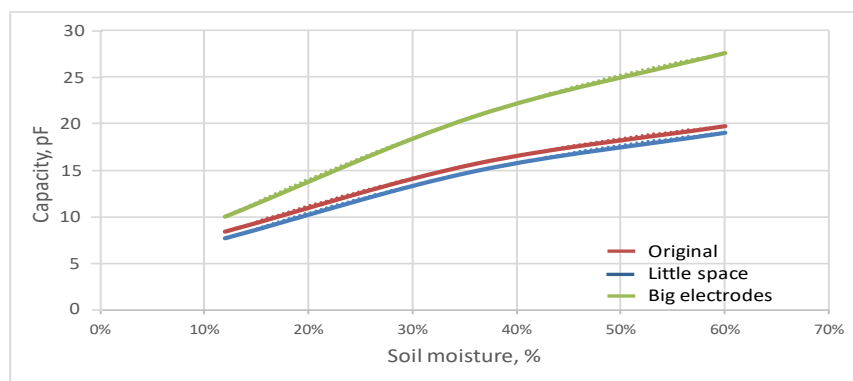


92

93

Figure 3. Density of electric field around cylindrical sensor

94 These simulation results show that a cylinder-shaped transducer with adapted electrodes
 95 (centred between $(-20 ; 0)$ and $(20 ; 0)$) make it possible to observe a 50mm radius with an electric
 96 field density higher than 50V/m , which means that soil volume of about 1.32 litres, with a sensitivity
 97 of $(0.26\text{pF}\cdot\%^{-1})$ is needed in order to electronically probe a sufficient volume of soil. Yet the copper
 98 surface needed is relatively significant (15080mm^2), which raises the cost of the sensor. To optimise
 99 the dimensions of the transducer and thereby reduce the surface of the electrodes, Table 1 and

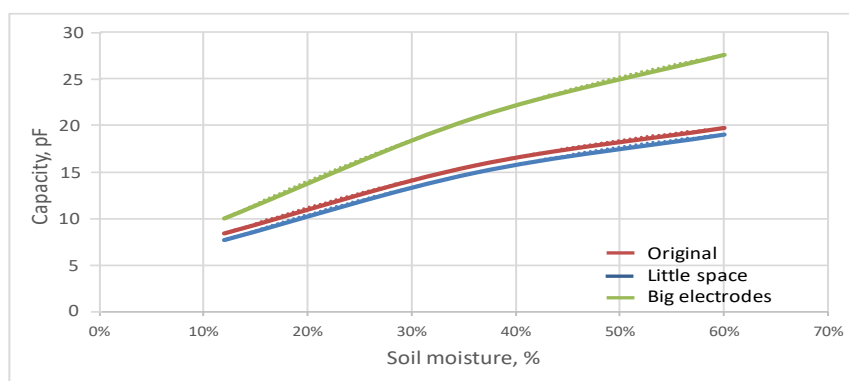


100

101 **Figure 4** present results obtained:102 **Table 1.** New electrode dimensions

Sensor	Diameter(mm)	Space between electrodes (mm)	Electrodes width (mm)	Electrodes surface (mm ²)
Original	20	8	30	3769.91
Little space	20	5	30	3769.91
Big electrode	20	8	50	6283.19

103



104

105 **Figure 4.** Capacity of different-sized electrodes as a function of moisture

106 Analysis of these results allows us to exploit them according to the “rules of electrode design”:

- 107 • If we reduce inter-electrode space, capacity is higher but sensitivity is reduced by 11%, from
- 108 an initial 0.265pF.%⁻¹ to 0.235pF.%⁻¹. This dimensional variation, therefore, is not viable.
- 109 • If we increase this space, capacity is too reduced and becomes impossible to exploit. It is
- 110 preferable, therefore, to preserve a 10mm space between electrodes.
- 111 • If we increase electrode width, we increase capacity as well as the sensitivity of the sensitive
- 112 element. In fact, we go from 0.265pF.%⁻¹ to 0.367pF.%⁻¹, an increase of 38%. However, we
- 113 also increase electrode surface by 67% which raises their cost. The increase in sensitivity is
- 114 not significant enough to justify the resulting cost increase.
- 115 • If we reduce the width of the electrodes, we reduce sensitivity but we gain on the cost.

116 At the end of this optimization work, Figure 5 presents the final shape of the sensor equipped

117 with cylindrical electrodes.

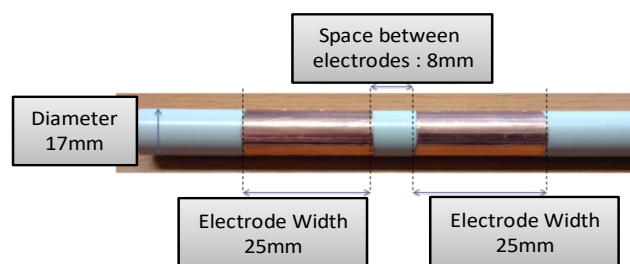


Figure 5. Optimized shape of first design

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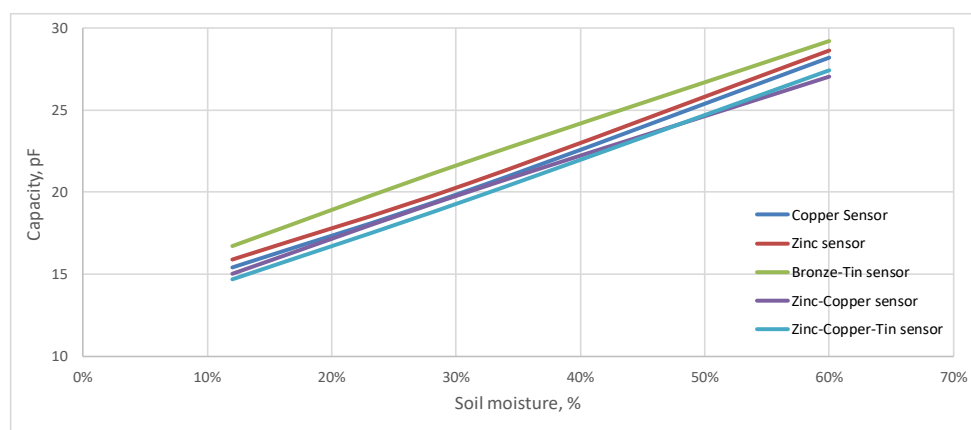
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Even if the geometric dimensions are now optimized, we want to evaluate the influence of materials that are less costly than copper but preserve the same electric characteristics as copper. Identified materials are zinc, bronze, tin or their alloys. To conduct this study, partnership with the company Gilbert SA made it possible to produce several prototypes that we evaluated with an impedance analyser. It should be noted that, in the absence of the exact composition of alloys (for reasons of confidentiality), we have not carried out simulations with the final elements. Figure 6 shows measurement results obtained.



