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mySense: A comprehensive data management environment to improve precision agriculture practices

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ABSTRACT

Over the last few years, an extensive set of technologies have been systematically included in precision agriculture (PA) and also in precision viticulture (PV) practices, as tools that allow efficient monitoring of nearly any parameter to achieve sustainable crop management practices and to increase both crop yield and quality. However, many technologies and standards are not yet included on those practices. Therefore, potential benefits that may result from putting together agronomic knowledge with electronics and computer technologies are still not fully accomplished.

Both emergent and established paradigms, such as the Internet of Everything (IoE), Internet of Things (IoT), cloud and fog computing, together with increasingly cheaper computing technologies – with very low power requirements and a diversity of wireless technologies, available to exchange data with increased efficiency – and intelligent systems, have evolved to a level where it is virtually possible to expeditiously create and deploy any required monitoring solution.

Pushed by all of these technological trends and recent developments, data integration has emerged as the layer between crops and knowledge needed to efficiently manage it. In this paper, the mySense environment is presented, aimed to systematize data acquisition procedures to address common PA/PV issues. mySense builds over a 4-layer technological structure: sensor and sensor nodes, crop field and sensor networks, cloud services and support to front-end applications. It makes available a set of free tools based on the Do-It-Yourself (DIY) concept and enables the use of Arduino® and Raspberry Pi (RPi) low-cost platforms to quickly prototype a complete monitoring application. Field experiments provide compelling evidences that mySense environment represents an important step forward towards Smart Farming, by enabling the use of low-cost, fast deployment, integrated and transparent technologies to increase PA/PV monitoring applications adoption.

1. Introduction

Precision Agriculture (PA), Smart Farming, Internet of Things (IoT), Internet of Everything (IoE), Cloud and Fog Computing, Big Data, Data Analytics, Machine Learning, among other technological concepts, are becoming quite popular when addressing the management of agricultural practices. Facing the economic, environmental, labor and sheer space constraints, successfully managing crops needs to go well beyond the way that knowledge about productive cycles, spatial and temporal variabilities are still regarded today. Indeed, it is increasingly necessary to create decision support systems based on data acquired in real-time, correlate data coming from various sources and forecasting models, so that the production process becomes the more efficient as possible. Even so, maximizing yields and crops' quality through sustainable practices, while reducing both the economic and environmental impacts, implies that (1) diseases and phytosanitary conditions need to be detected as early as possible, thus reducing the implications of inputting phytopharmaceuticals; (2) irrigation must be more efficient; (3) field-interventions should be carried out considering the variable rate policy and acting only when and where is necessary.

The replacement of wired-based complex systems by wireless sensor networks (WSN), supported on efficient power management techniques constitutes one of the greatest innovations of the last decade in infield monitoring. As such, simple monitoring systems, based on low-cost

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Table 1
Works published in the last decade (2009–) related to the use of data acquisition devices in PA/PV applications.

Work	Node type	Communication between nodes	Gateway	Communication with remote	Sensors	Applications
Ghobakhlou et al. (2009)	Microcontroller based	N/A	Yes (Base station)	Internet	T, RH, SR, LW, AP, WS, WD, RF, SF, ST, SM	Telemetry system for environmental and microclimate data
Lloret et al. (2011)	Wireless router based (with OpenWRT firmware)	Wi-Fi	Yes	Internet	Camera	Using image processing to detect any unusual status in the leaves of a vineyard and notifies the wine-grower
Togami et al. (2011)	eKo Pro Series based	RF (IEEE 802.15.4)	Yes (Linux based)	Wi-Fi	T, RH (ES2000 Weather Station Suite), RF, WS, WD, AP, SR	Long-term and reliable data acquisition system
Matese et al. (2012)	Wireless device based	RF	Yes (Agrometeorological station based)	GSM/GPRS	T, SR, SM	Low cost and open-source WSN used to characterize vineyard variability
Kubicek et al. (2013)	Sensor unit	VLIT at RFID frequency (686 MHz)	Yes (ARM based)	GSM/GPRS	T, RH, ST, SM	Support for effective decision making in agricultural management based on heterogeneous data and services
Smiljkovikj and Gavrilovska (2014)	Waspmote based (centralized topology)	XBee radio modules (869 MHz)	Yes	Internet	T, RH, AP, SR, UVR, WS, WD, LW, ST, SM	Monitoring of resources consumption and cost decrease of water and pesticide usage in wine production
	Waspmote based (distributed topology)	GSM/GPRS	No	N/A		
Patil and Thorat (2016)	Device where several sensors are connected	ZigBee (XBee modules)	No	N/A	T RH, SM, LW	Early detection of downy and powdery mildew
LL.C.D.S.L. (2018)	Microcontroller based (Waspmote)	ZigBee, Wi-Fi, RFID, NFC, Bluetooth	Yes (Meshilium, Libelium)	GSM/GPRS, Wi-Fi, LoRa	T, RH, AP, RF, WS, SR, UVR, ST, SM, LW	Grape diseases prediction
Pérez-Expósito et al. (2017a); Pérez-Expósito et al. (2017b)	Microcontroller based (ESP8266)	Wi-Fi	Yes (RPi 2B and Arduino)	GSM/GPRS	Nodes: T, RH, SM; Gateway: AP, RH, SR, T, RF, WS	Weather station to support vine grower decisions
Karimi et al. (2018)	Microcontroller based (Arduino)	RF (nRF24L01)	Yes (Arduino)	GSM/GPRS	Micrometeorological	Monitoring system to collect data from vineyards and grape drying structures
Matese et al. (2013)	MDA300 (Crossbow Technology, Inc) based	ZigBee	Yes (Asus eeePC based)	GSM/GPRS	T, RH, SR	Data to support vineyard management, disease control and water management practices
Kabilan and Selvi (2016)	Microcontroller based (Arduino)	ZigBee	Yes (Arduino)	Wi-Fi	Camera, T, RH, HI, SR, RF, SM	Smart irrigation system using weather data, crop images and a commercial IoT cloud server
Sales et al. (2015)	eZ430-RF2500 Kit based	RF (2.4 GHz/SimpliciTI)	Yes (Base station)	Ethernet, Wi-Fi, GSM/GPRS	T, SM	Cloud-based solution for smart irrigation system using a wireless sensor and actuator network
Charalampidis et al. (2017)	Zolertia Re-Mote based	RF (2.4 Ghz/ 863–950 MHz)	Yes (RPi 3 and Zolertia Re-Mote based)	Ethernet/Wi-Fi	T, RH, SR, air quality, noise	Cloud-based system for IoT storage data and high level data processing
Gennaro et al. (2017)	Microcontroller based (Arduino compatible)	Bluetooth, Xbee, Wi-Fi, RF	Yes (WSN coordinator)	Wi-Fi	T, RH	Vineyard thermal dynamics using remote (UAV) and proximal (WSN) sensors
Garcia-Sanchez et al. (2011)	MICAz or Imote2 based	ZigBee (CC2420)	Yes (Crop-Gateway Imote2 based and FarmerCrop-Gateway)	Ethernet, GSM/GPRS	T, pH, SM, SC, soil salinity, SR, PIR, Camera	PA monitoring tasks adding intruders detection and identification procedures
Gutiérrez et al. (2014)	Microcontroller based (PIC24FJ64GB004)	ZigBee	Yes	GSM/GPRS	ST, SM	Automated irrigation system to optimize water use for agricultural crops
Medela et al. (2013)	TSmarT IoT platform based	ZigBee	Yes	GSM/GPRS	T, RH, ST, SM, LW, TD, AP, WS, WD, SR, UVR	Optimize the overall management of the entire wine production chain
Salam et al. (2019)	Underground transmitter	SDR (100–500 MHz)	No	N/A	SM, SP	Soil moisture monitoring and soil properties estimation

Legend: AP: Atmospheric pressure; LW: Leaf wetness; RF: Rainfall; RH: Relative humidity; RPi: Raspberry Pi; SC: Soil conductivity; SDR: Software defined ratio; SM: Soil moisture; SP: Soil permittivity; SR: Solar radiation; ST: Soil temperature; T: Temperature; TP: Trunk perimeter; UVR: Ultraviolet radiation; VLIT: Very Long range Identification Tag; WD: Wind direction; WS: Wind speed.

microcontrollers, can be spread out over wide areas without restrictions, according with each crops' needs. With wireless and standardized communications (e.g IEEE 802.15.4, IEEE 802.11, IEEE 802.15.1, LoRa®, 3G/4G/5G, SigFox), this type of systems has dominated the publications spectrum in this field (Hamouda and Elhabil, 2017; John, 2016; Sahitya et al., 2017), being presented as easy-to-use solutions and promoters of data gathering with an adjustable granularity, compatible with the desired spatial and temporal variability. From solutions that directly transmit sensor data to remote locations to those using infield base stations, large volumes of data are acquired and are readily available for further analysis and to support decision making in PA/PV management practices. Following this evolution, the recent paradigm of IoT began to be interesting in the field of agriculture. The availability of physical devices in the field– above or underground (Vuran et al., 2018) – taking measurements and exchanging data with a cloud server, has enabled the design of simpler, cheaper and more energy efficient IoT devices, towards a real ubiquitous access (anywhere and anytime) to data and services.

