Monitoring High-Quality Wine Production using Wireless Sensor Networks

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Abstract

This work reports the experience on the design and deployment of a WSN-based system for monitoring the productive cycle of high-quality wine in a Sicilian winery. Besides providing the means for pervasive monitoring of the cultivated area, the project described here is aimed to support the producer in ensuring the overall quality of their production, in terms of accurate planning of interventions in the field, and preservation of the stored product.

Wireless Sensor Networks are employed as the sensing infrastructure of a distributed system for the control of a prototypal productive chain; nodes have been deployed both in the field and in the cellar, where wine aging is performed, and data is collected at a central unit in order to perform inferences that suggest timely interventions that preserve the grapes' quality.

1 Introduction

This paper describes the experience gained during the deployment of a wireless sensor network for the monitoring both of a cultivation of grapevines and of the wine-aging area. The project intended to address the requirements of a high-grade wine producer operating in the Sicilian countryside. The process of high-quality wine production may be resource consuming at various levels, and requires accurate planning; in order to obtain the desired quality, the producer needs to collect as much information as possible about the whole process. In particular, it is widely accepted that a product may be classified as "typical" only if it is endowed with specific quality features and if it satisfies specific requirements, such as a specific geographic origin, controlled quality of the raw product, and accurate selection of productive techniques; consumers' demand is thus nowadays heavily influenced by information about origin and quality, which may only be obtained by ensuring constant monitoring of the wine production chain, and requires cooperation from different actors, ranging from the agronomist, up to the enologist. This limited chain management process begins with thorough monitoring of relevant quantities in the vineyard, during the growth of the grapes and vines, which results in the collection of a large amount of data from which useful information needs to be extracted. For instance, information could be gained about land composition, the presence of parasites, the influence of the application of chemical products. Such information is extremely valuable to the enologist during decision making; for instance, productive factors such as fertilizers, weed killers, may be specifically weighted out for a particular cultivation in order to optimize productivity; also, farm machinery may be used more cleverly, with a consequent reduction in production delays and costs.

However, producing high-quality grapes does not directly translate into high-quality wine; to this end, the product must be accompanied by a complete set of information that can be univocally coupled with the product during its many transformations, and up to the final customer; this may be considered the first step toward the setup of the traceability of the productive chain with the aim of providing the customer, and all the participants to the production, with reliable documentation about the product history.

The project described here aims at improving the quality of the overall winemaking process by using an innovative infrastructure based on Wireless Sensor Networks [6, 1]. The present project proposes a real-time, pervasive, non intrusive, low-cost, and highly flexible data analysis methodology, and WSNs appear to fit this goal. Many applications are reported in literature that describe projects where wireless sensor networks have been applied to habitat monitoring, such as in the case of the famous Great Duck Is-land project [4]; more recently, WSNs have also been employed in the more specific area of farming monitoring and a few preliminary works describe applications for precision agricultrure [2, 7, 3].

An immediate advantage arising from the adoption of a WSN-based approach is that corrective actions on the cultivations may be timely and selectively chosen; furthermore, the system allows to build a history of past events, and stored data may be analyzed in order to extract potential hidden correlations among the sensed environmental variables and the obtained result. The availability of a considerable amount of precise data, superior to what is commonly attainable through traditional random sampling, allows for the construction of accurate models, and thus favors the proposals of improvements in the cultivation process. This methodology does not merely suggest to increase the granularity of sensing by deploying a large number of sensors in the environment, or to increase the sensing rate; rather, the proposed infrastructure offers the possibility of carrying on advanced analysis by acting as a more complex intelligent distributed system. The technical advantages arising from the pervasive control over the vineyard conditions will then allow for a rationalization of the interventions and will result in an increase in the overall quality of produced wine.

In the present project, we propose the use of two networks, one for the vineyard, and another for the wine cellar. The goal is twofold: on one hand, we wanted to monitor the micro-climate at the grapevines, in order to infer potential correlations with the macro-climate of the entire vineyard, while on the other we want to provide some traceability capabilities. In other words, the framework does not merely allow for "real-time" data gathering and monitoring, but also provides some of the basic functionalities that may expanded to obtain complete product traceability, from the grapes to the bottle.

