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Adaptive robot control based on Wireless Underground Sensor Network in Agriculture 4.0

Christophe Cariou

University Clermont Auvergne

INRAE, UR TSCF

F-63178 Aubière, France

christophe.cariou@inrae.fr

Laure Moiroux-Arvis

University Clermont Auvergne

INRAE, UR TSCF

F-63178 Aubière, France

laure.moiroux-arvis@inrae.fr

François Pinet

University Clermont Auvergne

INRAE, UR TSCF

F-63178 Aubière, France

francois.pinet@inrae.fr

Jean-Pierre Chanet

University Clermont Auvergne

INRAE, UR TSCF

F-63178 Aubière, France

jean-pierre.chanet@inrae.fr

Abstract—From sensor nodes fully buried at a few dozens of centimeters deep in Wireless Underground Sensor Networks (WUSN), the soil moisture information can be measured anywhere, including in the passage of vehicles. This opens new opportunities, in particular in Agriculture 4.0, to adapt the speed and work of agricultural mobile robots to the ground conditions. By integrating a collector node in a robot, connected to its CAN bus, this paper experimentally demonstrates the possibility to adapt in real time the speed of the robot with respect to the soil moisture information transmitted in LoRa by a buried sensor node. The hardware and software developments are presented, and the first experimental results discussed. Future research directions are given to extend the capabilities of the system proposed. The innovative approach presented in this paper enables to envision new possibilities in the combination of WUSN and robotics technologies.

Index Terms—IoUT, WUSN, mobile robotics, agriculture

I. INTRODUCTION

Internet of Underground Things (IoUT) and Wireless Underground Sensor Networks (WUSN) are new emerging technologies, particularly relevant for Industry 4.0 and Agriculture 4.0, see [1], [2]. In comparison to their aboveground counterparts, the electronic devices are fully buried below the surface, from a few centimeters to several dozens of centimeters deep, see Fig. 1, [3]. This new paradigm is particularly interesting as it enables to install sensor nodes anywhere, including in the passage of vehicles, while offering a protection against climatic events and human degradations (e.g. theft, vandalism).



Fig. 1. Sensor nodes with their moisture probe buried at 15 cm deep in a pasture, before being recover by soil

Current research on WUSN and IoUT focuses primarily on the improvement of the communication ranges, especially for the underground to underground (UG2UG) communication

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link (the electromagnetic waves are highly attenuated in the soil, about 20 to 300 times worse than in the air [4]), the energy consumption and the quality of service [5]–[7]. The measurements of the buried sensor nodes are transmitted to either aboveground gateways connected to the cloud or collection vehicles (e.g. mobile robot, drone) passing through the vicinity [8]. At the time being, the main targeted applications of WUSN and IoUT are the collection of soil moisture and soil temperature information to feed decision-making tools in precision farming (e.g. irrigation management), but other applications are progressively emerging as the monitoring of infrastructures (e.g. leakage of pipelines), sport field maintenance (e.g. golf course) and landslide detection [9]–[11].

At the same time, mobile robotics is progressively transforming the agricultural sector by enhancing productivity and performing environmentally friendly operations [12], [13]. With Big Data, IoT, and Artificial Intelligence (AI), robotics is today full part of Agriculture 4.0. The task of robots is to go back and forth between crop rows to perform operations as soil tillage, weeding, pesticides spraying or disease scouting. However, one of the major challenges for an agricultural robot is to accurately follow the planned trajectories, all the more in presence of ever-changing grip conditions [14], [15], and adapt both its speed and work to the encountered ground conditions (while not staying stuck), see Fig. 2. The problem is that the volumetric water content (VWC) of a soil, which impacts directly the presence of sliding and the tuning of the agricultural implement, is an information difficult to access from sensors embedded on the robot and to know before entering in the area. The microclimate weather stations positioned at the edge of the field are not sufficient to establish



