Moisture measurement in crops using spherical robots

Abstract

This work presents an innovative solution for moisture monitoring in precision farming by using ground vehicles. The real innovation lies on using non-common robots such as spherical robots. This particular vehicle has turned out to be suitable for performing monitoring tasks in crop fields mainly due to its spherical shape, small size, low weight and traction system that do not produce soil compacting or erosion. These features allow the robot to perform measurements for intra-crop moisture. The work briefly explains the design of the robot as well as the results obtained from the experiments carried out at a cornfield when the crop was at its early stage, in order to build a geo-referenced water stress index map.

Motivation

Since farm management costs, and consequently crop results are directly associated with the environmental moisture, water control optimization becomes a critical factor in performing sustainable agricultural practices. Irrigation management in large crops is consequently an essential practice in precision agriculture (PA). Modern control techniques are applied to make this control effective (Capraro et al., 2008) (Rahangadale and Choudhary, 2011) (Quanxing et al., 1996). These techniques use moisture estimation (i.e. indirect methods such as photography or crop analyses) or measurement methods (i.e. environmental variables monitoring such as temperature, moisture, pressure, etc.).

Typically, crop humidity is quantified by using water stress index (WSI) that can currently be obtained from multispectral satellite or plane images. Nevertheless, these methods are very costly, scarce and highly dependent on the weather.

Currently, Unmanned Aerial Vehicles (UAV) are also used for such purposes with lower cost compared to previous solutions, but still require a service company to perform the task. UAV mission consists of taking aerial images of the crop fields. The images acquired are used for building high-resolution maps, not only for hydric stress studies but also for weed detection. An important research effort has been dedicated to computing optimal trajectories for mini UAVs, such as quad-rotors (Valente et al., 2011a), (Valente et al., 2011b).

Nonetheless, ground methods such as single sensors or wireless sensor networks (WSN) probe to be good static solutions (Patil, P., et al,2011) (Ke, Li.,2011) but require lots of devices in large fields with heterogeneous characteristics, being most of the times too expensive. Considering static sensor monitoring, acquisition systems could be classified according to their range and precision. Taking into account that range (not only individual sensor range, but also coverage) and accuracy are inversely related, a balance is thereby required.

On the other hand, using mobile sensors, i.e. sensors shipped on ground mobile robots, would reduce the cost of the entire WSN, but obviously a robot is required. Apart from the cost of the robot, the impact in the farming process (e.g. as they may damage the cultivation) and the human effort required to operate the robot are the main drawbacks of this solution.

Purpose of the work

This paper presents the work carried out in this field in order to minimize the adverse effects of using mobile robot for sensing in farming. Thus, a rolling robot with a spherical shape, named "ROSPHERE" (RObotic SPHERE) has been designed and tested as a low-cost robot that minimizes the damage to the crop while performing monitoring task. The main purpose of using this alternative vehicle is to minimize crop alterations, and at the same time, to be able to have direct measurements from plant surroundings. In such manner, the action required is only applied on the affected area. These actions may include water irrigation, application of pesticides or fertilizers, etc. This precise action has consequently an effect on the economical and environmental cost minimization and, at the same time, it maximizes revenues.

Nevertheless, the aim of the proposed system is not to completely replace what aerial systems do, but complement them in their daily work. Thus aerial units can only be required to perform their task in specific moments, which thereby reduces the final cost of the process.

Approach

As previously mentioned, the main objective of PA is to minimize environmental impact while maximizing the use of non-renewable resources (e.g. water). Local measurements of control variables such as temperature, pesticide concentration, luminosity, humidity, etc. are useful indicators in order to determine if an action is required on the crop.

Based on the mentioned above, the main goal is to be able to evaluate the real status of the crop, not only from a global point of view but also locally. Therefore, the solution must be able to assess the state of the crop without affecting the involved plants. Thus, the capability of the robot to navigate in crop rows in order to monitor variables is the foremost requirement to be considered. The analysis of this requirement links two more aspects such as size and weight. Taking into account the previous considerations, a robotic sphere is proposed as a solution. Robotic spheres are systems in which movements are induced by instability. Besides, considering their regular shape, the robot may recover easily from collisions. Regardless the direction of the impact, the robot tends to fall into a recoverable configuration. Finally, regardless its size, a robotic sphere is relatively lighter compared to analogous robot of the same size.