With increasingly cost-effective technological solutions for infield monitoring devices, image acquisition (Murugan et al., 2017; Narvaez et al., 2017; Ponti et al., 2016) is now complementary to the range of solutions for measuring crops' status. Whilst remote sensing is a consistent research area, with proven applications in PA/PV when using imagery acquired by satellites and through manned air-flights, it has more recently known significant and disruptive advances due to unmanned aerial systems (UAS) – that combine an unnamed aerial vehicle (UAV), a sensor as payload and a ground station, which has software to manage the flights (Pádua et al., 2017). Indeed, UAS enables non-invasive monitoring with spatial and temporal variability tailored to the crop and monitoring needs. Moreover, UAS have low-cost solutions, are very flexible platforms and enable the acquisition of different data through the use of various sensors. It is with these platforms that image is becoming the pivotal element in monitoring crops.

Managing of data acquired by a systematic collection of a vast array of heterogeneous sensors, continues to be as complex as the knowledge needed to make a decision on the practices of an agricultural process, as it requires processing in the various temporal and spatial dimensions of the acquired data. This task implies that data should become available in a suitable time window and format to be promptly viewed and stored, but also to feed decision-making support systems. Managing data and extracting information is quickly becoming also a key issue.

When a huge amount of data is collected over time, more advanced processing techniques should be employed. Big data, data analytics and artificial intelligence techniques are beginning to provide predictive insights and driving real-time decisions, innovating business processes. But, as stated in the review paper (Wolfert et al., 2017), big data and analytics applied to PA/PV are still at an early stage. It is of interest to encourage greater use of these concepts in agriculture since it is expected that in the coming years the volume of data will increase exponentially.

mySense is a contribution to the dissemination of tools that facilitate the use of different kinds of data inputs and low-cost hardware devices that, in a simplified way, can be used to quickly create PA/PV monitoring applications. This article is structured as follows: after this introductory section, where some recent technologies that are being applied in PA/PV practices are briefly presented as the core motivation, the following section presents a state-of-the-art survey of the entire data processing chain in PA/PV applications, starting with data acquisition systems, data transmission technologies, support in the field and data integration interfaces. Section 3 presents the mySense environment as well as the prototypes that become available at the sensor and gateway level, as tools that address common issues found on field monitoring applications. In the experimental results section, the developed hardware and web/cloud platform were intensively evaluated in a vineyard monitoring application yielding relevant practical considerations. Finally, appropriate conclusions about the potential of this type of free and open approach are drawn and it is discussed how this research contributes to the improvement of agricultural practices in the concept of PA/PV.

2. Materials and methods

This section reviews published works in the last decade that use WSN technologies and data acquisition on the scope of how these systems have been used in PA/PV applications. The goal is to evaluate the interface systems between sensors and processing hardware as well as the data communication technologies used to exchange data with either remote services (based on web/cloud systems) or with local gateway devices. It is also interesting to know what kind of processing is performed as sensor data becomes available so that monitoring effectively becomes an input to decision support systems to produce an useful decision. The most significant studies that emerged from this review are highlighted in Table 1. The following criteria considered in this selection: 1) Type of node where sensors are connected to understand what type of hardware has been used; 2) What protocols have been used to establish a WSN between nodes; 3) If a field gateway was used; 4) How the gateway communicates with a remote web/cloud server; 5) What parameters are measured, and finally; 6) What was the presented system target application.

From the review, it is clear the existence of several common denominators such as the heterogeneity of low-cost devices, low-power sensor nodes (based on well-established Arduino® and ESP8266 microcontrollers) and communication protocols. Indeed, many of the revised works use the ZigBee protocol (that builds over IEEE 802.15.4) to establish a non-IP WSN. IEEE 802.11 (Wi-Fi) connections are also used to create IP-based networks. Almost all studies use a gateway (which acts as a data aggregation element and may perform some local processing tasks within the Fog computing concept), and few ones transmit data directly to a remote service based on the web/cloud. For remote locations, without IEEE 802.11 support (wireless or Ethernet), GSM/GPRS is the predominant solution. On the server side (remote web/cloud system), it seems that a higher number of data analytics services are becoming available to the end user, through mobile or PC applications. The large processing capacity and services to which the cloud can access (for example, meteorological data from various sources) enable the collected data to be processed with greater efficiency, considering a large volume of data collected by means of many low-cost devices. An interesting aspect that begins to emerge in proximity monitoring scenarios is the use of images, which raises the processing requirements both at the level of the capture elements and in the transmission to a remote server.

It becomes clear that in the majority of the revised works, 4 levels of management can be identified in the sensors' data integration chain, schematically illustrated in Fig. 1.

It also appears that the current trend is to provide open solutions and easy implementation for a variety of applications within PA/PV and even in other areas. Big data, data analytics and artificial intelligence are being applied to agriculture and it is expected that in the coming years the volume of data, related to agriculture practices, will increase astronomically, such as services that depend on them.

The following section describes mySense environment, depicted in Fig. 2, developed based on the field experience acquired over the last 15 years (Morais et al., 2008b; Morais et al., 2008a; Cunha et al., 2010; Peres et al., 2011; Fernandes et al., 2013; Pavón-Pulido et al., 2017).

3. The mySense environment

mySense was conceived to provide support for the rapid creation of monitoring applications in PA/PV scenarios, based on the 4 levels previously described and depicted in Fig. 1. Consequently, its main goals are: 1) to give support to the deployment of low-cost data collection stations that acquire and transmit data (level 1) using common

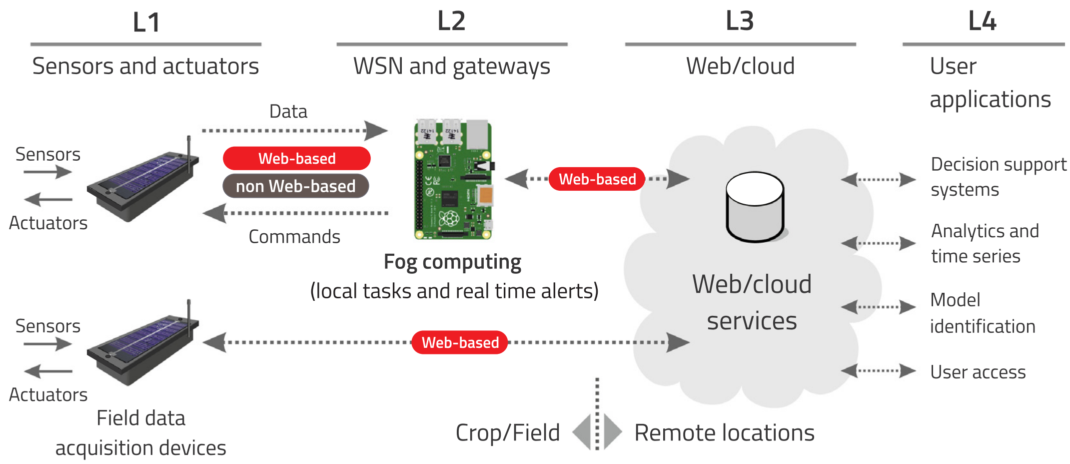


Fig. 1. 4-level management arrangements identified in the PA/PV data integration chain.

standardized data transfer technologies (IEEE 802.15.4/ZigBee, IEEE 802.11, GSM/GPRS, LoRa®, among others); 2) to give support for field installation of gateways (level 2) with the possibility of running local tasks as part of Fog computing paradigm, as well as to give support for storing data in the cloud (level 3); 3) to promote high-level and more complex applications (level 4) that communicate with mySense cloud using machine-to-machine (M2M) methods to make use of stored data. The following sections show how these objectives and levels were approached by the mySense concept.