Fig. 2. The agricultural robot can stay stuck when entering in a muddy soil, requiring the tedious and costly intervention of the farmer.

high-resolution soil moisture maps. In addition, aboveground devices can not be installed and multiplied inside the field as they represent obstacles for the farming activities. To give the robot the capacity to anticipate and adapt its behavior to the changing ground conditions within a field, from the beginning of the day to the end, we propose to combine the recent advances in WUSN and robot navigation to adapt the speed of the robot, adjust the tuning of its agricultural implement and avoid wetland areas. To that end, we developed a system based on a WUSN measuring the soil moisture information. This information is collected in real-time by a collector node connected to the CAN bus of the mobile robot, to adapt the setpoint values of the controllers accordingly.

This paper is organized as follows. A brief review related to data collection from buried sensor nodes is presented in section II. The methodology used to develop our adaptive robot control system based on WUSN is detailed in section III. The experimental devices and experimental results are presented in respectively sections IV and V. Section VI discusses future research directions, and the paper ends with some conclusions in section VII.

II. RELATED WORK

A. WUSN

A WUSN usually comprises several communication links, as presented in Fig. 3, namely Underground to Underground (UG2UG) links, Underground to Aboveground (UG2AG) links, Aboveground to Underground (AG2UG) links, and eventually Aboveground to Aboveground (AG2AG) links. In comparison with WSN, a major feature of WUSN is that the inter-node communication range varies considerably with respect to numerous environmental factors, as the nature of the soil (percentage of sand, silt and clay [16]), the Volumetric Water Content (VWC), but also the burial depth due to reflection phenomena with the ground surface. The UG2UG link is difficult to establish beyond a few meters, whether it be from technologies based on electromagnetic waves or magnetic induction [17]. Recently, we demonstrated however that the UG2AG link can reach communication ranges of more than 270 meters in LoRa at 868 MHz, with a particular antenna configuration and low burial depth (15 to 30 cm), see [18]. The quality of the AG2UG communication link is usually poorer than UG2AG, see [19].

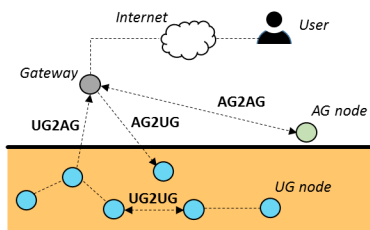


Fig. 3. The different communication links in a WUSN

Another major difference in comparison with aboveground devices, is that the buried sensor nodes have no access to

external power source (e.g. solar panels). The energy consumption must therefore be minimized as much as possible to obtain operational lifetimes of the WUSN of ideally several years without battery replacement. To that end, low power communications (e.g. LPWAN: LoRa, SigFox, NB-IoT) and optimisation strategies (e.g. standby mode, wakeup time window, radio parameter adaptation) are sought, see [20].

B. Data collection

To collect the data of buried sensor nodes in a WUSN, several ways have been investigated in the literature from static gateways and mobile vehicles, see Fig. 4. For example, [21] buried 23 sensor nodes at 40 cm deep within a large area. A gateway with an antenna mounted at 10 meters high received the data (SigFox, 901.2 MHz). The results showed that half of the packets were lost when the UG2AG link exceeded 250 m. Recently, we demonstrated the possibility to use an Unmanned Aerial Vehicle (UAV) to collect the data of buried sensor nodes in hovering or dynamic modes [8]. The measurements on the RSSI (Received Signal Strength Indication) levels with respect to the position of the UAV highlighted the interest to maintain a high altitude when the UAV flies far from the buried sensor node. The planning of the optimal trajectories for the UAV is another challenge requiring to address the Close Enough Traveling Salesman Problem (CETSP), which can be aborred from the developement of evolutionary algorithms completed with heuristics approaches, see [22]. Terrestrial mobile robots can also be used to collect the data during their navigation in the field, as presented in [23].

In the end, all the data collected are intended to be stored in large databases and big data processing algorithms are studied to define the best actions to be performed.

