An Experimental Evaluation of IoT Technologies in Precision Viticulture

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Abstract. There is no doubt that the introduction of IoT-assisted applications will become an invaluable asset to optimize farm performance. Through the data collected by sensors deployed in the fields together with other sources of information and facilities, farmers will have at their disposal a set of tools allowing them to make informed decisions on the day-to-day operation. Since 2005, a multidisciplinary team of researchers from the Albacete Research Institute of Informatics and the School of Agronomical Engineers of the University of Castilla La Mancha (UCLM) has been exploring the use of information and communication technologies in the agricultural industry. This paper reports on the main findings acquired through the deployment and experimental evaluation of IoT technologies in a vineyard. Our results also provide insight into future directions on the use of IoT technologies in precision viticulture.

Keywords: IOT · Wireless sensor networks · Web-based applications · Precision agriculture

1 Introduction

Latest developments of IoT technologies have spurred the interest on their application to numerous and diverse sectors [1]. It is now widely recognized that the use of IoT technologies in the agriculture sector will allow the monitoring and control of agricultural products during the whole life cycle: from farm to fork. IoT technologies should therefore help farmers on their day-to-day operations and management planning processes. The design process of IoT-based systems for the agricultural sector should start by identifying those areas where their introduction may have an impact on improving the overall food chain, such as, decreasing the use of water and fertilizers, lowering ecological footprints and economic costs as well as increasing food security. The activation of irrigation systems and pesticide sprayers can be timely and wisely planned based on the information extracted from the data gathered by wireless sensor nodes. In the case of viticulture, the selection of the best grapes will be largely based on

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the information extracted from the data automatically collected by the sensors throughout the season.

Since 2005, our research team at the Universidad de Castilla La Mancha has been involved on the design and implementation of information-and-communications-technologies solutions for the agriculture industry [2]. Our activities have mainly focused on the introduction of IoT technologies into an important sector in Castilla La Mancha: vine growing. The main goals of our early activities have comprised the development and deployment of full operational wireless sensor networks for the data capture, processing and visualization of environmental parameters: temperature, soil and air humidity among others. Farmers have been provided with friendly user interfaces allowing them to visualize the data collected by the sensors deployed in vineyards. Various visualization tools have been developed in order to assist farmers on their decision making tasks.

Current efforts are focusing on developing tools offering valuable information to grape growers and wine producers. Our main goals go a step ahead on assisting farmers and IoT specialists on the deployment and use of IoT technologies in viticulture. From a farmer's point of view, the data collected should provide valuable information on parameters affecting the quality of the grapes. As for the IoT specialists, experimental trials allow them to gain invaluable experience on the design and deployment of IoT system in vineyards.

In this paper, we present the results obtained from the design and experimental evaluation of an IoT-based system deployed in a vineyard. Our results show that the deployment of wireless networks and other computer-based systems in a vineyard requires cost-effective and reliable solutions. Throughout the integration of networks of sensors, Internet-based services and machine intelligence principles, IoT sets the basis to the development of invaluable sources of information to winegrowers.

In Sect. 2, we start by motivating the use of IoT technologies in precision viticulture. We then review the main organization and relevant parameters of a vineyard to be taken into account when developing an IoT precision viticulture solution. Section 3 describes the overall architecture of our proposed IoT solution for precision viticulture. We also identify the vineyard features to be taken into account when defining the network layout of a precision viticulture application. Section 4 describes the methodology and challenges involved in the planning and deployment of a wireless network composed of power-constrained devices (sensor nodes). Section 5 describes the information made available to winegrowers and IoT specialists. Section 6 draws our conclusions and future work plans.