3.1. Transducer level and data acquisition devices

A closer look of Table 1 reveals that some key factors need to be considered when developing data acquisition platforms for PA/PV high-density monitoring applications. In addition to its inherent low-cost, a data acquisition system must support the heterogeneity of existing sensors for this type of applications. It is common to find sensors with analog output (voltage, current, frequency), as well as sensors that use specific protocols (SDI-12, SPI and I^2C, as examples). In addition to these requirements, many different communication protocols (IEEE 802.15.4/ZigBee, 6LoWPAN, LoRa®, Bluetooth®, IEEE 802.11, GSM/GPRS/3G/4G/5G, Sigfox, LTE) exist, which poses additional difficulties to choose one. Finally, having a reduced form factor for minimal invasion and being equipped with efficient energy management systems so that they can be powered by renewable sources. At software level, data format normalization, such as the use of JSON or XML descriptive languages, as well as incorporation of sensor interoperability standards like IEEE 1451, SensorML or TransducerML, can be an advantage.

Most PA/PV applications require the use of heterogeneous sensors such as rain gauges, leaf wetness sensors (e.g., based on electrical conductivity), sap flow sensors (e.g., Granier probes), soil moisture sensors (e.g., 10HS or 5TE from Decagon or low-cost sensors such as Watermark from Irrometer), solar radiation sensors, wind speed sensors, besides the traditional air temperature and relative humidity and others. The well-known DHT22 (Aosong Electronics Co., Ltd, PRC) for temperature and relative humidity measurements is a good example of a low-cost digital sensor, yet lacking long-term reliability. Regarding low-cost platforms to accommodate all or part of these sensors, Arduino® might be a convenient open-source microcontroller platform, easy to use, with a widespread online support community. However, many other manufacturers release their own modules for IoT applications. There is so much to choose from, which makes it harder to select one module over another.

Based on field experience of testing hardware targeted to low-cost,

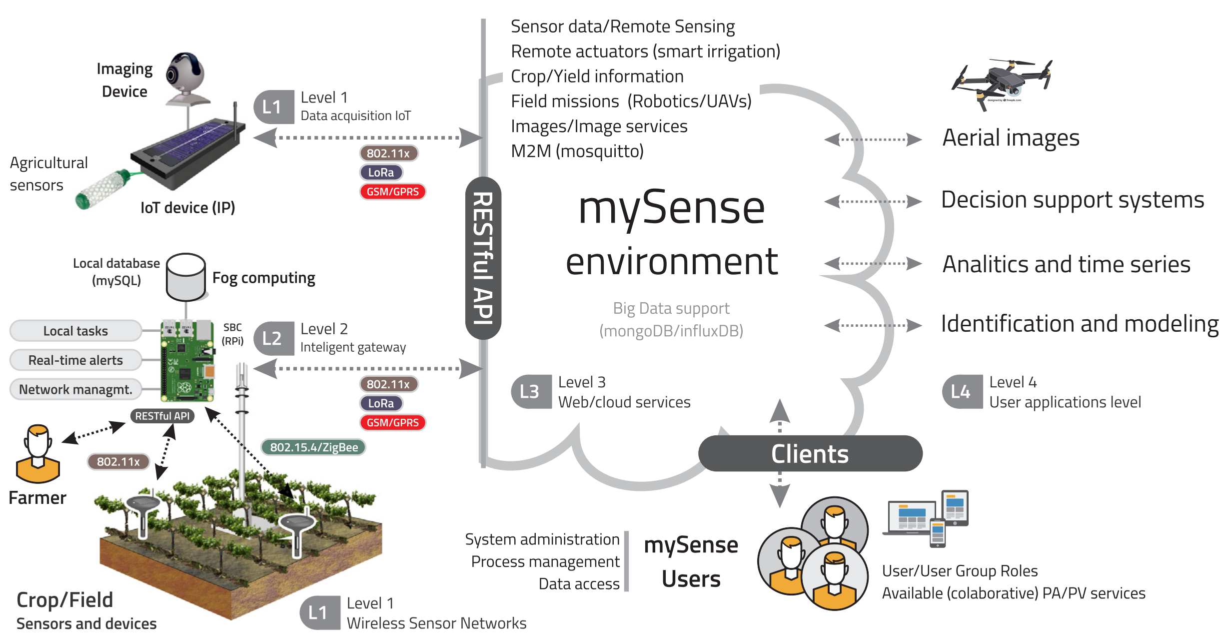


Fig. 2. Overview of the mySense environment.

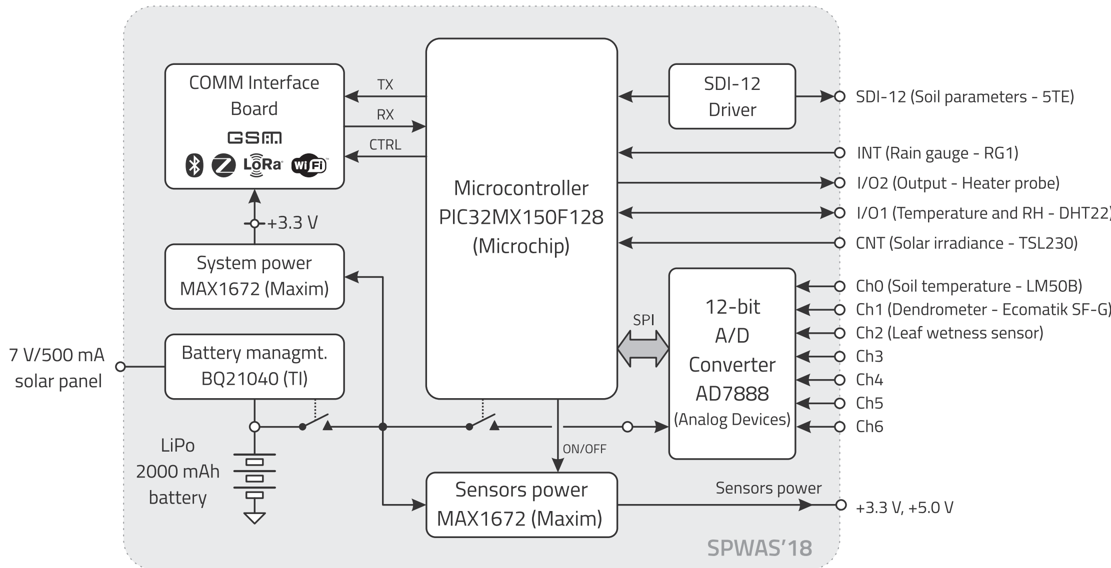


Fig. 3. SPWAS'18 simplified block diagram.

small, unattended data acquisition devices, SPWAS'18 (Solar Powered Wireless Acquisition Station, 2017 edition) has emerged as mySense reference IoT device for PA/PV monitoring applications. Fig. 3 illustrates the functional diagram of the SPWAS'18 device, developed to accomplish the goal of a low-cost solution to gather data from a wide variety of sensors, powered by solar energy and having a low form factor of 97 × 56 mm.

The SPWAS'18, described originally in Morais et al. (1996), is built around a high-performance RISC microcontroller (PIC32MX150F128, Microchip, USA). Analog voltage and current output sensors are handled by a 12-bit A/D converter (AD7888ARZ, Analog Devices, USA). System and sensors power are provided by an ultra-low supply current linear regulator (MAX882, Maxim, USA) to achieve a total power consumption below 80 µA. The 2000 mAh LiPo battery is recharged using a 7 V/500 mA solar panel and a LiPo battery charger chip (BQ21040, Texas Instruments, USA). Digital I/O pins are used to interface with temperature and air relative humidity (DHT22) and solar irradiance (TSL230BRZ, TAOS, USA) sensors, as well as to generate a digital output (irrigation valve control, heating on/off control). To interface with SDI-12 sensors, a RS-485 driver (SN75176, Texas Instruments, USA) is used. A 64 kB flash EEPROM (25LC512, Microchip, USA) stores up to 500 data records.