Spherical robots: concepts and first prototypes

Although robotic spheres are not widely used as mobile platforms, it is possible to find quite significant references focused on this kind of robots in the literature, regarding concepts and new prototypes proposals. Initially, research activities were focused on validating concepts about physics. In this regard, several authors have proposed different approaches, where the main objective was to create a mechanical system that allows shifting the centre of mass of a sphere and consequently inducing self-motion. Five typical methods can be found in literature in order to achieve this goal (Armour et al., 2006).

- Spring central member. A central body that includes a driven wheel in one of its ends and a passive wheel in the other, with a spring that guarantees contact between both wheels and the spherical shaped body. The main disadvantage of this design is the loss of energy due to friction between both wheels and the sphere.
- Car driven. The robot relies on a vehicle inside in order to induce motion. The main drawback is the lack of contact when the robot moves on surfaces with depressions and bumps.
- Ballast mass with fixed axis system. This system uses an inner pendulum with two rotational degrees of freedom. The first DoF rotates around a fixed transverse axis and the second around a longitudinal axis. (Michaud and Caron, 2002), (Kayacan et al., 2011). This configuration was chosen in order to design the ROBOSPHERE robot.
- Ballast mass with moving axis. It also has an inner pendulum, but in this case with an additional DoF that allows the main axis to move.

Due to the method chosen for designing the robot, the ROSPHERE prototype is a non-holonomic robot. Therefore, the vehicle requires forward or backward displacements so as to rotate. Nevertheless, several alternatives to create a holonomic vehicle can be found based on mobile masses system (Amir and Mojabi, 2002) (Shengju et al., 2010). Thus, the prototypes that use this concept take advantage of the movement of masses along radial axes in order to modify the position of the centre of mass.

Several robotics spheres have been developed for quite different areas of applications. Perhaps the most cited and ambitious application of robotic spheres has been the one proposed by Zhan et al. (Zhan et al., 2008). They propose to explore unstructured and unknown environments by exploiting the robustness and versatility of spherical robots. Meanwhile Bruhn et al. (Bruhn et al., 2008) or Michaud et al. (Michaud et al., 2001.) have also proposed their use for planetary exploration. Other fields of application can take advantage of the mentioned characteristics, such as security, surveillance and inspection (Seeman et al., 2006), where robotic spheres are endowed with sensors and cameras in order to allow the teleoperation of the robot.

On the other hand, since one of the primary requirements for service robots is the capability for harmless interaction with humans and the environment, robotic spheres have also been applied as service robot in direct interaction with humans, validating this feature. Thus, Michaud et al. in (Michaud et al. 2005) used a robotic sphere equipped with some special control routines and sensors in order to monitor child development while it was being used as a toy.

Finally, more academic contributions presenting robotics spheres to study kinematics, dynamics and control of non-holonomic systems can also be found in literature (Bicchi, 1997).

System description

ROSPHERE is a spherical-shaped robot with the capability to self-induce non-holonomic movements. In order to make that possible, the robot has an inner two-degree-of-freedom pendulum. The robot includes *a)* a spherical shaped body (30 cm of diameter), *b)* a fixed main axis, *c)* a central unit or ICU (Internal Control Unit) and *d)* the ballast or hanging mass. The first DOF rotates the ICU (consequently the hanging mass) about the fixed axis, while the second has a mechanically limited range of rotation, and rotates about a perpendicular axis. Current version of the robot (see **Error! Reference source not found.Figure 1** and **Figure 2**) was designed to get the Centre of Mass as far as possible from the geometrical center in order to induce the movements more easily.