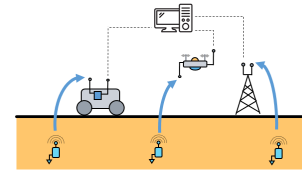


Fig. 4. Different ways to collect the data from buried sensor nodes

III. METHODOLOGY

The approach proposed in this paper is innovative and complementary to the work presented so far, as the objective is, in addition to the data collection task, to adapt in real time the behavior of an autonomous mobile robot with respect to the measured soil moisture information provided by a WUSN. To that end, a collector node is embedded on the mobile robot and communicates with the steering, speed and implement controllers from a CAN bus interface. In addition to the soil moisture information collected from the buried sensor node, this collector node has reading access on the CAN bus to obtain essential informations about the current position and speed of the robot, as well as the state of the agricultural implement. It has calculating capabilities, and can send CAN

messages to the robot to adjust the setpoint values of the different controllers, see Fig. 5.

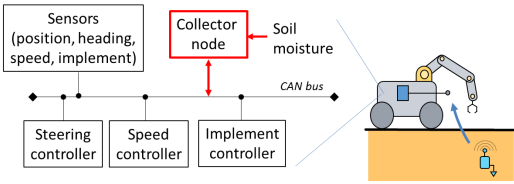


Fig. 5. A collector node of soil moisture is integrated to the robot to adjust in real time the setpoint values of the steering, speed and implement controllers.

When the robot will enter in the coverage range of a buried sensor node, the collector node will measure first the RSSI signal (Received Signal Strength Indication). If this value is above a threshold (set to -65 dBm), the soil moisture information is used to calculate the setpoint values to send to the controllers of the robot, namely:

- **The speed controller:** an adaptive function is defined to establish the optimal speed setpoint for the robot with respect to the soil moisture (see Fig. 6),

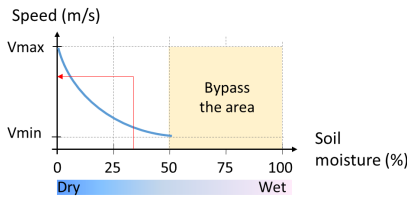


Fig. 6. Adaptive function: speed of the robot with respect to the soil moisture

- **The implement controller:** the setpoints are defined for the actuators of the implement (e.g. nozzles of a spraying boom, lift of a soil tillage implement),
- **The steering controller:** in case of an excessive soil moisture, the order is given to deviate the trajectory from this area similarly as an obstacle avoidance procedure. If the area to be avoided has a large size, a complete replanning procedure of all the trajectories to be followed by the robot in the field can be required.

When the RSSI signal falls below a given threshold (set to -80 dBm), the collector node gives back the control to the robot.

IV. EXPERIMENTAL SETUP

The objective of this paper is to demonstrate the feasibility to adapt the behavior of an experimental mobile robot with respect to the soil moisture information measured from a WUSN. To that end, an experimental setup was defined, based on hardware and software developments.

A. Hardware

We developed several sensor nodes, see Fig. 7 (left), which will be buried underground at 15 cm deep. The electronic board is composed of an Atmega328-AU 8 MHz microcontroller manufactured by Microchip, and a RFM95W LoRa

radio module manufactured by HopeRF. This radio module comprises the SX1276 transceiver of Semtech operating at 868 MHz. A quarter wave whip antenna (RF FLEXI-SMA-868, 2 dBi gain, 13.6 cm) is used for the transmissions and a rechargeable lithium battery 3.7 V/8.8 Ah supplies the board. A temporal reference DS1378 enables to switch between a deep-sleep mode (energy consumption: $4 \mu\text{A}$) and an active mode (energy consumption during measurement or data transmission: 50 mA). A 8 bit memory EEPROM with I2C-bus interface enables to store the measurements. A SMT100 probe (range 0-60 %, accuracy 3 %), manufactured by Truebner, is connected to the board to measure the moisture, temperature and permittivity of the soil. The electronic board is housed within a box to protect it underground.