2 IoT-Based Precision Viticulture

2.1 Rationale

In traditional viticulture, winegrowers overlooked the natural variability within a vineyard and applied identical treatment to all plots. In fact, winegrowers did not count with the tools allowing them to monitor and manage each and every plot. Precision viticulture is a differentiated management approach aiming to meet the real needs of each plot within a vineyard [3]. Its ultimate goal is to maximize the grape yield and quality while minimizing environmental impacts and risks. Nowadays, precision viticulture makes use of information and communications technologies that help in the monitoring and control of various vine growth parameters. Monitoring tools have been developed using remote and land sensing instrumentation. For many years, remote sensing have been used on the monitoring of vineyards. Remote sensing is an image acquisition technique capable of describing the vineyard status by detecting the sunlight reflected from the vegetation indices and soil. The actual platforms used in remote sensing have evolved throughout the years. Satellite images have been used in precision agriculture for more than 40 years. However, their resolutions and the limitation of capturing the images from different angles prevent their use for precision viticulture due to the dimensions and orientation of the vines and natural slopes of the land [3, 4]. Furthermore, costs of the images are only economically feasible for large areas. Remote sensing has benefit from recent developments in the area of unmanned aerial vehicles (UAVs) and sensor technologies. UAV applications in remote sensing offer highly flexible and timely monitoring, due to reduced planning time. UAV imaging systems are particularly suitable for vineyards of medium to small size (1–10 ha), especially in vineyards characterized by high fragmentation due to the heterogeneity in training systems, grape varieties, slopes and elevation.

Regarding current land sensing instrumentation being used in precision viticulture, solutions are being implemented around wireless sensor networks (WSN), land vehicle and portable devices [5]. Numerous initiatives around the world have made use of WSNs to monitor important biophysical factors such as solar radiation, soil moisture, and temperature regimes [2, 3]. Up to date, most solutions have explored the feasibility of deploying a wireless network in a vineyard and developing data visualization tools.

In this work, we undertake the implementation of an IoT solution integrating a monitoring tool comprising a wireless sensor network, UAVs and a data processing and visualization engine. From the end-user's point-of-view, the ultimate goal of our proposal is to develop tools allowing winegrowers to gain access to the data being collected. Throughout a friendly user interface, winegrowers can consult and process the data collected by the WSN and UAVs. Among the data processing tools, winegrowers can through a friendly interface carry on statistical analysis, analyze the data collected by all or some of the sensors.

From the IoT specialist's point-of-view, our work analyzes the challenges when planning the deployment of an IoT system in a vineyard. Based on our past experience, we start by characterizing the organization of a vineyard and identify the main parameters of interest to winegrowers. We then describe the overall architecture of our proposal. Throughout a study case, we undertake the definition of the wireless sensor network having been implemented in our experimental trial.

2.2 Vineyard Characterization and Parameters

In this section, we describe the main features characterizing a vineyard. We also motivate the main parameters to be captured by the sensor and UAVs. Recall that precision viticulture aims to address the needs of each individual crop. In a vineyard, production depends on two factors: climatic conditions and management practices. The sensitivity of the grape quality to the climatic conditions varies with the phenological stage of the crop making necessary a proper planning of the actions to be performed by the wine-growers throughout the season.

The choice of the training system is one of the first and most important management decisions to be made when planting a vineyard. Vine training consists of the fixed supports upon which the plant develops providing sufficient aeration and sun exposure to the grape. Besides providing the basis for the management of the vegetation cover, training systems have also been designed to facilitate the viticulture tasks, such as, the pruning and the application of pesticides. The management of the vegetation cover in a vineyard is closely linked to the impact of the climatic conditions on the natural processes of transpiration, photosynthesis and respiration. The ultimate goal when installing a training system is therefore to match the vineyard design to the anticipated vine vigor and climatic conditions. Nowadays, training systems range from single to divided curtain systems and employ both horizontal and vertical canopy division [1]. Figure 1 depicts one of the most commonly-used training systems in Southern Europe, namely, the sprawl systems. It is therefore common practice that within a vineyard, different training systems may be used for each crop. For the purpose of this work, we will consider that the vineyard is divided into crops characterized by the use of a given type of training system.