127

128

Figure 6. Capacity of different materials as a function of moisture

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In Figure 6, we can see that copper, zinc and zinc-bronze-tin are suitable for the fabrication of electrodes. Nevertheless, in view of the steam fabrication process, copper, in spite of its higher cost, is the easiest to work with. It turns out, also, that the deposit process is more reliable for the fabrication of the electrodes. This explains why the metal electrodes of the transducer will be made of copper.

134

3. Toward new shapes with higher performance

135

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With the cylindrical shape having been optimized from a geometric as well as a technological point of view, we now focus on a more complete optimization of the sensitivity and/or the volume of the probed soil. To do so, we propose to optimize the electrodes' shape factor.

138

3.1. New sensor shapes

139

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The first parameter to optimise is sensitivity. Knowing that this parameter depends on the contact surface between the soil and the electrodes, it would seem to make sense to increase the contact surface. But in order to stay within initial cost limitations, the useful surface of the electrodes cannot be augmented. It must be distributed differently along the full length of the sensor. The

143 conceptual idea that we defend consists of spreading the electrodes longitudinally around the
 144 cylinder by shaping them into a double helix (Figure 7). This approach is directly inspired by the
 145 strands of DNA. The second parameter to optimise is the volume of soil probed. Knowing that this
 146 parameter depends on the paths of the transducer's field lines, optimization depends on
 147 augmenting these paths. In practice (Figure 8), we distribute the electrodes in the shape of branches
 148 on the periphery of the cylinder, placing them diametrically opposite each other.

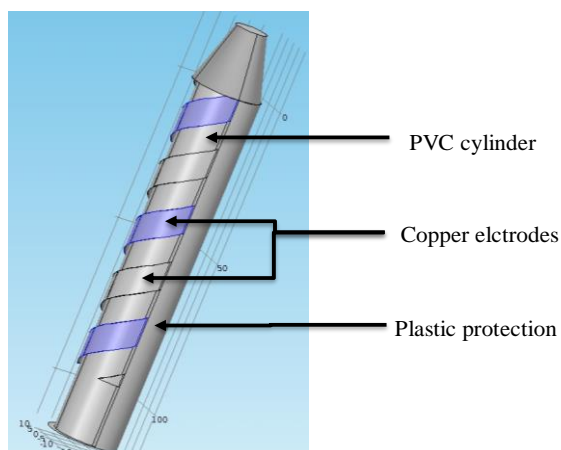


Figure 5. Sensor in the shape of a helicoid

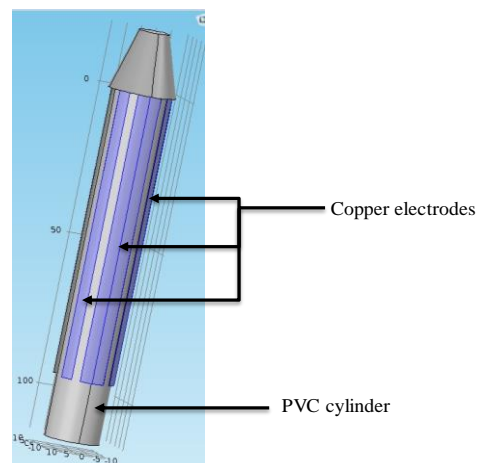


Figure 6. Sensor shape with "vertical ribbons"

149 The sensor with vertical ribbons (Figure 8) is equipped with two electrodes broken down into
 150 three ribbons, a main one in the centre and two 110mm lateral ones, for a total copper surface
 151 of 2670mm².

152 3.2. Determination of volume of soil probed

153 Simulation results confirm that the field created by the helicoidal sensor (Figure 7) is more
 154 uniform than that generated by the cylindrical shape. Assuming that the soil probed is traversed by
 155 an electric field of at least 50V/m, the helicoidal transducer probes a volume of 0.277L as opposed to
 156 1.13L for the cylindrical shape. This decrease is subsequent to the division of the contact surface with
 157 a consequent reduction in the paths of these electric fields.

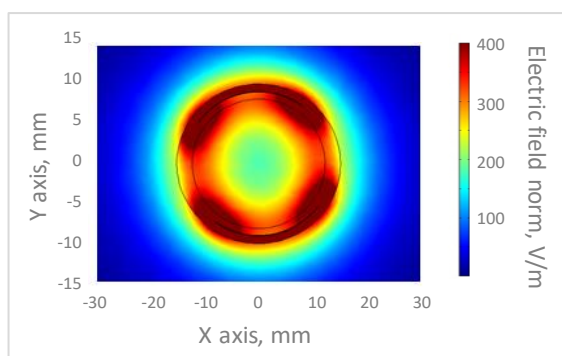


Figure 7. Electric field density around
helicoidal sensor

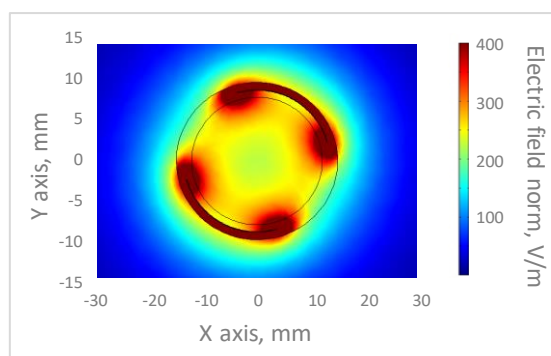
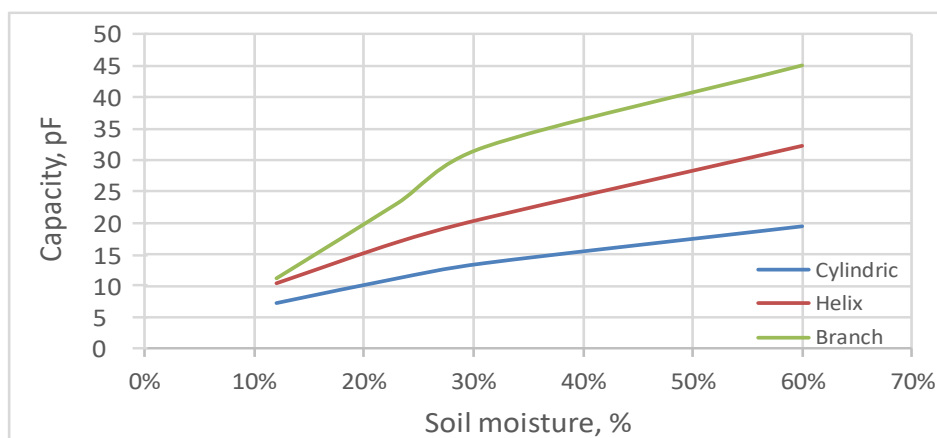


Figure 8. Electric field density around
sensor with branches

158 As for the sensor with branches (Figure 8), its range of action is greater compared to the
 159 preceding shape. The volume of soil probed reached 1,737L, or six times more than with the

160 helicoidal framework, as well as 1.5 times more than the initial structure (cf. §2). This, therefore, is
 161 the new shape factor that permits soil testing on a larger scale.