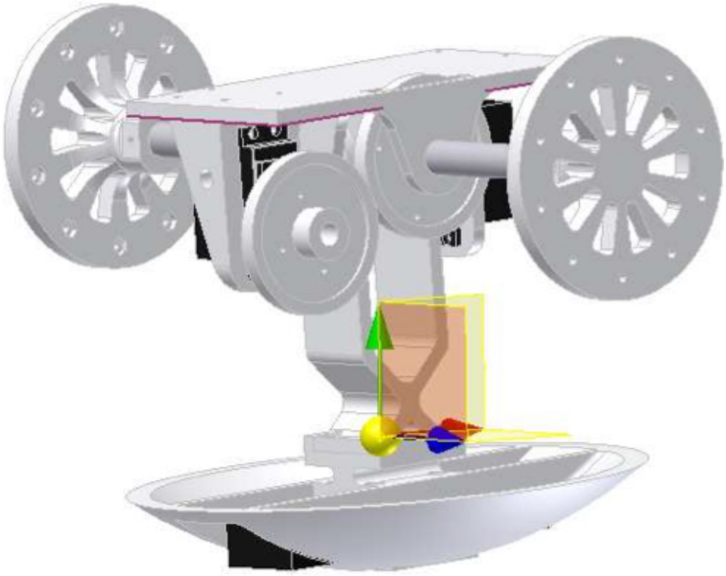

Figure 1. ROSPHERE CAD Design.

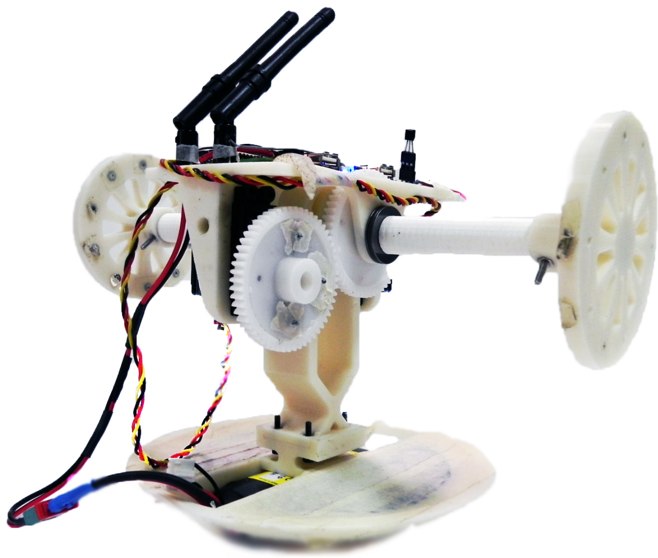

Figure 2. ROSPHERE ABS model.

In order to allow a comprehensive visual inspection of how the pendulum works during the operation of the robot, the ROSPHERE prototype has been made by using a commercial transparent ball, as shown in **Figure 3**. Although good results have been obtained by using this commercial ball, a more suitable material should be used in its final version in order to increase friction and consequently, the efficiency of its traction. The grooves of the case have been sealed using special rubber bands in order to keep the robot protected from dust and humidity, as shown in **Figure 6**. Different sensors can be placed on both of its sides, out of the tread contour, in order to avoid shocks. Nevertheless, if a heavy sensor (e.g. a camera) is used, a counterweight should be added to the other side of the sphere in order to maintain the center of gravity in the same position.

Figure 3. ROSPHERE prototype

Hardware architecture

ROSPHERE is equipped with all necessary resources in order to behave as an autonomous vehicle. Thus, the equipment includes a novel embedded computing system composed by a Robovero and an Overo Fire embedded computer.

Considering communication capabilities, ROSPHERE relies on Wi-Fi, Bluetooth and Xbee modules as communication alternatives, not only with the base station but also with external sensors.

Regarding sensing capabilities, the system includes the equipment required for guidance, navigation and control (GNC) systems, such as a low cost inertial measurement unit (IMU) in order to measure angular velocities and accelerations, a magnetometer with pan-tilt correction capability and a single GPS. Additionally, an optical encoder is required (still under development) in order to measure the rotational speed of the sphere and compare it with the real speed of the robot. This will allow developing more robust control algorithms that are useful when the traction is very low (e.g. very wet surfaces).

External sensors such as humidity and temperature are currently connected by using an analogic-digital (A/D) converter. **Figure 4** shows the hardware architecture of the system.