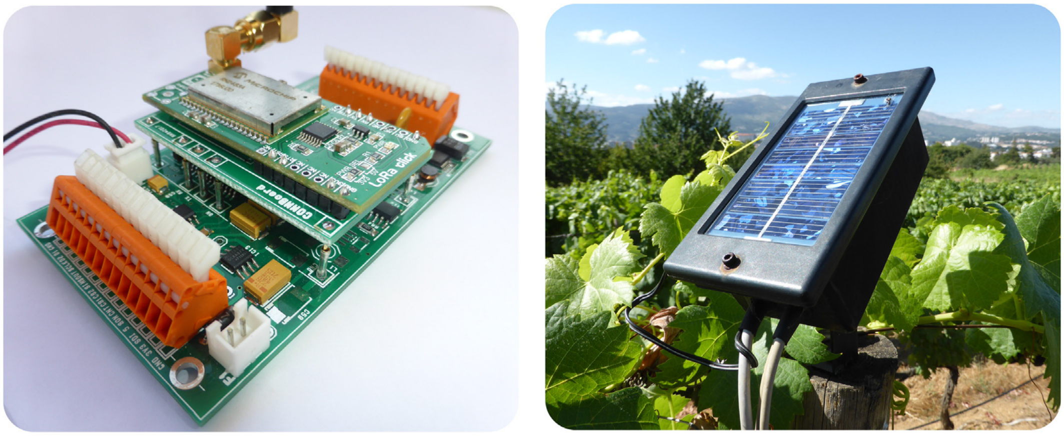
Regarding communications, the SPWAS'18 device has a communication interface enabling the use of several slave boards, each one with a communication module. With this approach, SPWAS'18 can communicate with the outside world using IEEE 802.15.1, IEEE 802.15.4/ZigBee, 6LoWPAN, Bluetooth®, GSM/GPRS 3G/4G/5G, LoRa®, Sigfox, and many other protocols, depending on the communication board used and its respective firmware. The choice of protocol depends on the area to be covered, the number of required sensor nodes, available energy, budget, among other technical reasons. To communicate with a nearby base station or a mobile robotic platform passing nearby, a cheap Bluetooth® module can be used. For a wider range, XBee modules (Digi International, USA) can also be used with added flexibility in network topologies and number of nodes. For cheaper but also wider range solution, RF modules such as nRF24L01+ (Nordic Semiconductor, Norway) can also be used. In specific applications, where a base station makes no sense or cannot be used, the use of low-priced GSM/GPRS modules such as the GSM click (Mikroelektronica, Belgrade, Serbia), with a GL865-QUAD GSM/GPRS module (Telit, UK), may be a solution. If the sensor network is in the range of a Wi-Fi network, like in a greenhouse application close to a building, cheap Wi-Fi modules – such as the popular ESP8266 module family – can be selected to create a sensor network able to communicate directly with some web/cloud service or with a nearby base station/gateway. LoRaWAN™networking is also possible by using, for example, the LoRa® click (Mikroelektronica, Belgrade, Serbia), which features an embedded LoRaWAN™Class A compliant stack, providing a long-range spread spectrum communication up to 15 km in line-of-view rural and open spaces.

Fig. 4(a) shows a SPWAS'18 device equipped with a LoRa® communication board for long range data transmission. In this case, LoRaWAN™stack was disabled and only the radio physical protocol was used to establish a peer-to-peer connection. Fig. 4(b) shows a SPWAS'18 device acquiring climatic data in a vineyard (41°17′13.3″N 7°44′07.5″W) to evaluate powdery mildew risk assessment.

3.2. Wireless sensor network support and gateway layer

Data acquisition elements are often constrained regarding both energy and processing capacity, so they can only send data over relatively short distances using energy management schemes and/or using energy constrained protocols. In most of the reviewed cases, the gateway bridges two levels of management: it operates between the sensor network and an online web/cloud infrastructure. The gateway, some times referred as a base station, can be materialized by a cheap single board computer (SBC) like the RPi platform. Either way, the base station must always communicate with the sensor network, meaning that it must use the same communication protocol/module as the one used in the sensor nodes. For example, robust and frequent IEEE 802.15.4/ZigBee-based solutions require a PAN (Personal Area Network) coordinator, which is usually part of the area's gateway to whom nodes' data is routed.

Fig. 5 shows the mySense approach of a field gateway, regarding hardware capabilities and required software modules. The SPGATE'18 (mySense designation for a Solar Powered Gateway) comprises a low-cost SBC (RPi 2 B+ or superior, Raspberry Pi Foundation, UK), a solar panel battery charger (Solsum 6.6F, Soltec), a communication module used as a LR-WPAN network coordinator, a GSM/GPRS 4G modem (GL865, Telit, UK) and an optional sensor board to connect local sensors, including a SDI-12 bus, allowing its operation as a stand-alone data acquisition device. The RPi uses the Raspbian operating system and is responsible for the execution of several software modules as Python 2.7 scripts. Data retrieved from WSN nodes is pushed into a



(a) (b)

Fig. 4. SPWAS solutions using mySense framework libraries: (a) A SPWAS'18 device, showing the LoRa® slave board; (b) SPWAS'18 used to acquire vine data.

MySQL database as a temporary data warehouse. The following sections describe each software module in more detail.

3.2.1. Data model and database management

The simplified E-R (entity-relationship) model of the SPGATE'18 gateway main database is depicted in Fig. 6(a). Each WSN node is described in the `Device` table. `DeviceMAC` stands for the physical address of the communication device used by the WSN node. `DeviceUID` and `DeviceAPIKey` are the device's unique identification and access key, respectively, related to the mySense cloud server. `DeviceCMD` is a field populated whenever some payload needs to be transmitted back to the device, when it becomes online. Regarding `Data` table, the `Device_idDevice` is the foreign key related to the WSN node and `DeviceChannel`, the channel of the device to which the data sample is related. `SampleValue` and `SampleTime` are also self-explanatory. Data status (`Status` table) may take the values 0: data inserted, 1: data transmitted and ack is pending, 2: data is ack, may be deleted from local database. The `DeviceSampPeriod` is an auxiliary field and indicates the sampling period (in minutes) of a particular WSN node, used under local processing tasks.

3.2.2. Real time alert system

The Real-Time Alert System (RTAS) is also an independent Python script that uses database data from all sensors and applies an algebraic expression to calculate some numeric value. It was conceived to be used to calculate risk assessment of grape diseases, such as downy mildew. The RTAS script uses the table depicted in Fig. 6(b) to describe active services (the ones to be used in real-time calculations) and to store the result. The `DeviceSampPeriod` of the `Device` table is used as the sampling period to calculate N samples before the actual time, in case of need. For example, if the `DeviceSampPeriod` of a particular device is 15 min, the sample $f(t - 20T)$ refers to a value $20 \times 15 = 300$