162 To best illustrate the evolution in terms of electrical sensitivity, Figure 9 presents simulation
 163 results for the different sensors: cylindrical, double helix and with branches.



164

165

Figure 9. Capacity of different electrode shapes as a function of sensitivity to moisture

166 Sensitivity of the double helix shape is 67% higher, with a sensitivity of $0.4417\text{pF}\cdot\%^{-1}$ compared
 167 with $0.265\text{pF}\cdot\%^{-1}$ for the cylindrical sensor. Moreover, response linearity is much better. The
 168 transducer obtained is, therefore, more sensitive for an equivalent cost. For the sensor with
 169 branches, sensitivity also is improved -- by $0.7188\text{pF}\cdot\%^{-1}$ or 171%. Nevertheless, the response
 170 obtained is not linear throughout the entire measurement. The graphic (Figure 9) shows two linear
 171 zones before and after 27% moisture in the soil. Electronic treatment will require two reading
 172 equations.

173

3.3. Choice of final shape

174 Table 2 reflects the characteristics of the three sensors studied. The overall performance of the
 175 sensor with branches stands out.

176 **Table 2.** Summary of sensor shape characteristics

Electrode Shape	Sensitivity ($\text{pF}\cdot\%^{-1}$)	Linear response	Probed soil (Litre)	Copper surface (mm^2)
Rings	0.265	Yes	1.32	2670.35
Double spiral	0.4417	Yes	0.277	2670.35
Branches	0.7188	No	1.737	2670.35

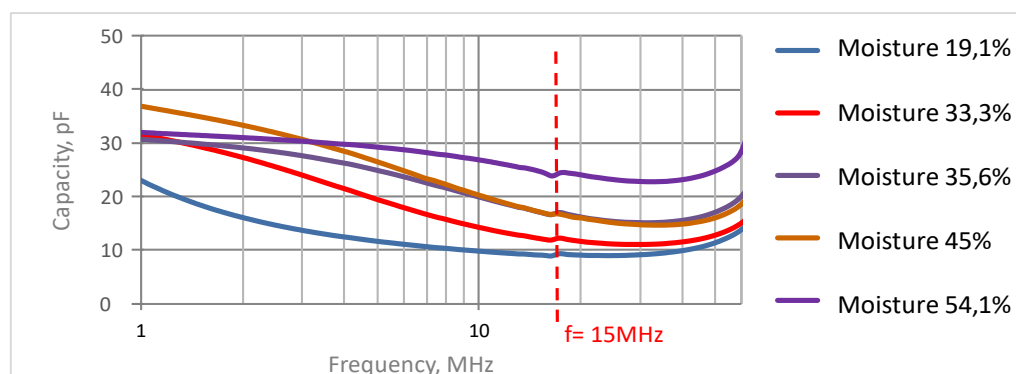
177 The sensor with branches is not only more sensitive, it also registers better soil volume. Clearly,
 178 its response is not linear, but this can be easily corrected with suitable measurement electronics.
 179 This shape is, therefore, the most suitable for our study. Nevertheless, in terms of industrialisation,
 180 this shape also is the costliest due to the discontinuous character of the electrodes. Manufacturers
 181 agree that the cost of fabrication is two times higher, compared to cylindrical or helicoidal shapes.
 182 Economic considerations therefore prevailed over performance in the choice of a helicoidal shape
 183 for the sensor.

184 3. Modelling the helicoidal-shaped sensor

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4.1. Frequency analysis

186 Given the sensor's macroscopic capacitive behaviour as a function of moisture in the soil, this
 187 analysis (Figure 10) is necessary to identify the useful measurement frequency ranges.



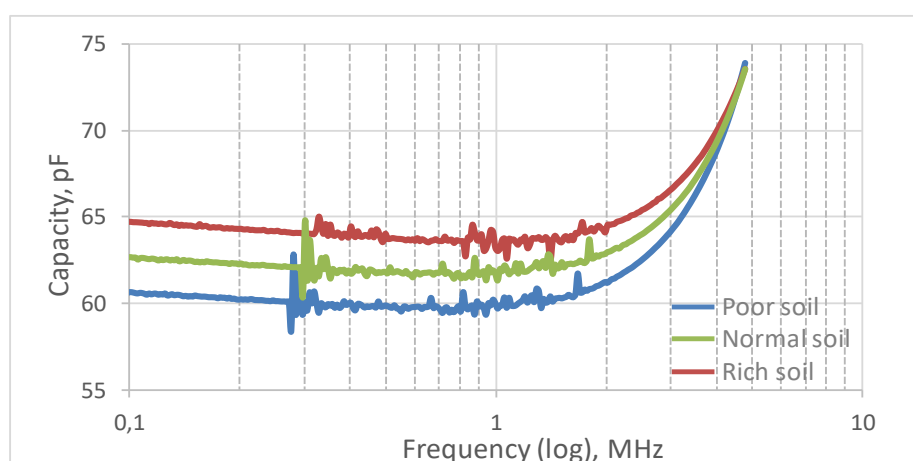
188
 189 **Figure 10.** Sensor capacity as a function of the frequency

190 Figure 10 shows that:

- 191 • Capacity variations are inversely proportionate to moisture in the soil, which confirms
 192 theoretical functioning.
- 193 • As expected, capacity platforms at about 15MHz.
- 194 • Beyond this frequency, the inductive parasitic effect is no longer negligible. This
 195 demonstrates that beyond 15MHz, it becomes difficult to devise an exploitable electronic
 196 conditioner. Measurements are carried out below this frequency.