We developed a collector node with the same architecture than the buried sensor nodes, see Fig. 7 (right). It comprises in addition a CAN bus interface to communicate with the robot. It has also a high data storage capacity with a 2 Go SD card, and can be powered from an external power source.



Fig. 7. The developed sensor node (left) and collector node (right)

The mobile robot used to perform the experimental tests is presented in Fig. 8. This robot was specifically designed and built in our lab to experiment new controllers and smart navigating functions. It is electrically propelled by 12.8 kWh Lithium-ion batteries. The wheelbase is 1.40 m for a total length of 2.50 m, the track is adjustable from 0.70 m to 1.30 m. It weighs about 550 kg with a maximal payload of 150 kg. It has four independent wheeled-motors and four independent steering actuators. Speeds up to 10 m/s can be reached in the wide track configuration. The implement at the rear is a horizontal sprayer. Four nozzles are placed at different working distances and can be activated independently.

The architecture of this robot is built around three main controllers (steering, speed, implement) joined by a CAN bus at 500 Kb/s. As our previous work enabled to develop steering control algorithms with trajectory following performances



Fig. 8. Experimental robot used for the tests. The collector node is embedded and connected to the CAN bus of the robot.

independent from the vehicle velocity [24], the steering and speed controllers can be separated. The collector node is connected to this CAN bus.

B. Software

The UG2AG communication link between the buried sensor nodes and the collector node is carried out in LoRa at 868 MHz, see the detailed presentation of the LoRa technology in [25]. The transmit power is tuned to +14 dBm/25 mW, the bandwidth at 125 KHz, the Coding Rate at 4/5, and the Spreading Factor is tuned to 7 (SF7). The advantage of the LoRa technology, based on a Chirp Spread Spectrum (CSS) modulation technique, is to have a high signal reliability and receiver sensibility while maintaining a low energy consumption. Although the data rate is limited (about 0.29 kbps to 5 kbps), it remains largely compatible for our application.

The buried sensor nodes are programmed to periodically measure the soil moisture with a configurable period. At the beginning, the radio modules are in listening mode. When a buried sensor node receives a message from the collector node, a data frame is emitted, including the sensor node ID, the increment of the number of frame, the timestamp, the battery voltage of the node and the measurements: moisture, temperature and permittivity of the soil). The RSSI signal is measured by the collector node. If this value is above a threshold (set to -65 dBm), the soil moisture information is taken into account to determine the setpoint values for the controllers of the robot.

V. RESULTS

The definition of the adaptive function (i.e. speed setpoint with respect to the soil moisture) is first established, see Fig 9. A first experiment is then carried out in a dry field (soil moisture $\cong 0\%$). A sensor node is buried at 15 cm deep. The mobile robot is directed toward its direction and comes back. Fig. 10 presents the obtained results. At the beginning (time 0 s), the buried sensor node is already detected but with a RSSI value equals to -80 dBm, i.e. it is not taken into account. At the time 40 s, the robot approaches the buried sensor node and the RSSI signal becomes upper than -65 dBm. The setpoint value for the robot is then calculated by the collector node (1 m/s) and sent to the robot until the time 65 s corresponding to the time where the RSSI value becomes lower than the threshold of -80 dBm. This is reproduced during the return trajectory between the times 110 s and 122 s. We can observe that the speed of the robot is effectively regulated to 1 m/s during these two periods.

A second experiment is performed with a soil moisture at 6 %, see the results in Fig. 11. The speed of the robot reached about 1.5 m/s at the beginning of the experiment. When the robot enters in the speed control area with the buried sensor node, its speed is constrained to be reduced by the collector node at the value of 0.7 m/s. We can observe clearly the regulation of the speed of the robot at 0.7 m/s between the times 24 s and 61 s.