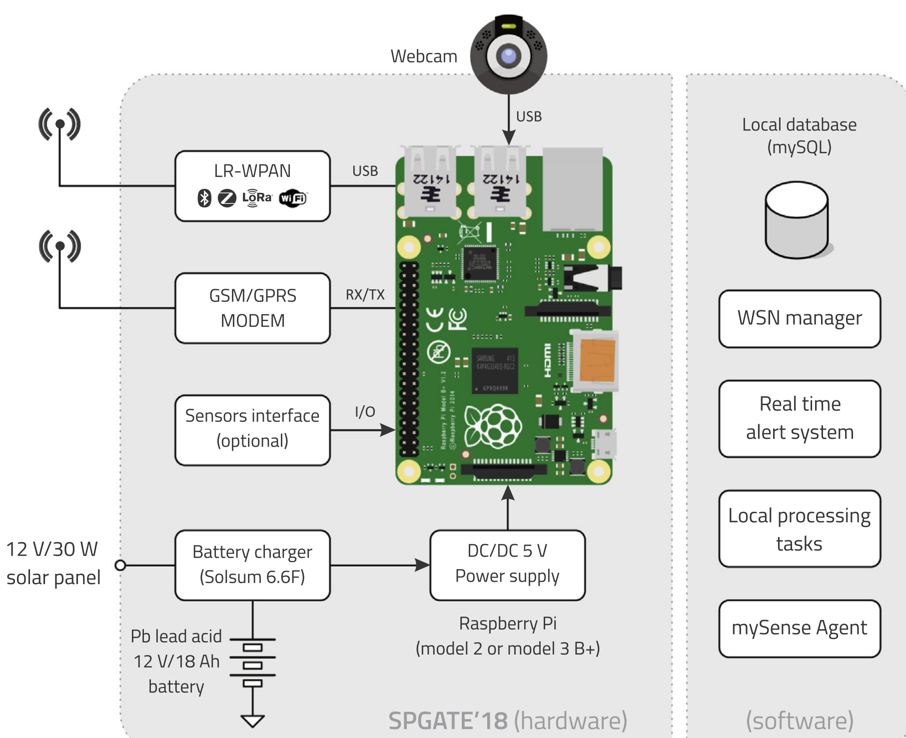
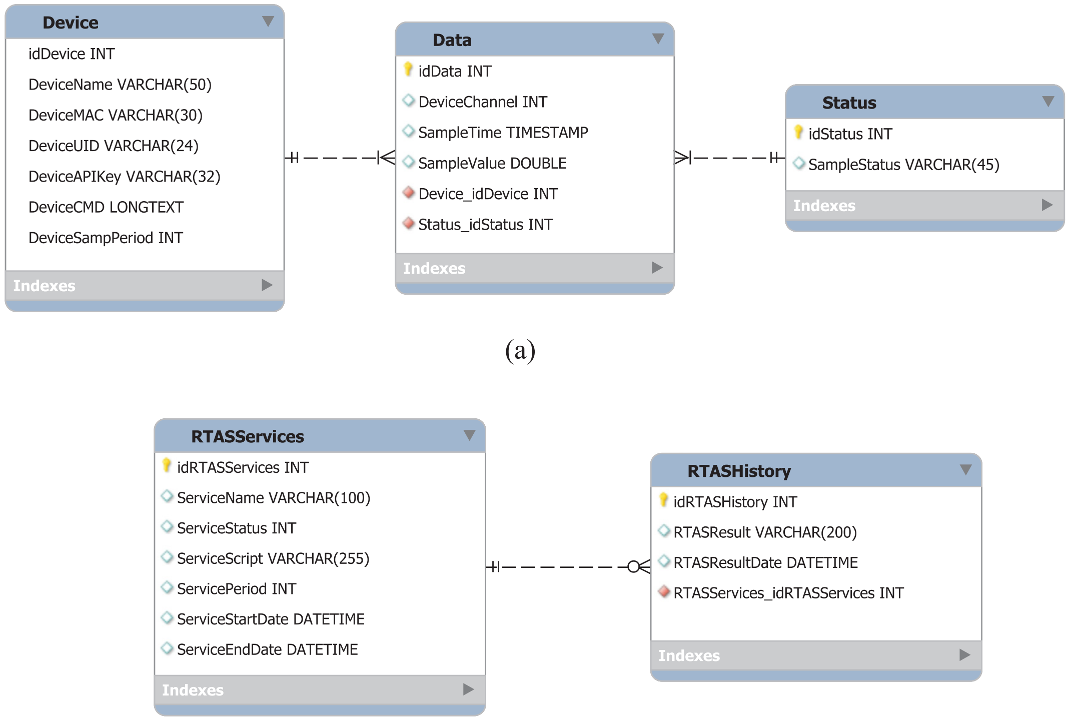


Fig. 5. SPGATE'18 simplified block diagram.



(b)

Fig. 6. E-R simplified diagrams: (a) Local (gateway) database; (b) RTAS service tables.

minutes = 5 h before. This is particularly useful when calculating risk assessment using diseases models that depend on past climatic data values.

As an example of using the RTAS service to generate a warning whenever the moving average of the air temperature rises above a thereshold value, consider Eq. (1), used to compute the moving average of a sequence of past temperature values.

$$T_i = \frac{1}{N} \sum_{j=i}^{i+N-1} T_j \qquad (1)$$

where T_i is the moving average value of the sequence of the last N temperature samples T_j. For the last 48 h, considering a sampling period of 15 min, $N = 48 \times 4 = 192$ samples. To use this example rule, the corresponding RTAS service Python script just needs to be registered in the `RTASServices` table.

3.2.3. WSN manager

The WSN manager is an independent Python script used to exchange data between the SPGATE'18 and WSN nodes, over a particular protocol, being responsible for handling communications and pushing nodes' data into the local database. If multiple connection types exist, different scripts can be used, as depicted in Fig. 7. This is particularly relevant if multiple WSN nodes are deployed in the field and some of them are far away to use the same protocol. In mySense experimental test beds, a ZigBee network with four nodes was deployed in a vineyard with other two different devices 4.3 km away using LoRa® radio protocol. In this configuration, two WSN manager scripts were used.

3.2.4. Local applications

Local applications are small scripts that can be downloaded from the web/cloud server and are intended to perform some type of operation on data aggregated into the gateway database. Examples of local applications are irrigation algorithms, which use soil water content sensor data and produce an irrigation action, and the generation of warnings for the probability of occurrence of any disease based in the temporal evolution of certain climatic parameters. However, these application are outside this paper's scope and will be addressed in future publications.

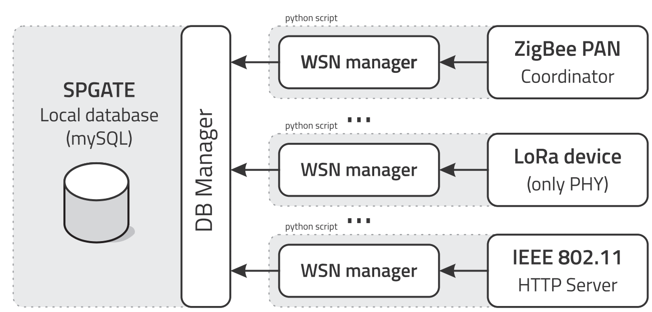


Fig. 7. Functional view of the software implementation of several possible WSN managers for different communication protocols.

3.2.5. mySense agent

The mySense agent is also an independent Python script that is periodically invoked (30 min, for example, using a cron job) to send local data to the mySense cloud system, using HTTP over a GSM/GPRS or a 4G connection. As an open-source software script, the mySense agent can be adapted to be used to transfer SPGATE'18 data to other cloud services such as AWS IoT, Azure IoT Hub, Google Cloud IoT, IBM Bluemix, Xively, among others. When updating SPGATE'18 data, this agent is also responsible for data/configuration updates and upgrades as well as to route cloud service data back to the gateway (notifications, actuating data, etc).

This agent's configuration is stored in a JSON file – for easy interpretation and editing – where some parameters are defined, such as: periodicity of sending data to mySense, how many records are sent in every socket created between SPGATE'18 and the cloud during each connection, dial configuration to access 3G/4G mobile internet, mySense and local database access credentials.

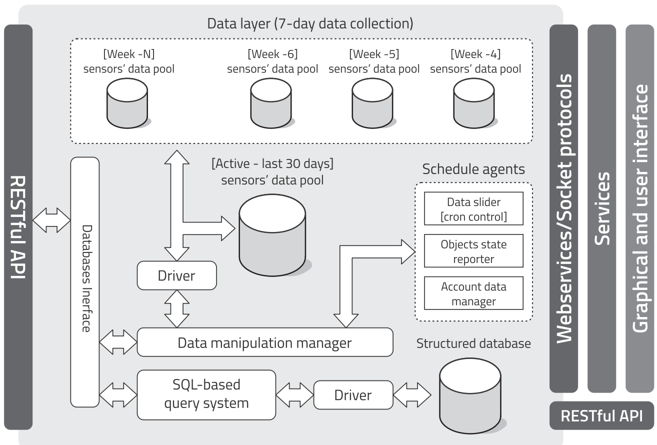


Fig. 8. The mySense core simplified view. It is composed of 3 layers – graphical interface, services and webservices/socket-based protocol – that work over mySense's RESTful API to access mySense's databases: one, SQL-based, used to store users', device' and other high latency data; and another, non-structured (MongoDB) to deal with the bulky and dynamic nature of sensors' data. Data Slider, Objects Reporter and Data Account Manager are time-based agents that rely on Data Manipulation Manager interface – as so database interface does – to optimize data storing and accessibility.