197 Since the greatest variances in capacity as a function of moisture fall between 1MHz and 15MHz,
 198 a working frequency close to 8MHz was chosen for the electronic conditioner.

199 Would it now be possible to endow the sensor with a second aptitude, so that it could measure
 200 salinity in the soil, depending on the possibility of finding a second frequency interval that would
 201 be sensitive to variations in soil salinity? To this end, we now install a measurement protocol
 202 analogous to the moisture measurement. Capacity is measured on a frequency ranging from
 203 kilohertz to around ten megahertz (Figure 11).

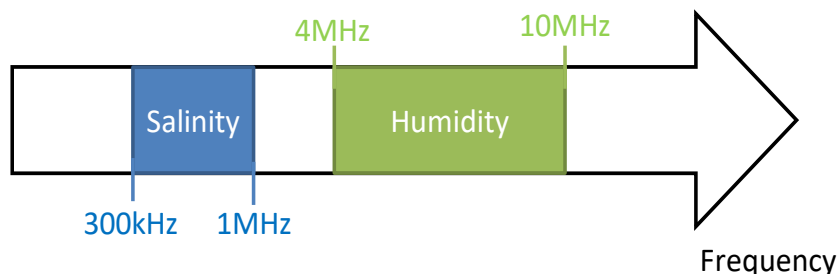


204
 205 **Figure 11.** Sensor capacity as a function of the frequency for different levels of salinity

206 We observe that for frequencies higher than 4MHz, salinity has no influence on the capacity of
 207 the sensor. This means that the moisture measurement of the sensor is not influenced by the salinity
 208 of the soil, which makes the measurement independent. But below 4MHz, capacity increases with
 209 salinity. Yet, capacity does not depend on the measurement frequency as it does for the moisture

210 measurement. There is no preferred zone in this curve but perturbations are observed below
 211 300kHz, which makes it necessary to avoid this zone. Measurement is, therefore, possible on all
 212 frequencies between 300kHz and 1MHz.

213 Figure 12 summarises all useable measurement frequencies.



214

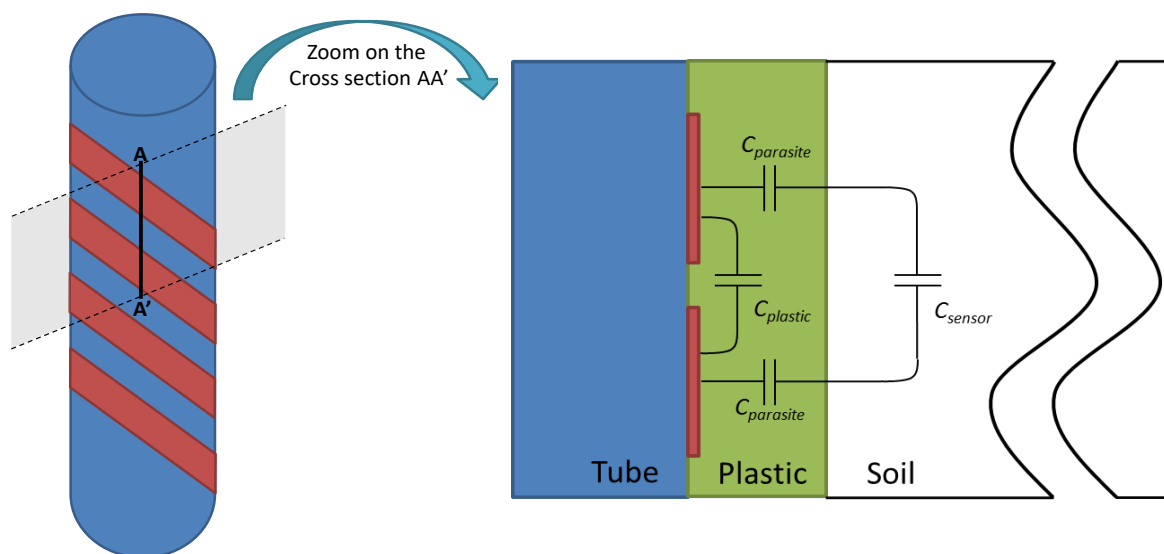
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Figure 12. Measurement frequency zones for sensor

216

4.2. Integration effect

217 For reasons of mechanical protection, we have studied the effect of plastic coating on the sensor.
 218 Figure 13 provides a zoomed view of a cross-section of the sensor. This cross-section localises the
 219 coupling capacity between electrodes, coating and soil.



220

Figure 13. Effect of plastic protection on the sensor

221

Two supplementary pathways generated by the moulding can be observed:

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The transducer system may then be modelled as coated, according to the equivalent electrical diagram presented in Figure 14.

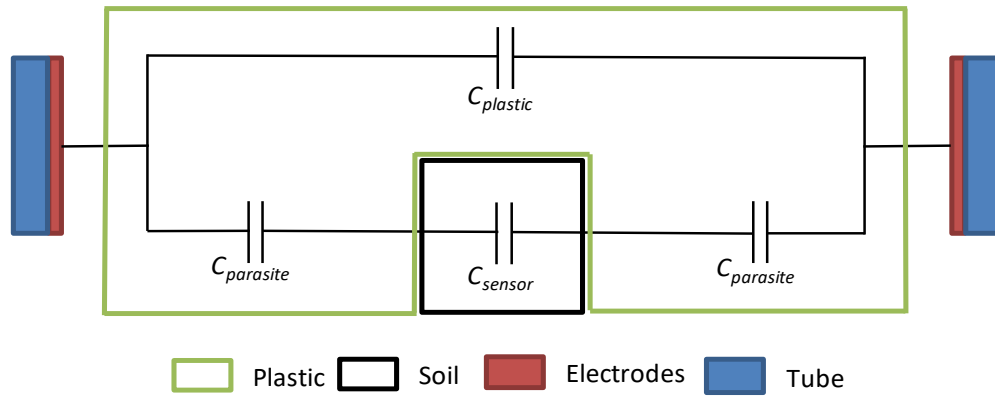


Figure 14. Model of the integration effect on the sensor

230
231
232

233 This model reveals two parasitic effects:

- 234
- Parallel $C_{plastic}$ capacity that adds to the $C_{humidity}$ measurement capacity.
 - A $C_{humidity}$ measurement capacity that is altered by two parasitic capacities $C_{parasite}$, that end up in serial association with capacity $C_{parasite}/2$. This new measurement capacity turns out to be inferior to that of a non-integrated sensor.
- 235
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239 Figure 15 shows the influence of the moulding on the sensitivity of the sensor.