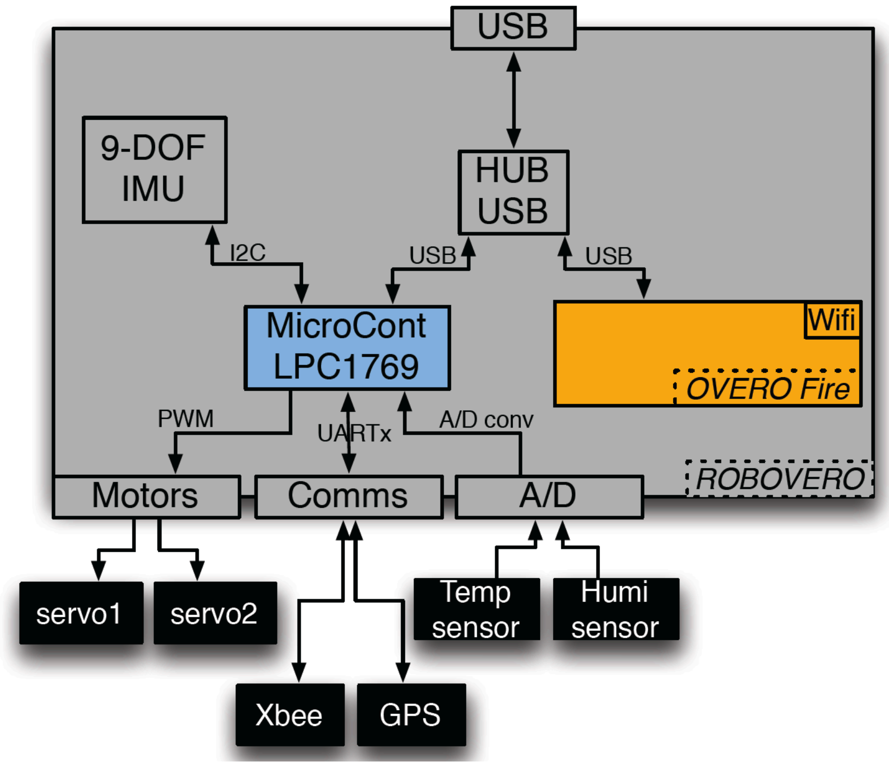

Figure 4. Hardware architecture of ROSPHERE.

Software architecture

System architecture can be split into two parts. The first part is responsible for the high-level and the second for the low level (sensors and actuators level).
The first part is in charge of interpreting remote commands from the base station and performing basic GNC tasks by using processed information from the sensorial system. Thus, this layer transfers teleoperation commands to low-level controller or calculates references to controllers in order to perform basic maneuvers. This part is executed on Overo board under Ubuntu Linux ver 11.0.4. Additionally, the ROS-Core has also been included in order to implement a standard ROS (Robot Operating System) architecture. The project aims to deploy a complete ROS compliance robot, which will allow using a wide spread of algorithm and already developed tools and their connection with robotic simulators (e.g. Gazebo or V-REP).
The Overo communicates with Robovero by using a USB hub. Robovero is responsible for low-level control and sensing. Thus, it reads all the sensors and performs basic filtering in order to create complete messages for the high level controller. An important development has been required in order to optimize Robovero firmware so as to improve update frequencies in sensors readings and processing.
Figure 5 summarizes the basic software modules of each part.

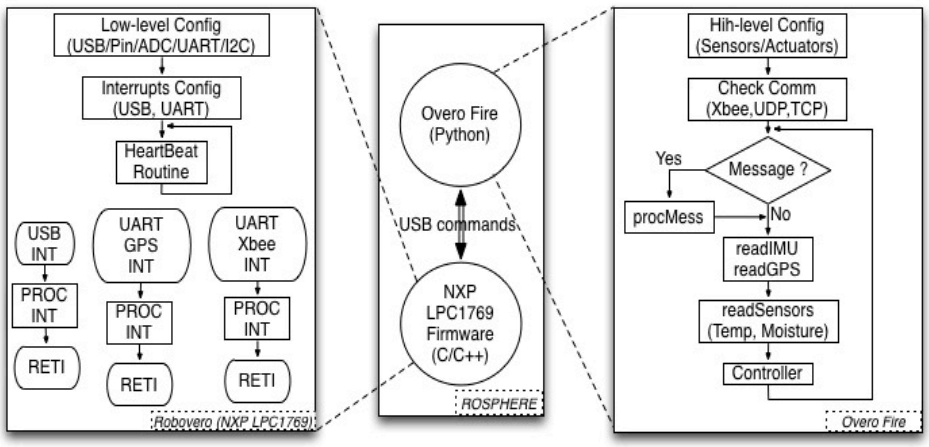

Figure 5. Software architecture of ROSPHERE

Tests and results

Preliminary tests.