3.3. Web/cloud services

Data integration from sensor networks into decision support applications has become somewhat critical as more and more data from multiple sources and different formats is used to improve the reliability of a decision and/or a forecast system. The third level identified above relates to the interface between the devices that produce data and a structure where such a data becomes available for visualization, storage, and for its use by more complex algorithms and/or end user applications.

mySense core, depicted in Fig. 8, is composed of multi-level layers, two types of databases and respective connecting interfaces, as well as software agents working accordingly with a specific schedule. The graphical user interface is a layer for interaction purposes. In this abstraction level, there is a layer composed of web-services and socket-based protocols (e.g. HTTPS) that communicates with mySense's RESTful API that, in turn, interfaces with mySenses's databases, which are of two types: a structured one (MySQL) to store data whose changeability is of high-latency and, typically, low volume (online physical devices such as sensors/channels, users, services, reports for expert analysis, etc.); and another to deal with the bulky and dynamic nature of sensors' data, identified as sensors' data pool (MongoDB). The latter is also supported by the following time-based agents running once per day: a sliding process to index sensors' readings into weekly data collections, while keeping the most recent 30 days of data in an active collection for prompt access. Moreover, there is a daily reporting process that notifies users owning IoT devices about their communication activities. The implementation of the main functions to access sensors' data pools is consolidated in the Data Manipulation Manager interface, including preliminary filtering of pools by date range to avoid unnecessary and time-consuming querying on out of temporal range

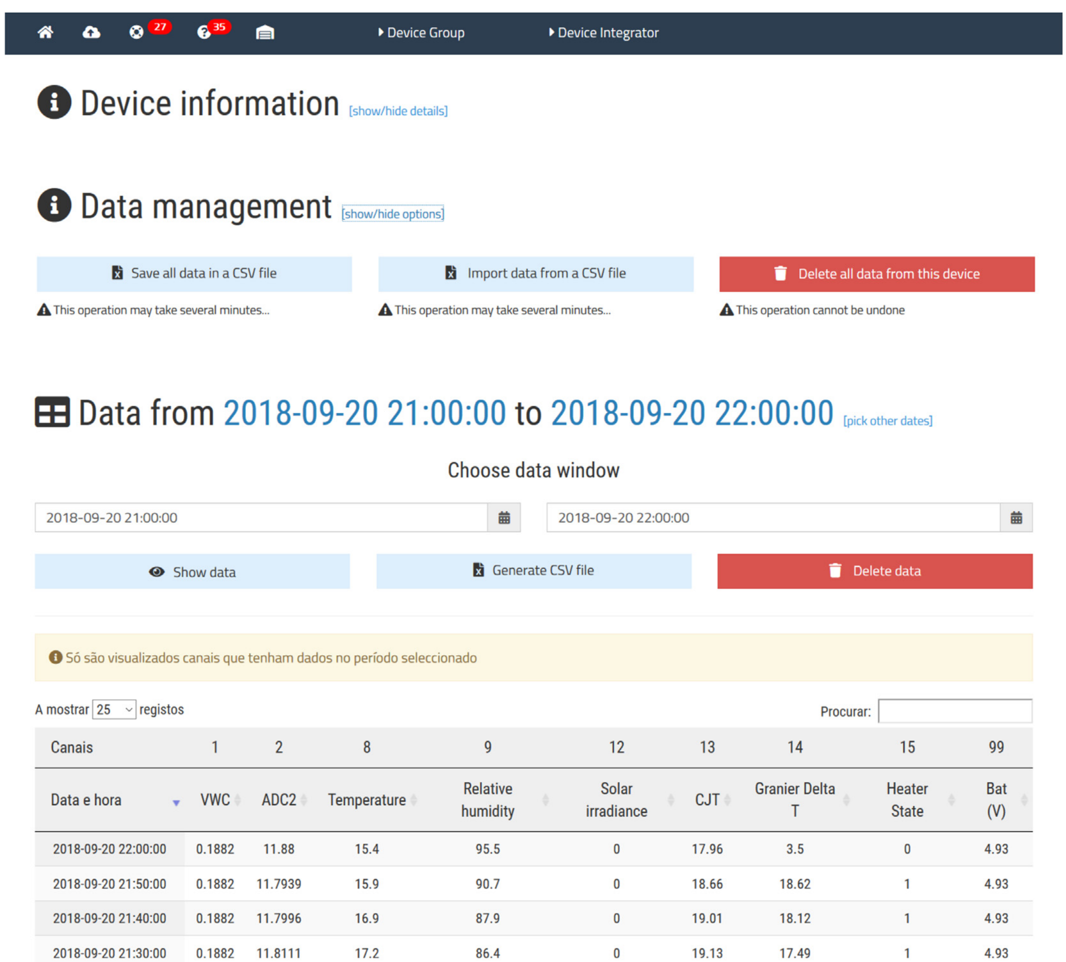
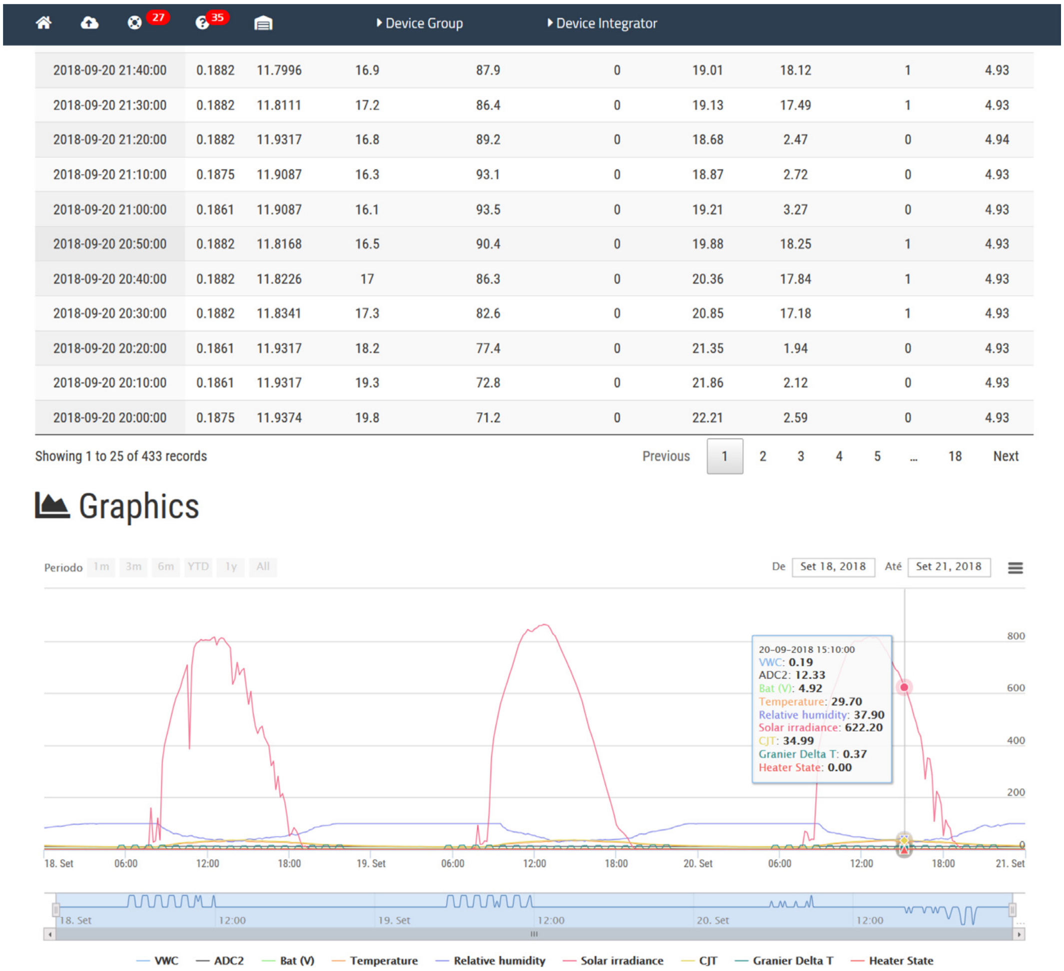


Fig. 9. Data visualization interface available at mySense web interface.