240

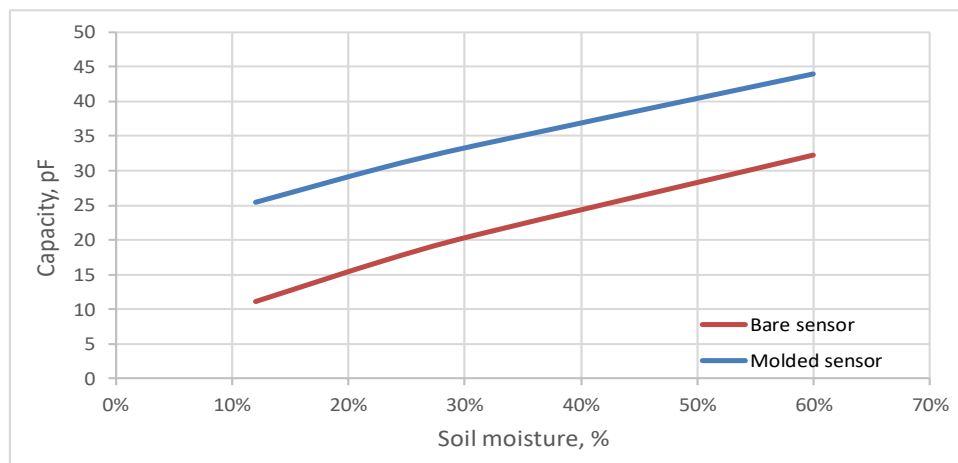


Figure 15. Moulded and unmoulded sensor sensitivity as a function of humidity

241
242
243

244 Two effects on the preceding model can be observed:

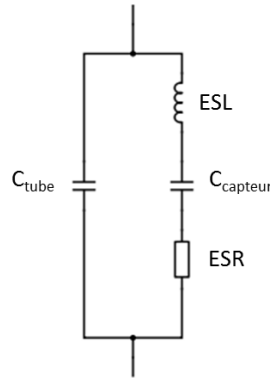
- 245
- The curve of the moulded transducer is superior in every way. It reflects the increase in C'_{hum0} , estimated at 14.7pF.
 - Sensitivity is reduced by 12% with an estimated value of $0.3875\text{pF}\cdot\%^{-1}$, a value always measurable by our system for a relative variation of 1% in moisture.
- 246
247
248

249 It should be remembered that the salinity measurement is affected on the same precise order of
250 grandeur as that of moisture.

251

4.3. Equivalent electric models for sensors

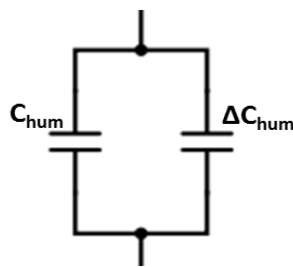
252 Since sensor capacity is not perfect, we want to quantify the ESR, ESL and $C_{\text{electrodes}}$
 253 imperfections of the equivalent model. The Equivalent Series Resistor (ESR) is the resistance that
 254 materialises contact between the two electrodes, with a measured value of $\text{ESR} = 105\text{m}\Omega$. Equivalent
 255 Series Inductance (ESI) consists of the connecting wires that induce the inductive behaviour beyond
 256 40MHz. Measurements show that $\text{ESL} = 60\mu\text{H}$. Finally, inter-electrode capacity is equal to $C_{\text{electrodes}}$
 257 $= 5.18\text{fF}$. Figure 16 reflects this model.



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 259

Figure 16. Electric model of the sensor

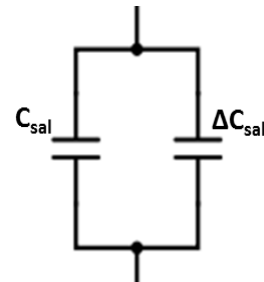
260 C_{sensor} capacity is associated with the type of measurement (moisture or salinity). Models
 261 equivalent to this capacity are shown in Figure 17 and Figure 18.



$$C_{\text{sensor}} = C_{\text{moisture}} = \Delta C_{\text{moist}} + C_{\text{moist}}$$

where $\begin{cases} \Delta C_{\text{moist}} & \text{capacity variation with moisture} \\ C_{\text{moist}} & \text{capacity for 0\% moisture} \end{cases}$

Figure 17. Final electric model for sensor
 as a function of moisture

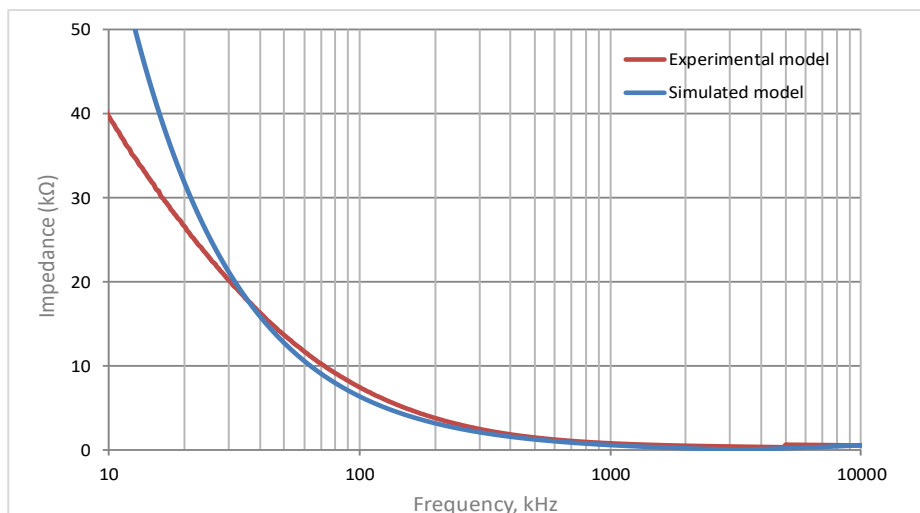


$$C_{\text{sensor}} = C_{\text{salinity}} = \Delta C_{\text{sal}} + C_{\text{sal}}$$

where $\begin{cases} \Delta C_{\text{sal}} & \text{capacity variation with salinity} \\ C_{\text{sal}} & \text{capacity for 0\% salinity} \end{cases}$

Figure 18. Final electric model for sensor
 as a function of salinity

262 To validate the transducer's electric model, a PSpice simulation makes it possible to check
 263 experimental results against the electric. Behavioural results are presented in Figure 21.