The remainder of this paper is organized as follows. Section 2 presents the considerations that motivated our work. The architecture of the whole system is described in Section 3, and Section 4 reports the design choices for the hardware, and some considerations about the implemented routing, and data gathering strategies. In Section 5 the actual deployment is described in detail, and finally Section 6 reports our conclusion and gives some directions on the ongoing work.

2 Project Scope and Goals

The quality of wine depends on many elements, besides the selection of the variety of grapes, the training system, and the pruning technique. In particular, influencing factors are the local and global environmental parameters, and the cultivation techniques performed in the vineyard.

Vineyards are typically organized into a hedgerow system, which is characterized by a supporting structure made up of zinc-plated iron, wooden, or concrete poles, and some lines of steel wires to hold the vine canopy. The micro-climate of the grapevine is thus affected by the environmental conditions of a limited area along each of the poles, where the vine grows; it is typically measured by monitoring the parameters that affect the growing and ripening of grapes, such as air temperature, relative humidity, and solar irradiation. For instance, light exposure directly affects sugar accumulation in the grapes and, thus, their quality; temperature is also a very important factor for the vegetative-productive growth, as it greatly influences the ripeness, and weighs upon the quality of wine in the period from flowering to ripening. Finally, it is also important to monitor relative humidity, since at certain period of the year, when the water vapor condenses producing dew, it does not bring any benefit to the grapevine, but rather facilitates the germination of some dangerous fungi that will pave the way for some dangerous infections that will be spread by the spring rainfalls.

On the other hand, wind increases the evapotranspiration in the vineyard, thus influencing the water balance of the plant-soil system and causing problems of water stress. This can be overcome by conveniently planning the irrigation schedule, but it obviously requires constant monitoring of weather conditions; moreover, wind can usually be regarded as a factor influencing the whole cultivated area, rather than the individual plant.

One of the goals of the project described here is to gain insight on potential relationships among the macro-climate of the entire vineyard, and the micro-climate on each vine in order to support the agronomists in deciding on the most appropriate interventions to be taken during the growing phase of the plants. Among these, probably the most influential are the cultivation techniques, such as soil management, pesticide treatments, green pruning, and harvest.

Soil management concerns all the operations aimed to improve soil fertility, such as for instance digging the superficial layer in order to remove the infesting plants, break the capillary pores, and air the soil; it thus modifies the micro-climate of the grape cluster and the vegetation. Pesticide treatments distribute chemicals on the canopy in order to fight against biotic adversities, which are likely to occur when exact values of temperature and relative humidity happen in certain phases of the vegetative-productive growth of the plant. Finally, green pruning and mechanical or manual harvesting also greatly influence micro-climate variations in different parts of the vegetation; the former consists in cutting the terminal part of the buds falling down between the rows and upon the structure of the hedgerow, while in the latter case, the grapes, or the whole clusters, are taken away. The detachment of the berries, in particular, causes a grape juice production varying with temperature and relative hu-