Fig. 1. Sprawl training system

As for the type of sensors to be installed at each network node and the UAVs, the most relevant climatic parameters are:

- Temperature: Particularly in the month prior to maturity, plays an important role in the quality of the grape. Generally, the higher the temperature fluctuation around the average, better characteristics in terms of flavor, aroma and pigment for a specific level of maturation.
- Relative humidity: It is another major parameter affecting the quality of the grape; very high or very low humidity levels adversely affect fruit development. The heat and water vapor released from the canopy change the temperature and humidity

conditions. In turn, these changes modulate the flow of heat and water vapor from the soil and vegetation. Low humidity causes stomatal closure even if the soil moisture is sufficient, an increase in the potassium concentration in grapes and, consequently, a decrease in acidity, and therefore must quality.

- Radiaton: In general, higher levels of radiation in both intensity and duration, higher yield, acidity and/or sugar content, and fewer leaf area required for cultivation. However, often high levels of radiation is accompanied by thermal variability and low levels of relative humidity, so it is convenient the proper handling of the cover to prevent excessive or inadequate exposure to sunlight.

All of the above parameters should be monitored throughout the season using a wireless sensor network. The main challenge for the network designer remains on the number of nodes and their location within the vineyards.

Another relevant parameter to be monitored is the variability of temperatures of the grape clusters and the canopy in order to derive the plant water stress. Such measurements are taken at various stage of development of the grape. Measurements are taken under a range of environmental conditions and on sunlit and shaded canopies to illustrate the variability of temperatures and derived stress indices. In our study, we have integrated this source of information using UAVs equipped with a thermographic camera.

3 IoT System Architecture and Functions

Figure 2 depicts the overall system configuration implemented as part of our research efforts. The system has been implemented using off-the-shelf components. More precisely, we have used a WSN manufactured by Memsic [6]. Each sensor node has been equipped with three different environmental sensor, namely temperature, humidity

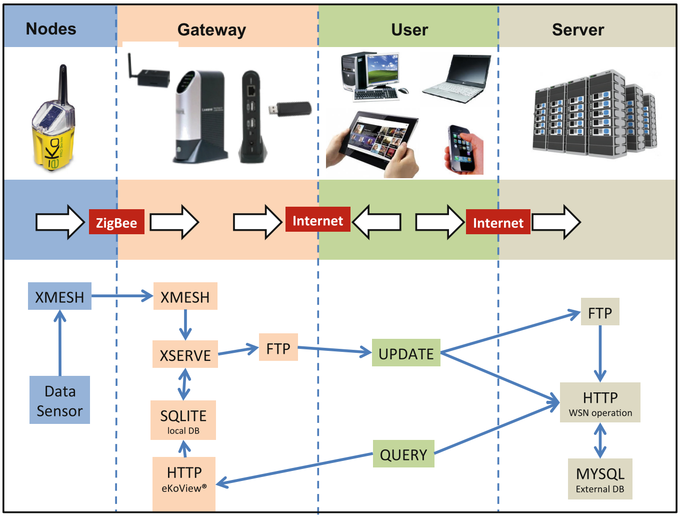


Fig. 2. IoT system architecture

and solar radiation. The WSN comprises all the routing and configuration functions. The main challenge when deploying the network remains on determining the number of nodes and their placement within the vineyard. This issue will be addressed in Sect. 4. Another major task has to do with the integration of the WSN and the UAV into the overall system architecture allowing for the rapid and accurate retrieval of the data collected by the sensors.

The end-user gets access to all the functions provided by the server using a friendly user interface implemented to operate in multiple platforms, i.e., from mobile devices to desktop computers. Figure 3 depicts the main functions implemented in the server. They have been organized into three main blocks:

- Data synchronization and verification: This module is in charge of ensuring the quality of the data collected by the sensors. One issue relates to the temporal reference of the data collected by the sensors. Each sensor reports asynchronously the various metrics every 15 min, i.e., the sensor nodes are not globally synchronized. This issue could have been solved using a clock synchronization mechanism [7], however since our application does not have strict timing requirements an alternative solution had to be found. Our proposal simply associates to a time epoch the data collected from all the nodes during a time window of 15 min. Furthermore, the data gaps are interpolated using the neighboring measurements.
- Data Visualization: This is one of the main functions of our proposal consisting of a series of visualization tools. These tools provide the means to visualize the data captured in various formats. Section 4 provides the main features of the data visualization tools.