264

265

Figure 19. Validation of the sensor model by electric simulation

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As of an impedance of $2.3\text{k}\Omega$ at a frequency of $f=35\text{kHz}$, the curves are almost the same, then, as of $f=400\text{kHz}$, the curves are absolutely the same. Since useful frequency ranges are well above $f=35\text{kHz}$, the electric model for the sensor can be considered validated.

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5. Measurement electronics

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5.1. Architecture

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The architecture that we have developed breaks down into two distinct parts (Figure 20). The first part is the front end. It permits the conversion of the sensor's capacity variations into one electric variation that is exploitable. Bearing in mind the frequency of readings and the low cost of the final system, the sensor is placed in a Colpitts oscillator to allow a capacity conversion frequency that depends on moisture or salinity. Since sensor must be able to perform two measurements, we decided to use two different oscillators set at $f_{osc}=8\text{MHz}$ for moisture and at $f_{osc}=500\text{kHz}$ for salinity.

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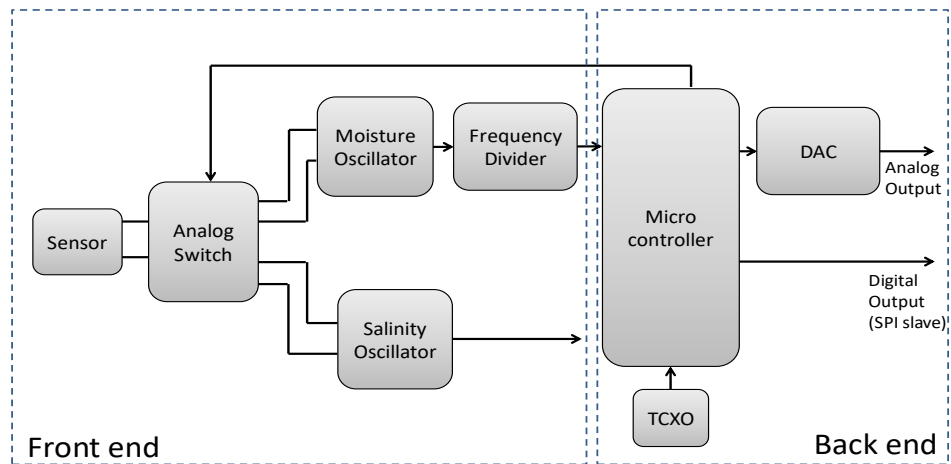
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The back end, or second part of the architecture, delivers readings of the variations. To this end, the back end is structured around one microcontroller embedded with a frequency metre algorithm dedicated to double measurement of a frequency. To minimise the effect of temperature on the measurement, the microcontroller is equipped with a TCXO-type precision clock. To reduce the cost of the system, this microcontroller's frequency performances are voluntarily limited, which explains why the frequency is divided. Once this electronic treatment is accomplished, the back end proposes two types of complementary outlets, an analogue outlet that makes it possible to deliver voltage proportionate to moisture or to salinity with the aid of a CAN and a digital outlet that can be configured to establish a communications link with a standardised protocol (slave SPI).



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Figure 20. Functional diagram of measurement electronics

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5.2. Material integration

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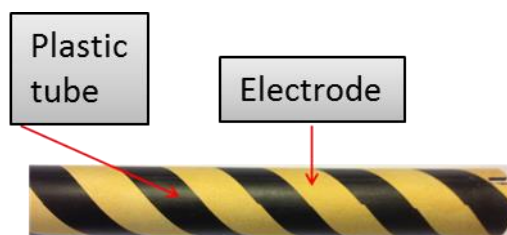
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In the process of industrial production of the sensor, the sensor tube will be manufactured according to an industrial procedure. The first stage consists of devising a cylindrical support tube. Then, the electrodes are produced according to photolithography and by electrochemical deposit of copper on a surface that has been made functional by a laser. Finally, a nickel/gold layer is deposited to protect the copper from oxidation. Figure 21 presents the finished sensor produced by this process.



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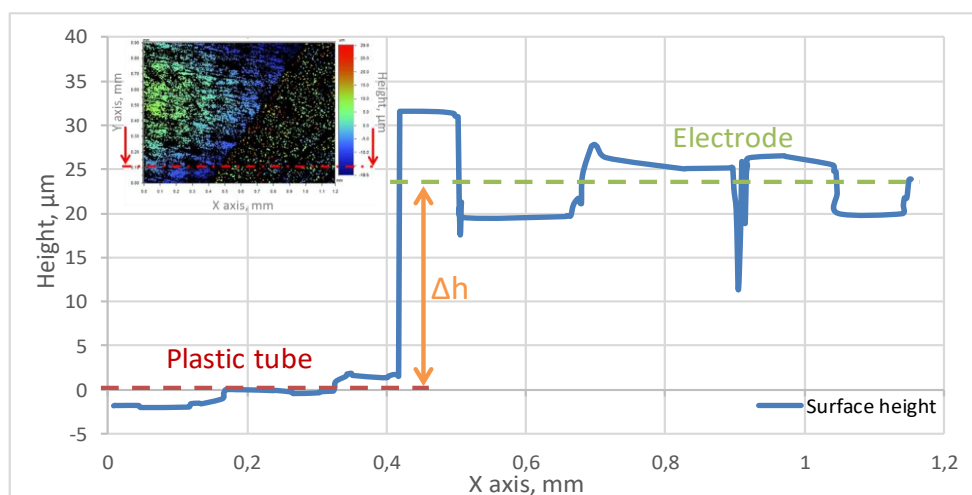
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Figure 21. Shape of the industrially produced sensor

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To control the thickness of the metallic deposit, measurement by optical profilometer is carried out. Readings of these measurements are presented in Figure 24.



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Figure 22. Electrode deposit profile

301 This figure shows:

- 302
- 303
- 304
- 305
- On the left of the graphic we can see the plastic tubing. It serves as reference to measure the height of the electrodes;
 - On the right, there is the measurement of the average height of the metallic deposit: $24\mu\text{m}$ ($20\mu\text{m}$ Cu, $4\mu\text{m}$ NiAu).

306 Since the sensor is to be inserted in the soil, it needs to be mechanically solid so that it is not
 307 damaged during its installation. As for the electronic board (Figure 25(a)), it is inserted in the sensor
 308 tube so that it forms a compact unit with no flexion points. To promote the mechanical longevity of
 309 the ensemble, recesses (Figure 25(b)) have been specifically sized.