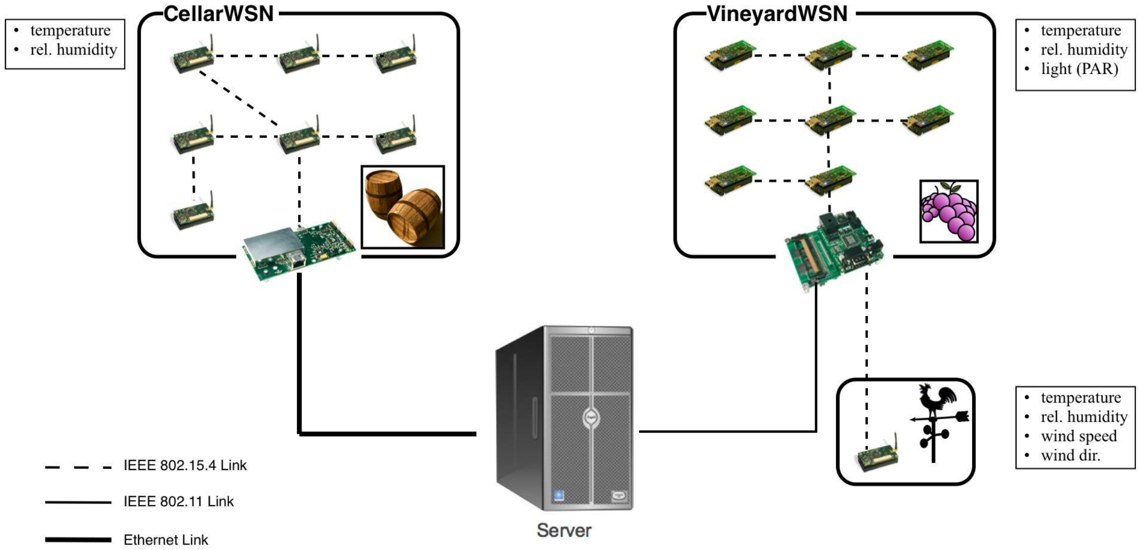

Figure 1. The system architecture.

midity values present during the harvest.

Although the actions undertaken in the field improve the quality of the produced grapes, it is nonetheless of the highest importance to control also the process of bulk aging in the cellar. High-quality wines, and red wines in particular, are usually aged in small wooden barrels containing roughly 500 l in order to be enriched with the tannic acids present in the wood; those acids give the wine its particular flavor, and allow for better conservation over time. Bulk aging in the barrels is a particularly critical phase in the whole production chain, and the containers must undergo strict controls, on a weekly basis, in order to be refilled to make up for evaporation of the liquid, so as to prevent unwanted variations of certain chemical factors that could compromise the content of the entire barrel. Wasting a barrel may represent a huge loss for the winemaker, as each of them could yield up to 700 bottles so, in order to constantly and effectively check the barrels, those are usually moved around the storage area; the configuration of the cellar is thus ever-changing and this may lead to dangerous variation of the micro-climate in different parts of the cellar.

In order to ensure a pervasive monitoring of temperature and relative humidity in such environments, a wireless sensor network was designed and integrated with the conditioning system of the cellar so that sudden anomalies may be readily reported, and the functioning of the whole system may be optimized.

3 The System Architecture

A functional description of the system architecture through its composing blocks is shown in Figure 1, where two different networks may be identified. According to the projects requirements, both the indoor, and the outdoor areas of the winery needed to be monitored; two independent wireless sensor networks have thus been deployed, the former one targeting the wine cellar, where ambient conditions must be constantly kept under control, whereas the latter is concerned with monitoring of selected measurements in the vineyards. Data is separately collected by each network, and is eventually gathered at a central storage unit, located in the administrative building. Collected data is to be subject to further analysis in order to extract useful information that serves as the basis for an expert system providing support to the decisions of the end user.

In the vineyard, sensor nodes were deployed along the vine rows; the current deployment has been limited to a prototypal system covering only a fraction of land right across the administrative building, amounting to about 20 $\times$ 40 m. Although the prototype includes a limited number of nodes, it will be increased in order to potentially cover the whole extension of the vineyards. Sensor nodes placed along the rows of grapevines form a connected multi-hop network; as the network needs to run unsupervised, and nodes are battery-powered as is typical in those cases, they have been programmed to run a data gathering protocol oriented to energy saving. An additional node, placed at the border of the field, is devoted to monitoring of macro-climate related quantities; this node has also been selected to act as the base station. Nodes in the vineyard are equipped with sensors for registering temperature, light exposure, and humidity; furthermore, additional sensors are placed at the border of the field for monitoring the same quantities, but with reference to the overall area, and additionally wind speed and direction.

Table 1. The sensors used in the project and their characteristics.

Measure	Sensor	Characteristics
Light	Hamamatsu S1087	Si Photodiode with spectral response range λ: 320 – 730 nm Peak sensitivity wavelength λp 560 nm Photo sensitivity S (A/W) Infrared sensitivity ratio 10%
Temperature and relative humidity	Sensirion SHT11	Temperature range: -40 °F (-40 °C) to +254.9 °F (+123.8 °C) Temp. accuracy: +/- 0.5 °C @ 25 °C Humidity range: 0 to 100% RH Absolute RH accuracy: +/- 3.5% RH Low power consumption (typically 30 μW)
Wind speed and direction	MTX VO 009	*wind speed* range: 0 – 180 Km/h, precision: 1.5 m/sec voltage 12 Volt, typical current draw: 9 mA *wind direction* range: 0° – 360°, precision: 1° voltage 12 Volt, typical current draw: 9 mA

The framework has been completed with a second wireless sensor network deployed in the area where wine aging is performed. The goal there is to provide a tool for monitoring and optimizing the environment conditions in order to ensure homogeneous quality to the barrels regardless of their position in the cellar. Wireless nodes in the wine cellar have thus been equipped with sensors for monitoring temperature, and relative humidity.