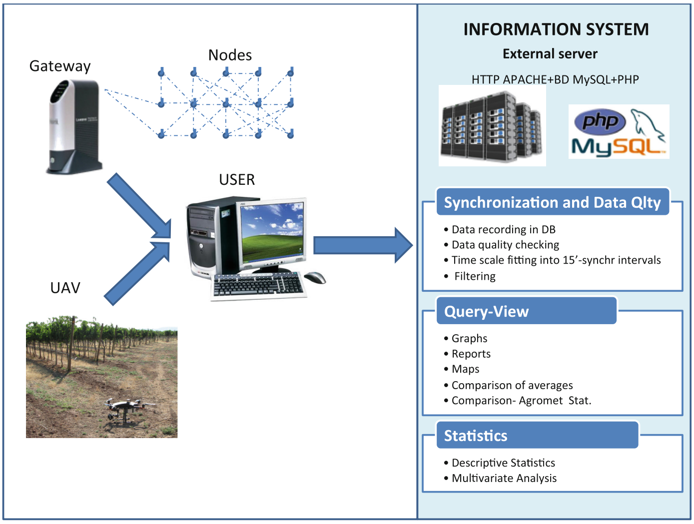


Fig. 3. IoT system functions

- Statistical Analysis: The statistical analysis comprises two parts. First, a comparative analysis of the behavior of the humidity and temperature of the nodes. It allows to compare these two parameters between nodes or groups of nodes. Second, a multivariate analysis used to determine the impact of the temperature and relative humidity over the agronomic conditions, i.e. water stress.

4 IoT Network Infrastructure

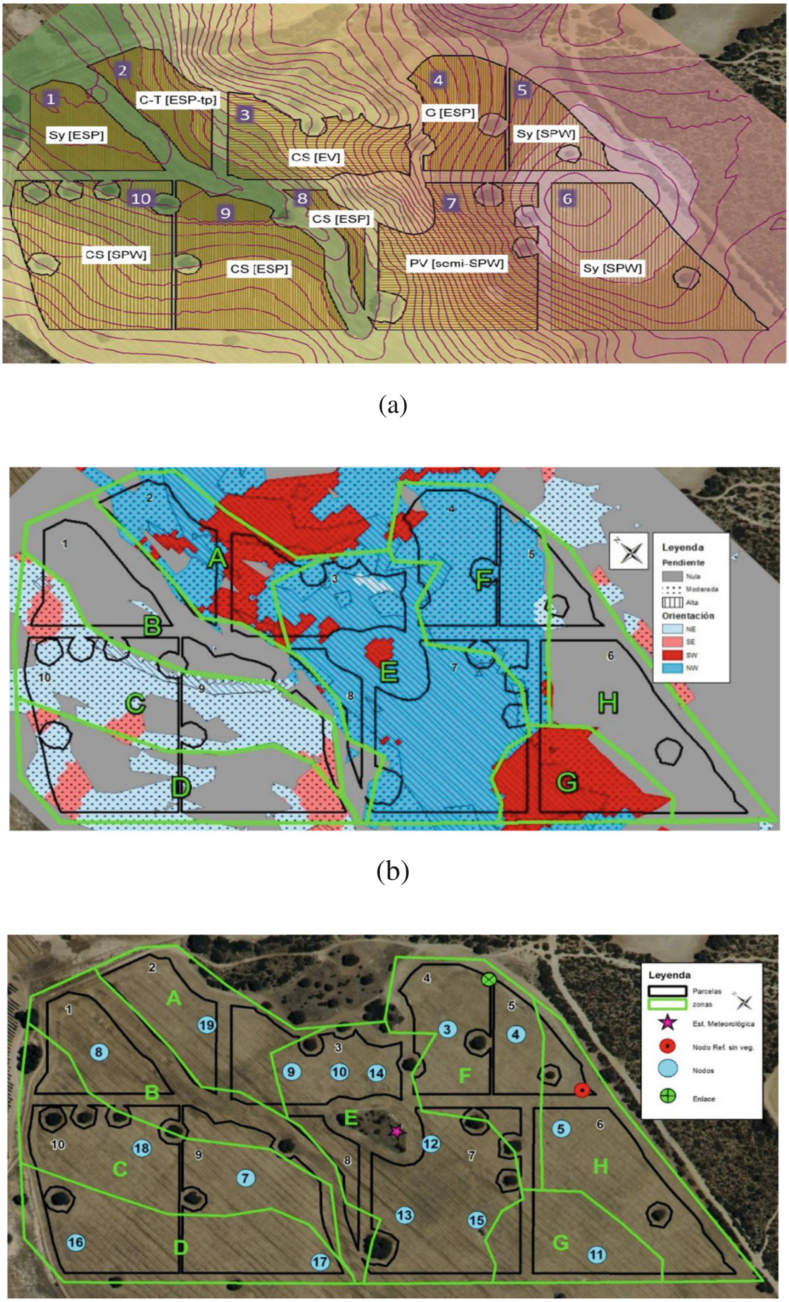
One of the main challenges when implementing an IoT solution for precision viticulture concerns the effective deployment of a WSN. By effective deployment, we mean that network has to be designed to capture the variability of the vineyard to be monitored [8, 9]. The structure, number and location of the nodes have therefore to be properly planned to meet the application requirements.