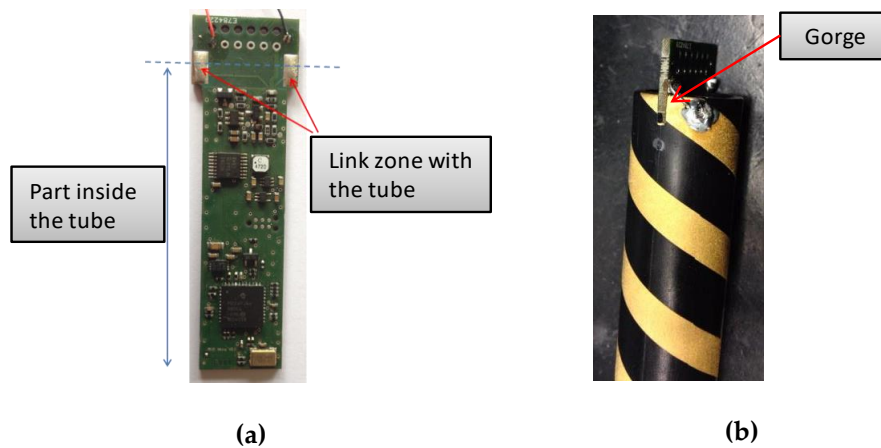


Figure 23. (a) Photo of the measurement electronic board; (b) Photo of the connection between the board and the sensor tube

310 To permit power supply and communication with the system, a protective shield is directly
 311 soldered onto specific landing pads. Finally, the sensor's water tightness is ensured by an injection
 312 of plastic into a mould. Figure 24 is a photo of the final sensor.

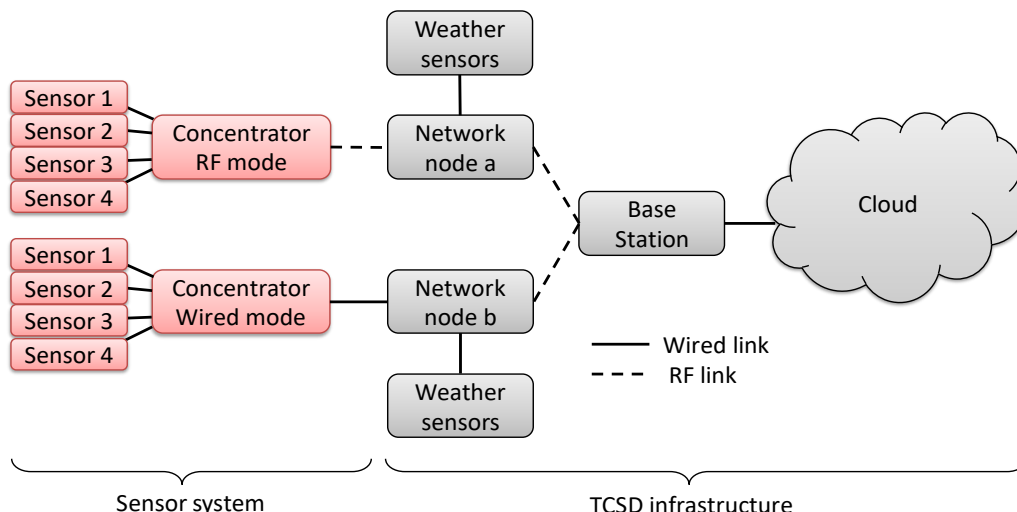


313

314 **Figure 24.** Photo of the industrially moulded sensor

315 *5.3. From the sensor to the final user*

316 With the aim of deploying the sensors in the cultivated fields, the architecture of the network is
 317 shown on Figure 27. It makes it possible to ensure the transmission of moisture and salinity
 318 measurement readings to the user. This infrastructure was developed with the support of the TCSD
 319 company. This company markets systems that collect data for agriculture (weather and soil).



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Figure 25. Architecture of sensor network

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Figure 27 reflects the different stages of data collection:

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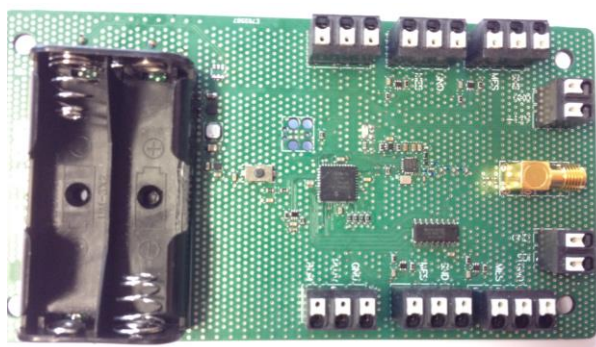
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- A concentrator supervises each sensor. Each concentrator can collect data from four sensors. It then communicates this data by a wire connection with an SDI-12 protocol, either by a radiofrequency link on the ISM 868MHz band to allow total control of the exchange protocol. Tests have demonstrated a radio range of 600m with a baud rate of 9600bits/s. Energy autonomy of the concentrator is provided by four AA batteries that last for an entire irrigation season (about 8 months). Figure 28 shows the electronic board.



330

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Figure 26. Photo of the electronic board produced

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- Data then goes through the other network nodes that could be concentrators used in repeating mode or weather data collection points that also could serve as the bridge.
- Data finally arrive at a base station connected to the Internet, where information is stored on an on-line server. From then on, the user can consult the data by means of a web interface or mobile application.

337

6. Longitudinal moisture measurements

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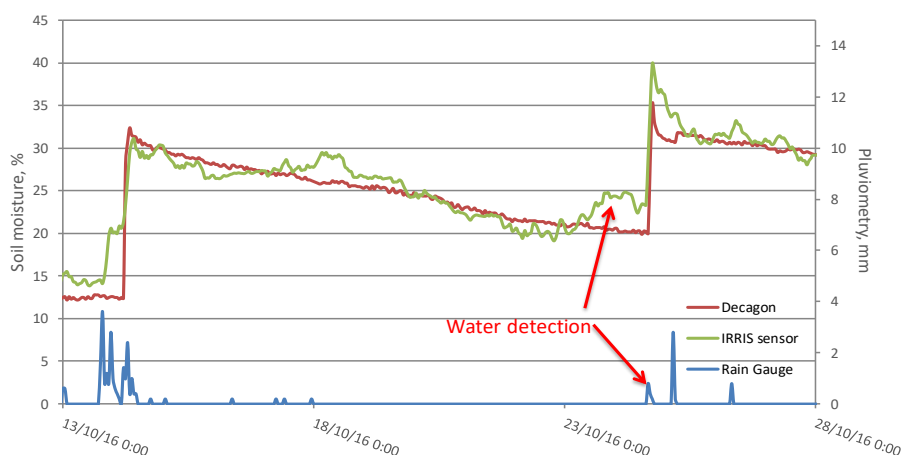
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After the system is installed and deployed in cultivated and irrigated fields, moisture monitoring performance is compared to that of two major players in the market: Decagon and Sentek Technologies. As this work continues, the sensor that we have developed is called IRRIS for IRRigation Ingénierie Systèmes.