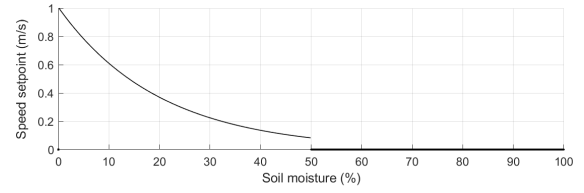


Fig. 9. Calculation of the speed setpoint with respect to the soil moisture ($V_{(m/s)} = \exp^{-0.05 * M(\%)}$)

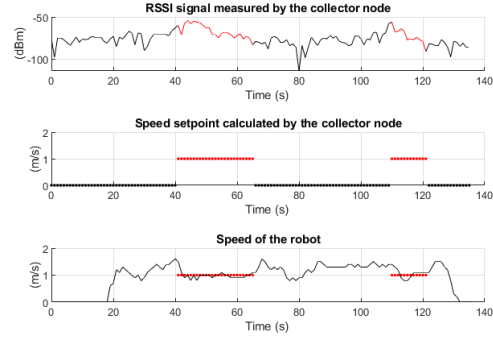


Fig. 10. Experiment performed on dry soil. The setpoint value calculated by the collector node is 1 m/s, it is applied during the periods (40 s, 65 s) and (110 s, 122 s).

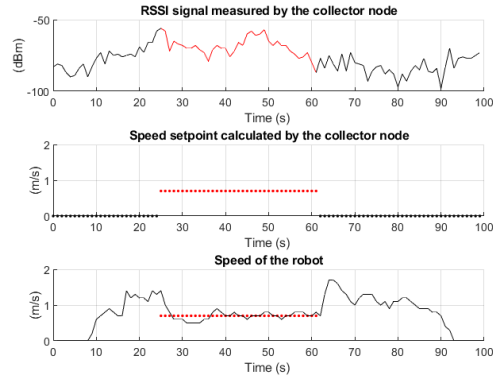


Fig. 11. Experiment performed on wet soil. The setpoint value calculated by the collector node is 0.7 m/s, it is applied during the period (24 s, 61 s).

VI. DISCUSSION

These first experimental trials demonstrates clearly the possibility to use buried sensor nodes to control the behavior of an aboveground vehicle passing at proximity. That opens up new prospects for both the autonomous and accurate control of agricultural mobile robots and the optimal tuning of the agricultural implements in precision farming.

These first developments are intended to be completed and extended in future work by following several research directions. In particular, the development of control algorithms enabling to anticipate the setpoint changes will be studied, as well as the trajectory planning task to avoid wetland areas, the construction of soil moisture map and the development of learning techniques.

A. Robot control and trajectory planning

At the time being, when the collector node receives the soil moisture information with a good signal reception, it has no idea of the distance and location of the measuring point. In fact, the communication range of the buried sensor nodes is highly varying, depending in particular on the Volumetric Water Content (VWC) and the compaction of the soil. An important element to be studied in future work is therefore to take into account the current position of the robot and a map with the positions of the buried sensor nodes. From such new information, different strategies could be implemented in terms of control (e.g. implementation of Model Predictive Controls in order to anticipate the change of setpoint values), and trajectory planning (e.g. modification of the trajectories of the robot to avoid wetland areas).

- **Robot control:** the speed setpoint values calculated by the collector node are currently send to the robot to modify its behavior immediately. However, from the knowledge of the position of the robot and the position of the moisture measuring point, predictive strategies could be developed. In particular, as presented in our previous work on robot control [26], the development of Model Predictive Controllers (MPC) enables to take into account the kinematic and dynamic capabilities of a mobile robot, and progressively reach the desired setpoint value after an horizon of prediction.
- **Trajectory planning:** Fig. 12 (left) presents an example of a trajectory planned for the robot, with an interdistance of 3.5 m between two adjacent tracks, see [27] for the construction of admissible trajectories. Once the robot is operating in the field, in case of detection of a large area with a high soil moisture, it could be required to replan the trajectory to be followed by the robot in real time. That requires to estimate the area to be avoided beforehand. Once this area is defined, the trajectory can be updated as presented in Fig. 12 (right).