The node structure concerns the sensors to be actually installed at each node. This is dictated by the climatic parameters to be monitored. In the case of our experimental system, the monitoring of the humidity and temperature in the immediate vicinity of the grape clusters should allow us to highlight the variability of the plot. The number and location of sensor nodes should respond to: (1) the criteria of variability of the test area, and (2) the technical requirements in terms of connectivity and operability, i.e., the network should be properly dimensioned to guarantee the reliable and cost-effective transfer of the data being collected. From the above discussion, it is obvious that the planning of the network involves as a first step a characterization of the vineyard to be monitored. In the following, we should illustrate the major tasks required on the design and deployment of an IoT network infrastructure for precision viticulture.

Figure 4a depicts the plot composition of the experimental vineyard. As shown in the figure, the vineyard consists of ten plots with a total area of 12.27 ha. A plot is identified by its perimeter boundaries and by the tuple: grape variety and training system (see Fig. 4a). The training system is a major parameter affecting the production and quality of the grapes. As shown in the figure, five different grape varieties are grown, namely, Cabernet Sauvignon (CS), Syrac (Sy), Graciano (G), Cencibel (C-T) and Petit Verdot (PV); and four different types of training systems are installed, namely espalier (ESP), espalier with manual clamps (ESP-tp), spraw (SPW) and vertical axe (EV).

Once having identified the various plots composing the vineyard, it is necessary to take a closer look at other variability features of the vineyard. The row orientation of the vines is another major agronomic variability parameter to be taken into account. As for the natural parameters to be considered, these include the soil, slopes and microclimate. In our case, we have considered the topographic characteristics of the vineyard, i.e., slopes. Based on the 1-m level curves topographic description of the vineyard, we developed a Digital Elevation Model (DEM) resulting into eight zones shown in Fig. 4b.

Once having completed the above viticultural zoning process, we proceed to define the number and location of the network nodes. According to their technical specifications, the nodes being deployed have a medium transmission range of 125 m [10]. However, we should bear in mind that in order to capture the variability of the vineyard, each plot should count with at least one node. Furthermore, to ensure a robust network



(a)

(b)

(c)

Fig. 4. Experimental vineyard (a) Plots, (b) Zones and (c) Network layout

deployment, we will have to install more nodes in those zones characterized by steep slopes, e.g., zone E. This is mainly due to the higher variability of the climatic parameters in such areas. Table 1 provides the list and distribution of the nodes deployed in the vineyard. Figure 4c depicts the location of the network nodes, number from 3 to 5 and 7 to 19. Each sensor node was placed as close as possible to a grape cluster of a plant. This should allow us to get an accurate estimate of the solar radiation perceived by the grapes.