Multiple tests have been carried out in order to assess the performance of ROBOSPHERE in different terrains. The movement capability on different surfaces was observed by using teleoperation mode. Thus, the robot was tested on a tarmac, cement, grass, sand, and gravel. Some of them are shown in **Figure 6**.

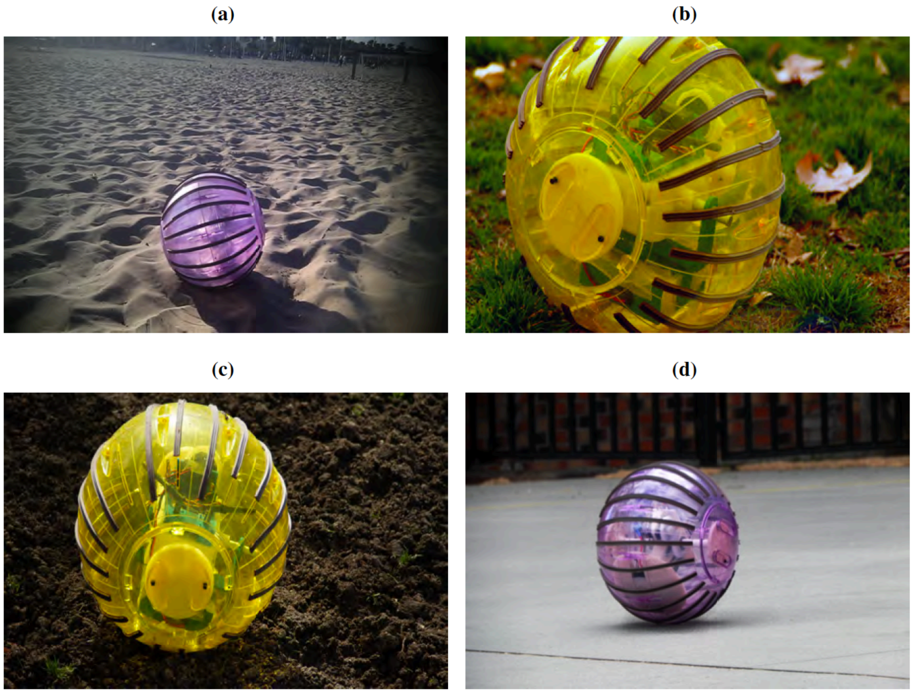

Figure 6. ROSPHERE tests on different surfaces. a) Sand on the beach b) Grass in the park c) Agricultural Soil d) Pavement.

In order to validate the capability of ROSPHERE for monitoring environmental variables, some tests have been performed at a large extension in a public park in Madrid (Retiro Park), as shown in **Figure 7**.

Figure 7. Trajectory performed at Retiro Park

During the test, not only was the capability for monitoring tested, but also the friendly relationship with people.

The temperature and humidity were successfully recorded and geo-referred as **Figure 8**