Fig. 12. Trajectories planned in our experimental farm for the mobile robot (interdistance 3.5 m), Google Earth © Digital Globe, 46°20'22.35"N, 3°25'44.28"E. Initial trajectory (left); Modified trajectory due to wetlands assumed to be present in the top left and bottom right corners (right)

B. Moisture map and learning techniques

Another improvement of this work will be to study the possibility to establish a soil moisture map of the field in order to better anticipate and plan the future motions of the robot. To that end, the determination of the optimal locations

to bury the sensor nodes in the field needs to be adressed. The placement strategy can be guided by the ground topology (e.g. bottom of a slope, top of a hill) based for example on a 3D model of the environment, by the required spatial frequency of the measurements, or the variability of the soil composition in the field. From an initial set of sensors and measurements, extrapolation algorithms based on soil moisture models could next be developed to produce the soil moisture map of the field. Learning techniques could moreover enable to progressively reduce the required number of buried sensor nodes in a field.

The global scheme, presenting the different components of the system proposed, is presented on Fig. 13. It is structured around four main blocks, namely the speed adaptive function, the trajectory replanning block, the extrapolation and learning techniques to create the soil moisture map and the Model Predictive Control block enabling to anticipate the actions to be performed by the robot.

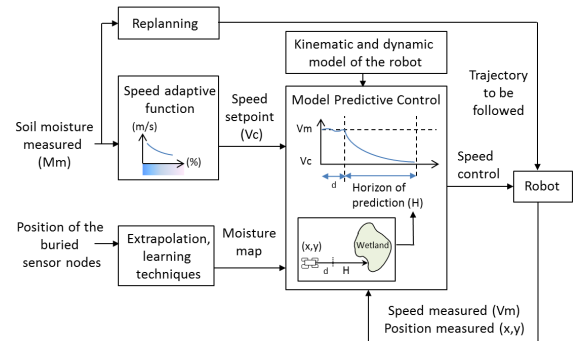


Fig. 13. Global scheme of the system proposed

VII. CONCLUSIONS

This paper presents an original system based on the combination of both WUSN and mobile robotics technologies. The soil moisture information is measured from sensor nodes buried at 15 cm deep in an agricultural field. This information is received by a collector node embedded on an agricultural mobile robot passing at proximity. The soil moisture information is used in real-time by the collector node to define the setpoint values for the speed controller of the robot, and adapt its behavior accordingly. The measurement of the soil moisture is filtered and sufficiently precise (3 % on the range 0-60 %) to define adequate speed ranges and not impact the robot control. The hardware and software of the system developed, based on the UG2AG communication link in LoRa at 868 MHz and on a collector node connected to the CAN bus of an experimental mobile robot, are detailed. First experimental results highlight the capabilities of the system developed. The speed of the robot is accurately regulated to different setpoint values (1 m/s and 0.7 m/s) calculated by the collector node from the measured soil moisture information.

Future research directions are discussed to extend the current capabilities of the system proposed, in particular in terms

of control algorithms (e.g. Model Predictive Control), trajectory planning, moisture map and learning techniques. These developments contribute to the challenges of Agriculture 4.0, but other activity sectors and applications, requiring to control an aboveground autonomous vehicle from a set of sensor nodes buried underground, could be addressed. In addition, these applications will require to address other subjects as the optimal deployment of the nodes [28], [29], the routing protocols [30], the lifetime of the nodes and the networks [31], as well as the security and privacy of data transmissions [32]. The buried sensor nodes could also be advantageously used for other purposes as the localization of the mobile entities [33], [34]. All these subjects represent exciting research directions and promising ways to the development of WUSNs and IoT.

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