2018-09-20 21:40:00	0.1882	11.7996	16.9	87.9	0	19.01	18.12	1	4.93
2018-09-20 21:30:00	0.1882	11.8111	17.2	86.4	0	19.13	17.49	1	4.93
2018-09-20 21:20:00	0.1882	11.9317	16.8	89.2	0	18.68	2.47	0	4.94
2018-09-20 21:10:00	0.1875	11.9087	16.3	93.1	0	18.87	2.72	0	4.93
2018-09-20 21:00:00	0.1861	11.9087	16.1	93.5	0	19.21	3.27	0	4.93
2018-09-20 20:50:00	0.1882	11.8168	16.5	90.4	0	19.88	18.25	1	4.93
2018-09-20 20:40:00	0.1882	11.8226	17	86.3	0	20.36	17.84	1	4.93
2018-09-20 20:30:00	0.1882	11.8341	17.3	82.6	0	20.85	17.18	1	4.93
2018-09-20 20:20:00	0.1861	11.9317	18.2	77.4	0	21.35	1.94	0	4.93
2018-09-20 20:10:00	0.1861	11.9317	19.3	72.8	0	21.86	2.12	0	4.93
2018-09-20 20:00:00	0.1875	11.9374	19.8	71.2	0	22.21	2.59	0	4.93

Fig. 9. (*continued*)

storage. Although it is outside the scope of this paper to discuss this level in more detail, the mySense environment provides an user-friendly interface to the data sent by each device, as can be seen in Fig. 9.

4. Experimental validation and results

The continued use of low-cost wireless devices in field monitoring applications, that runs from energy harvested from the environment and transmits heterogeneous sensors data periodically during years with minimum maintenance, poses numerous challenges regarding reliability and robustness of such solutions. Over the last two years, beginning at April 2016, solutions such as SPWAS'18 and SPGATE'18 devices have emerged as the result of these intensive field tests, where they have accumulated numerous hardware evolutions and firmware changes that are now intended to be made available as open-source resources. A set of four SPWAS'18 devices (as the one illustrated in Fig. 4(b)) and one SPGATE'18 gateway were deployed in the University of Trás-os-Montes e Alto Douro (UTAD) campus vineyard (41°17′12.0″N 7°44′07.8″W), as depicted in Fig. 10, to study vine disease dynamics, such as downy and powdery mildew, correlated with micro-climate data.

Each SPWAS'18 device was used to acquire solar irradiation, air temperature and relative humidity, rain (one RG-2 rain-gauge from Delta-T Devices, UK, was connected to one SPWAS'18 device), leaf-wetness, thermocouple temperature differences between two Granier probes used in sapflow measurements and soil moisture. Fig. 11 illustrates the SPGATE'18 gateway. An 18 Ah lead-acid battery was used to provide enough energy to the Granier's heating probe demands, being recharged by a 30 W solar panel. Although Granier probes were not used during winter, heating of one probe was continuously used to evaluate energy management of the entire system.

The experimental validation was conducted keeping in mind aspects related to system performance, fail recovery, data loss, connectivity issues, energy supply, RTAS behavior and local processing tasks' functionalities.

One major issue was energy supply. Solar energy, harvested during winter season, and battery degradation play an important role when supplying energy to small unattended systems. These issues become critical if energy demands rise, as in the case of using Granier probes, that requires continuous heating of one probe. To address this issue, energy supply and reservoir of each SPWAS'18 device, that were used in sap flow measurements, have changed to a 7 Ah lead-acid battery, recharged with a 20 W solar panel. In addition, heating was only turned-on during the daylight period and, during winter, heating was turned off. Data loss was observed whenever system runned out of energy and thus, unable to operate. Since the system turns off when battery voltage falls below 3.4 V, sensors were not sampled, usually during the night. Another data loss cause was related to connectivity issues. Until April, no vegetation exists in the vineyard and thus no fade in RF paths have been observed. When the vegetation began to appear, the first signs of RF attenuation appeared and connectivity issues started. RF antennas, initially placed in an inferior position, had to be moved to a higher position.

Fig. 12 shows part of sensors' data of two particular devices, within the same time period: solar irradiation, air relative humidity and temperature, leaf wetness, Granier's ΔT, battery terminal voltage were some of the measured parameters.