Table 1. WSN nodes

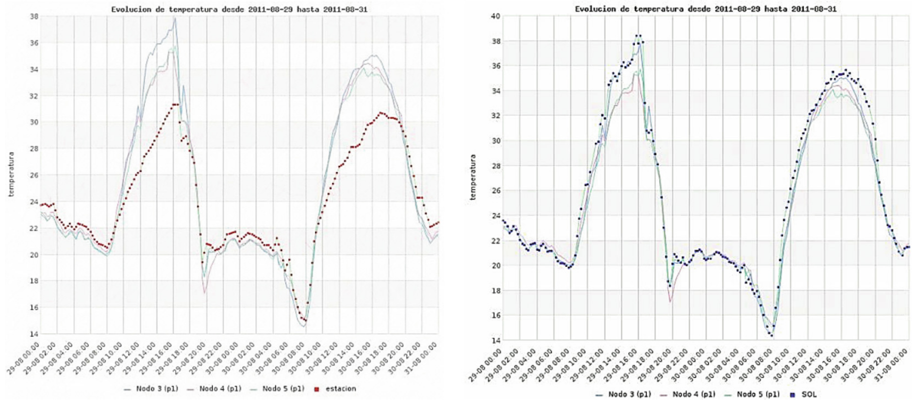
Grape variety	Training	Zone	Nodes
Syrah	espalier	B	1
Syrah	sprawl	F	1
Syrah	sprawl	H	1
Syrah	sprawl	G	1
Cabernet	espalier	C	1
Cabernet	espalier	D	1
Cabernet	sprawl	C	1
Cabernet	sprawl	D	1
Cabernet	vertical axe	E*	3
Graciano	espalier	F	1
Cencibel	espalier*	A	1
Petit Verdot	semi sprawl	E*	3

As shown in Fig. 4c, the vineyard counts with a climatic station, denoted in the figure by a star. Furthermore, we have installed an extra node whose sensor always remains exposed to the solar radiation. By comparing the data collected by the extra node and the climatic station with the data captured by the sensor nodes we should be able to evaluate the effectiveness of our system. Our main goal is to show that the data collected by the network effectively captures the natural variability of the vineyard.

5 Data Processing and Visualization

As already mentioned, the system prototype comprises a set of data processing and visualization tools. In this section, we present some of the major services of our system prototype. Rather than describing the mode of operation of the user interface, we focus our efforts on highlighting the quality of the information provided by our proposal. We also provide an example of the information provided by the UAV. We finally present the system management tools: an essential element to guarantee the wide acceptance of a novel IoT system applied to precision viticulture.

Figure 5a depicts the temperature reported by the climatic station and by sensor nodes 3, 4 and 5 during a two-day period. From the results, it is clear that the temperature values reported by the sensors and the climatic station are quite different during the hottest periods. The fact that during these periods the values reported by the station are lower than the ones provided by the nodes can be explained by the fact that the climatic station is located at the top of the hill. These results clearly show the effectiveness of our IoT solution on capturing the natural variability of a vineyard.



(a) (b)

Fig. 5. Temperature: (a) Sensor nodes and climatic station; (b) Sensor nodes vs. reference node

Figure 5b shows the values reported by the three aforementioned sensor nodes and the reference nodes. As expected, the values reported by the reference node are higher than the values reported by the sensor nodes. In the case of node 5, the values reported by this node are in very close to the ones reported by the reference node. This result can be explained by the fact that the node 5 has been placed closer to the reference node and in a flat area. Figure 5b shows that during August 29, the temperature reported by node 5 were particularly higher that the one reported by the reference node. In a real setup, the winegrower may take corrective actions based on this piece of information, such as fixing the training system of the plant.