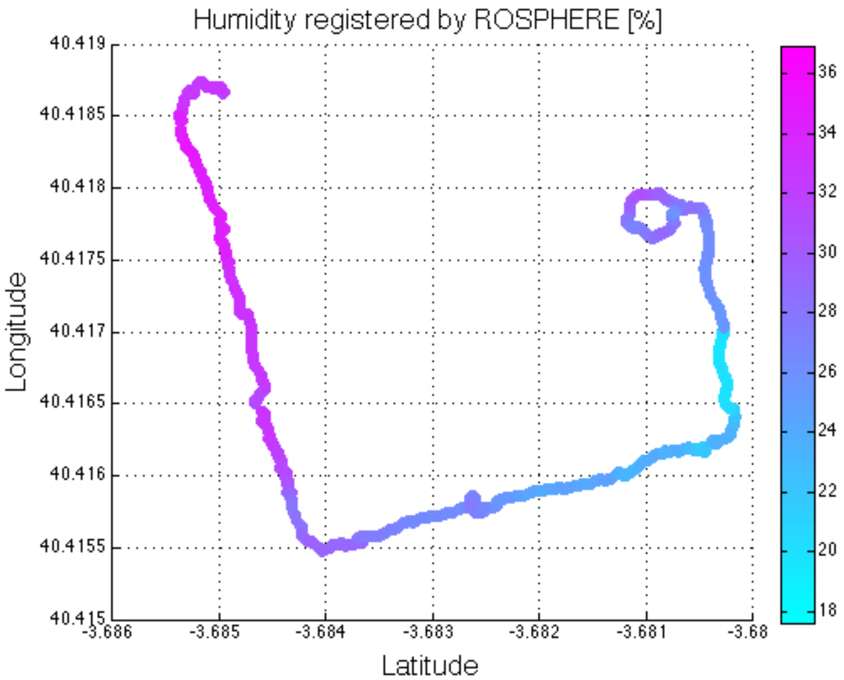

Figure 8. Humidity map.

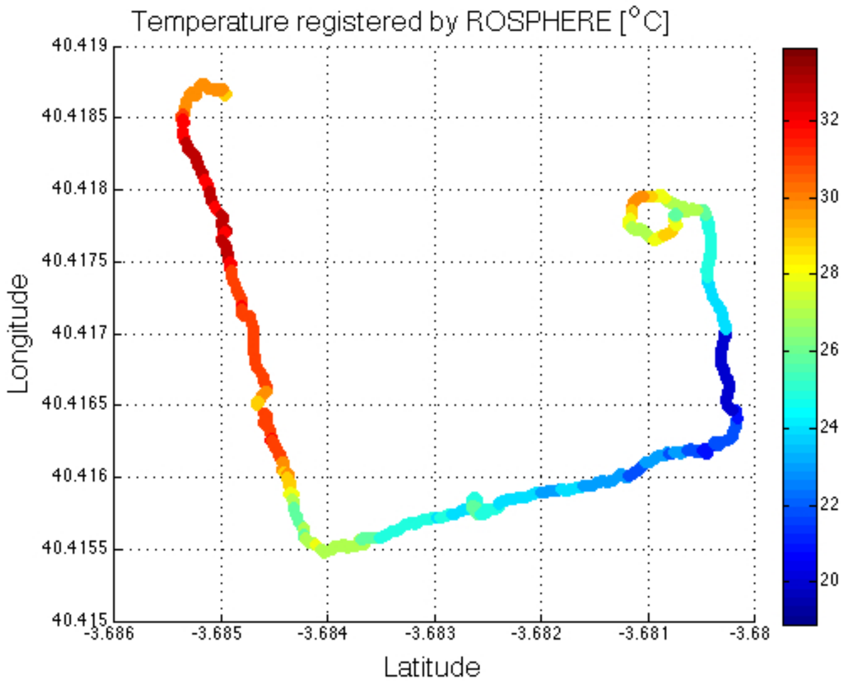

Figure 9. Temperature registration (differences due to sun or shade are appreciated)

Final tests

ROSPHERE was finally tested in two different crops; narrow rows crop such as winter cereal (**Figure 10**) and wide row crop such as corn, as shows.

Figure 10. ROSPHERE working on winter cereal field.

Figure 11. ROSPHERE working on Maize crop field.

In order to test the capability of ROSPHERE to move across crops lines, the robot was teleoperated while collecting the above-mentioned variables. The chosen field for winter cereal had a smaller crow raw spacing than expected (farmers decision); nevertheless the robot was able to perform its mission.

Temperature and humidity evolution were registered and are shown in **Figure 12** and **Figure 13**. As expected, both moisture and temperature remained stable along the crop. Nevertheless, a slight increment (lower than 3%) could be appreciated in the humidity, near the irrigated area. On the other hand, it can be seen that three different plots compose the temperature-monitoring chart. The black and red ones correspond to the raw data of both sensors (LM31 and SHT71, respectively). The blue line corresponds to the compensated data, where LM31 provides the accuracy and the SHT71 contributes with a higher stability.