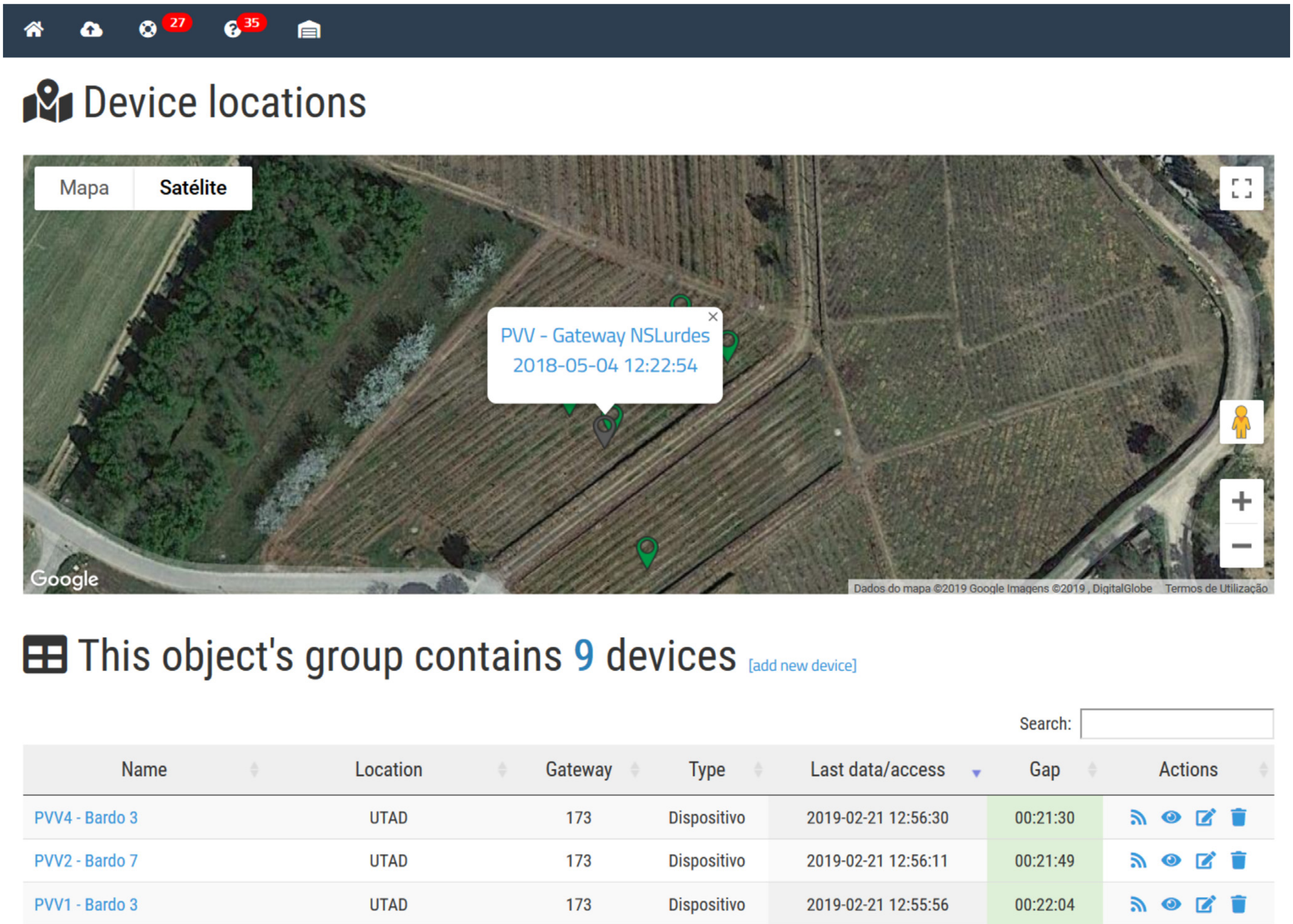
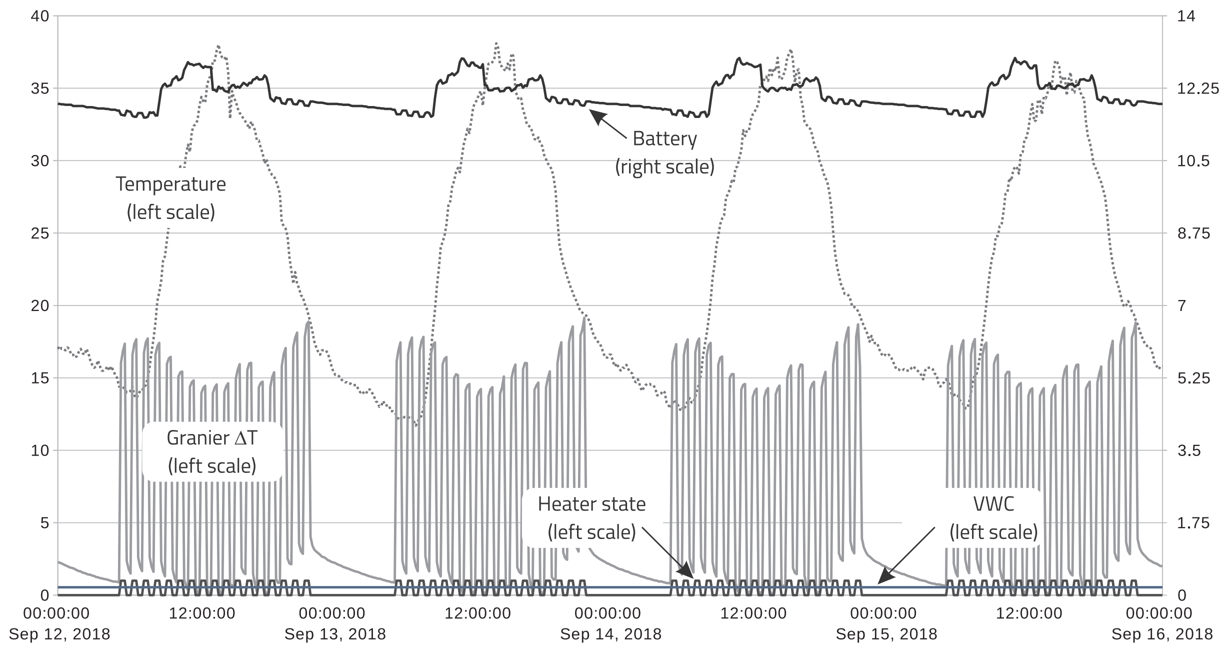
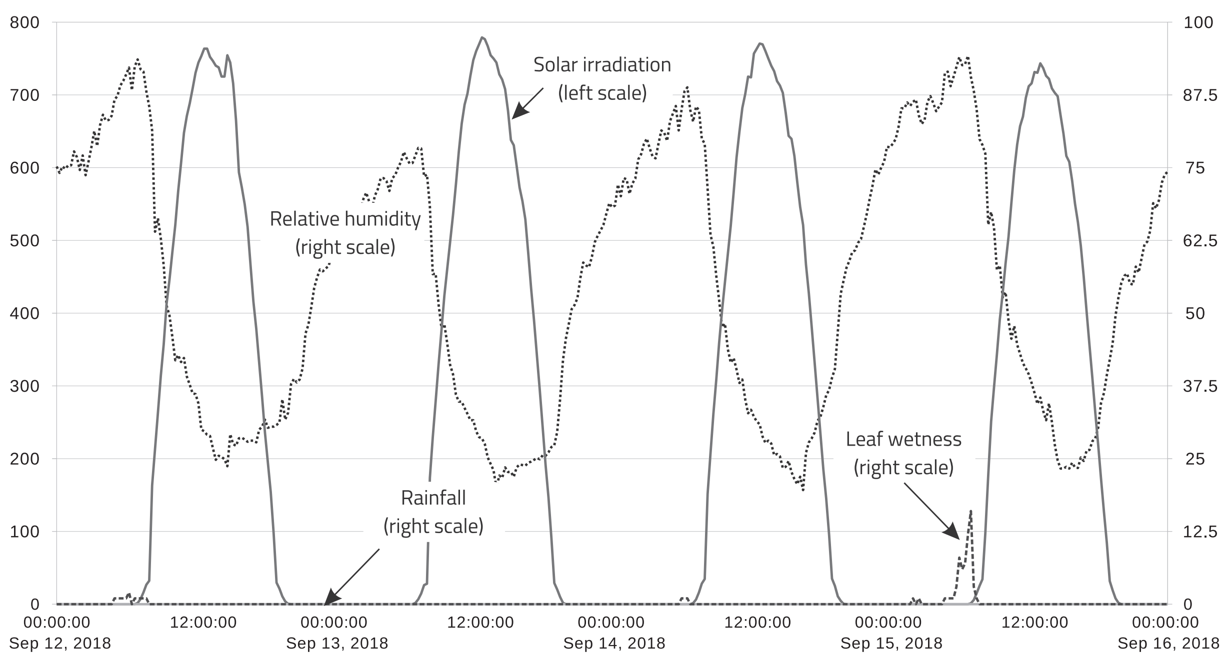


Fig. 10. Geolocation (41°17′13.3″N 7°44′07.5″W) of the WSN deployed on a vineyard during 2 years.

Fig. 11. SPGATE'18 images.



(a)



(b)

Fig. 12. Data gathered from two different SPWAS'18 devices for the same period: (a) Data from PVV1 device; (b) Data from PVV4 device.

The RTAS service, used to calculate risk assessment in vine diseases, and the local processing task engine operation was satisfactory. In fact, these Python scripts have proven to be very easy to write and modify, so that they become suitable for making use of the SPGATE'18 capabilities.

5. Conclusions and final remarks

Assessing crop parameters has become vital within PA/PV concept for modern crop managers and/or viticulturists. To this effect, wireless sensor networks, still present several constrains to their easy installation and deployment. This difficulty rises with the broad range of sensing devices and interfaces needed in monitoring functions. Nevertheless, the last few years have been guided by the maturation of the technology to support these functions and there are now many agricultural facilities that use standardized technology to monitor agricultural processes. However, access to everyone is still hindered due to the scientific and technological knowledge required to deploy an effective data acquisition solution.

An open-source environment to help anyone to deploy a PA/PV monitoring application has been described and successfully evaluated throughout this paper. The main goal was to offer full and free support for common low-cost hardware unattended devices that may be used to support an extended range of environmental sensors and to manage its generated data. In addition, a multi-user web application allows the use of common visualization tools, the possibility to share proximity sensor data among registered users and offers a way to create rules based on simple operations relating sensors' data. Regarding SPWAS'18 devices, a low-cost solution that can boost many applications due to its versatility in accommodating different sets of sensors and using different communication protocols has been presented as a result of two years intensive infield evaluation.

As far as the gateway is concerned, it allows, by choosing one or more communication protocols, to establish a data access point and a local data processing device, enabling fog computing in the field. Indeed, some applications such as smart irrigation are scheduled to be downloaded as applications that can be executed in the gateway itself. The SPGATE'18 is based on a very low-cost SBC which can act as a gateway between several data acquisition systems and a cloud computing system to enable easy data integration and consequent use by users who do not have extensive knowledge in electronic and computing technologies in the field of data acquisition. The same SBC can also be used as a stand-alone data acquisition device (following the IoT concept), with image acquisition capabilities, to send data directly to the mySense web/cloud server.

For demonstration purposes and to facilitate the deployment of easy-to-use IoT solutions, a Wi-Fi USB dongle (Mini Wi-Fi Adapter, Deal Extreme, China) was employed to allow simple wireless devices, based on Arduino® and Wi-Fi shield, equipped with sensors and/or actuators, to interchange data with the low-cost gateway. To implement these solutions, hardware and software open-source resources regarding SPWAS'18 and SPGATE'18 are available at https://mysense.utad.pt/web/downloads.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.compag.2019.05.028.

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