342 Figure 27 presents measurement readings in an orchard that is cultivated all year round. Data
 343 from the IRRIS sensor shown on the graphic reflect three weeks of surveillance and are compared
 344 with that of the Decagon sensor.



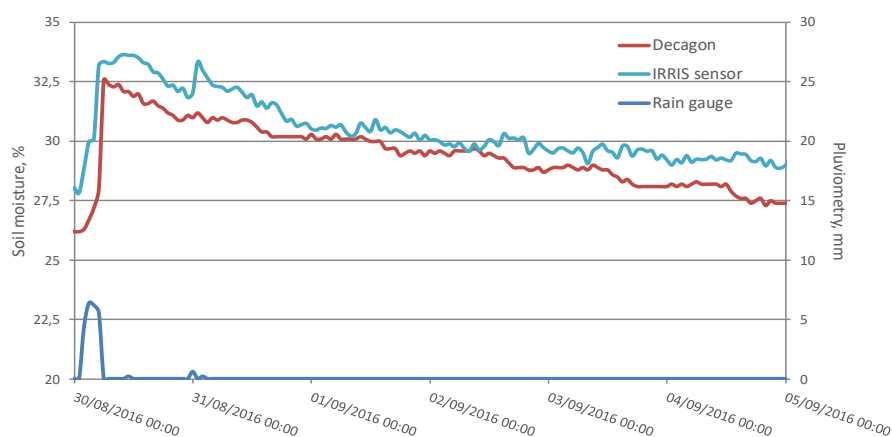
345

346

Figure 27. Results of a sensor in an orchard

347 The greater sensitivity of the IRRIS sensor is noticeable. As soon as the presence of water is
 348 detected by the IRRIS sensor, the moisture measurement increases, while the Decagon sensor does
 349 not detect this presence of water until after a few hours (red arrows). Detection, therefore, is better
 350 with the IRRIS sensor. The rising dynamic (+20%) and the descending dynamic (-2% per day) are
 351 identical for the two sensors, which validates the good performance of our sensor on this piece of
 352 agricultural land.

353 The second study addresses the surveillance of a corn field. Measurement readings reflect
 354 several days of continuous surveillance because of an installation made at the end of a cultivation
 355 cycle before the lot is harvested. Figure 28 presents results obtained.



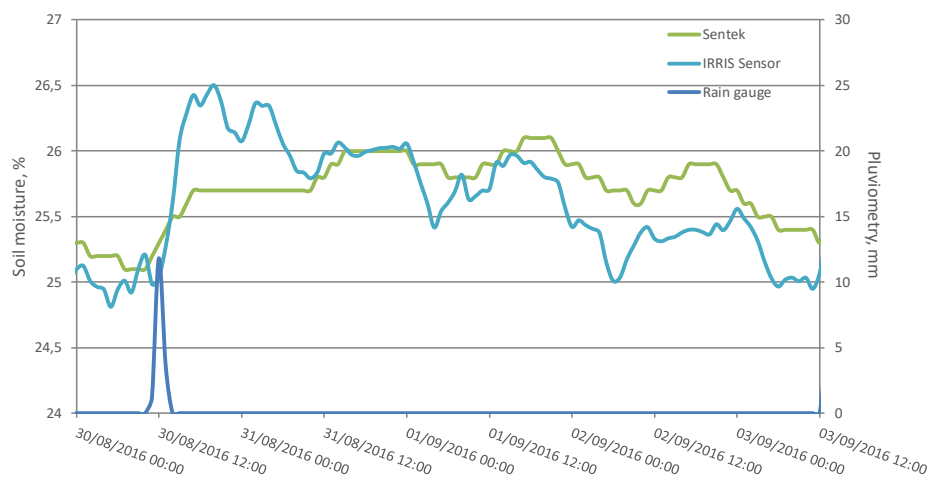
356

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Figure 28. Sensor results in a corn field

358 This figure compares the dynamic and the response time of the IRRIS sensor compared with the
 359 Decagon sensor. In terms of reactivity, the IRRIS sensor reacts 30 minutes before the Decagon. With
 360 regard to dynamics, the moisture measurement rise due to the supply of water is identical for the
 361 two sensors (+7%). The descent dynamic is more rapid for the Decagon since it has been placed
 362 closer to the plants, and water is, therefore, more rapidly absorbed by the plants. These
 363 measurement readings testify to the good performance of the IRRIS sensor on this type of crop.

364 The last test is conducted with a Sentek sensor in another corn field. Figure 31 presents the
 365 results.



366

367 **Figure 29.** Sensor results compared with the Sentek sensor in a corn field

368 IRRIS sensor dynamics resemble those of the Sentek sensor. A measured rise in moisture after a
 369 supply of water followed by a slow descent on the scale may be clearly observed. What's more, this
 370 graphic shows the evapotranspiration effect. In fact, during a day/night cycle, it possible to observe
 371 a characteristic oscillation that displays this phenomenon. The IRRIS sensor also measures the
 372 phenomenon, which validates its performance.

373 To conclude on these tests, comparative response curves for the IRRIS sensors and the
 374 industrialised sensors attest to the superior performance of the IRRIS sensor. In this paper, we have
 375 shown that it is possible to detect small amounts of water more rapidly. This work clearly
 376 demonstrates the possibility of following these dynamic variations of moisture in the soil, when
 377 water is being supplied, as well as when the soil is drying out due to lack of water.

378 7. Conclusion

379 The sensor therefore is capable of measuring moisture and salinity in the soil for different types
 380 of crops. Thanks to its cylindrical shape, the sensor may be installed easily in the soil, and its
 381 different outlets (analogous wire, digital with or without wire) allow for a direct connection on most
 382 existing systems. Moreover, with a cost of fabrication estimated at less than 50€ per unit, its price
 383 makes it possible to multiply measuring points to better chart the hydric state of cultivated soil.

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390

391

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 393 analyzed the data; J.Y.F administrated the project; C.E. and J.R wrote the paper.

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