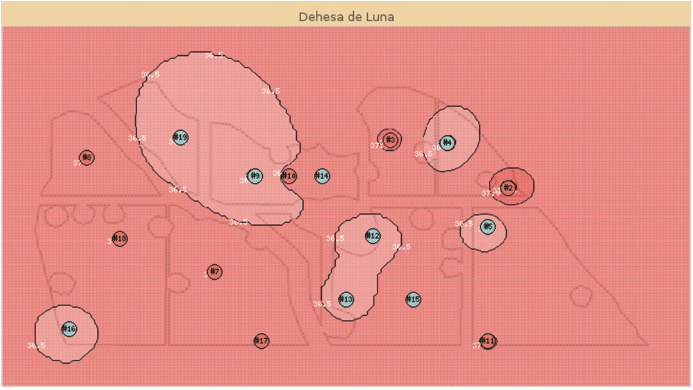
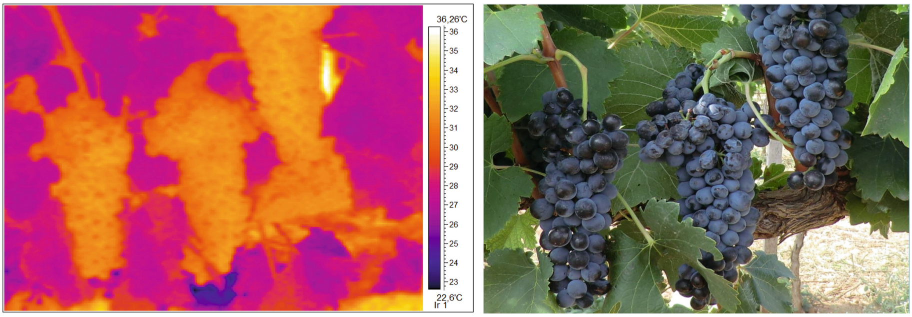


Fig. 6. Georeferenced temperature map

Georeferenced climatic maps are one of the most relevant visualization tools of our IoT solution. This powerful tool allows the user to generate maps with both spatial and temporal components. The system comprises a friendly user interface allowing the user to choose the climatic parameter and time period of the data to be visualized. The maps are based on the mean values reported during the period of time of interest. Figure 6 shows a sample georeferenced map generated based on the data captured by the nodes. We based the interpolation used to generate the maps on the Inverse Distance weighted method (IDW). This algorithm is one of the simplest and most commonly used. Thanks to its property of spatial dependence, the IDW method is based on the assumption that the value of an attribute at some unvisited point is a distance-weighted average of the data points occurring within the neighborhood surrounding the unvisited point [11].

Figure 7 shows a sample thermal and optical image taken by the UAV making part of our proposed solution. The UAV has been equipped with a portable thermal camera SDS-Infrared hotfind-D. As previously explained, our system incorporates these images into its database. The thermal measurement of the grape clusters under different exposure conditions allow winegrowers to determine the temperature differences that may exist between them and the rest of vegetative organs: an important parameter having a direct impact on the quality of the grapes.



(a) (b)

Fig. 7. Sample (a) Thermal and (b) Optical image

6 Conclusions

In this work, we have undertaken the design of an IoT system applied to precision viticulture. We have argued that the design of an IoT solution requires a careful planning of the two main system elements: the sensor network and the information system. The design of the network requires not only having a clear understanding of the main goals of the end application, but equally important to consider the technical constraints of the network technology. As for the design of the information system, a set of tools should be integrated including the storage, processing and visualization of the data collected by the sensors. Our immediate research efforts will be focused on:

- Development of a tool allowing us to easily define the IoT network layout. Our main goal is to develop a tool facilitating the configuration and reconfiguration of the network based on the quality of the results reported by the system.
- Development and evaluation of additional data processing and visualization tools. One of the first tasks will be to incorporate pattern-matching tool applied to the prevention and detection of anomalous situations.

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