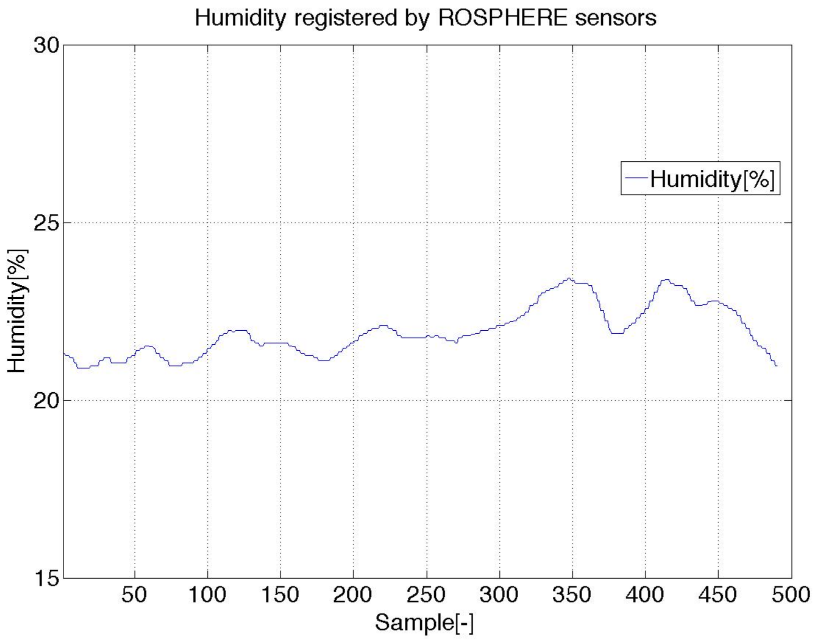

Figure 12. Humidity registration during tests.

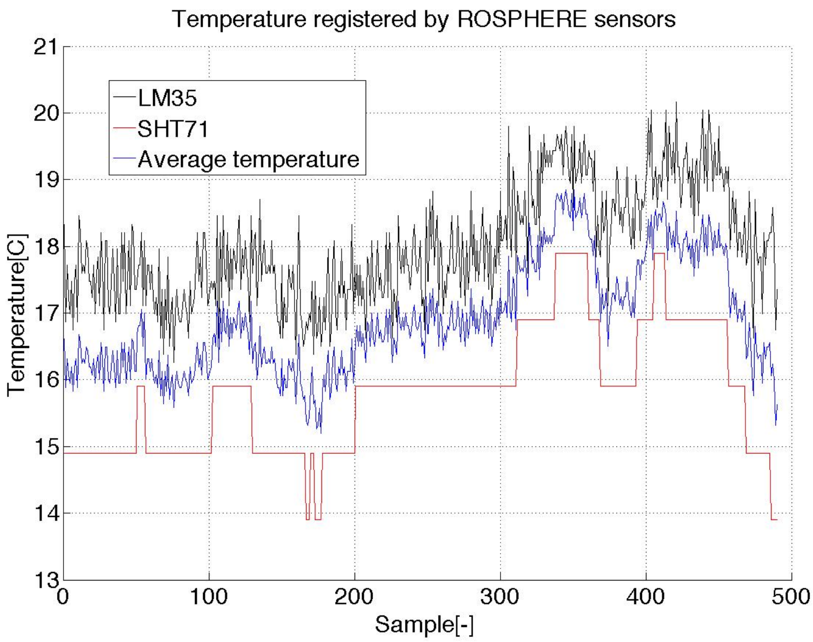

Figure 13. Temperature registration during the tests.

Conclusion and Future work

The present paper summarizes the work carried out in order to create a small, light and low-cost robot for moisture monitoring in crop fields. The performed tests have validated ROSPHERE's capability to move along wide crop rows while obtaining and geo-referring environmental data. It has been concluded that a smaller robot has to be designed for working in narrow crop rows so as to guarantee the integrity of the plants.

Considering its control features, an additional sensor that measures the rotation speed of the sphere is required in order to develop advanced controllers for extreme slippery surfaces. Furthermore, a wireless link for external sensors will enhance data accuracy and make connectivity easier.

Acknowledgements

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