Both networks gather sensed data at a central processing unit, where inferences are carried on in order to provide timely warnings in case of anomalous events that could degrade the quality of the grapes or of the wine. The underlying idea is that over time we will collect enough data from both areas, so that we will also be able to extract correlations between them in order to provide some simple traceability; for instance, interventions such as pruning, or pesticide application, will be recommended by the system when necessary, properly described and logged, and finally traceable by the end user that would then be able to track their influence on the quality of the final product.

4 Design Choices

Different kinds of sensor nodes have been employed throughout the project in order to comply with the diverse requirements relative to the two considered areas. Commercially available boards have been used in order to speed up the design process; however, they had to be customized for the presence of application-specific sensors.

At the earlier stage of the project, during the requirements elicitation phase, the agricultural engineers had pointed out that the two most relevant factors for the development of healthy grapes are temperature, and solar radiation. The former one greatly influences the ripening; in the time period ranging from blooming to fruit ripening, it affects the quality of the wine to be produced, and is beneficial only when confined within a limited range of values; the latter, on the other hand, has more influence on the speed and duration of the grapevine growth. Finally, the importance of measuring the relative humidity in the cellar is related to the fact that upon reaching the saturation point, the water vapor contained in the air condensates into dew which, in summer or spring time, is not beneficial to the vine as it facilitates the growth of dangerous fungi that may later cause infections, such as blight.

Nodes have thus been equipped with the corresponding sensors; in particular, for the vineyard the *Hamamatsu S1087* light sensor, and the *Sensirion SHT11* combined temperature/relative humidity sensor have been used; their characteristics are summarized in Table 1. The light sensors, in particular, are able to measure what is called Photosynthetically Active Radiation (PAR), i.e. a limited spectral range of solar light from 400 to 700 nanometers that triggers the photosynthesis process in plants, and roughly corresponds to the range of visible light for the human eye.

As regards the processor and radio units, the TelosB nodes, produced by Crossbow, have been selected as they offer good performances in terms of transmission range; moreover they already come with an integrated sensor board containing the sensors necessary to sense micro-climate-related quantities. The wind speed and direction sensor, on the other hand, had to be manually integrated in this architecture, so we made use of an MDA300 data acquisition board, also provided by Crossbow, that allows for easy integration of external sensors, and may be coupled with a MICAz mote. It also includes an onboard temperature/humidity sensor of the same kind as those described above, so it is perfectly suited for serving as the "macroclimate sensor", and may also act as the base station for the TelosB nodes as described later in this section.

Table 2. Characteristics of the different types of sensor boards employed in the project.

Sensor type	CPU			Memory	Radio		
	Description	Energy per computation	Sleep power		Description	Energy per bit	Idle power
MicaZ 	ATMega128 8 bit	4 nJ/instr 31 mJ/beamform	30 μW	128KB RAM 512KB Flash	CC2420 250Kbps IEEE 802.15.4/Zigbee	430 nJ/b	7 mA
TelosB 	TIMSP430 16 bit	*Active power* 3 mW	15 μW	48KB RAM 1MB Flash	CC2420 250Kbps IEEE 802.15.4/Zigbee	430 nJ/b	7 mA
Stargate 	Intel PXA255 32 bit	1.1 nJ/instr 1 mJ/beamform	20 mW	64MB SDRAM 32MB Flash	Orinoco Gold 11Mbps 802.11b	90 nJ/b	160 mA

For the cellar area, only the temperature and relative humidity needed to be monitored; in this case MICAz motes have been used, coupled with an MTS310 sensor board which includes, among others, the same *Sensirion SHT11* sensor as the TelosB motes.

The nodes' behavior has of course also been customized for the specific application. The sensing rate of each node was not required to be particularly high and was set to 4 times per hour, which appears to be reasonable also for the goal of maximizing the network lifetime.

Nodes in both networks communicate on a IEEE 802.15.4 link, but at the application layer a specialized protocol was designed in order to ensure robust data gathering, while limiting energy consumption. In order to optimize the overall network lifetime, we exploited some of our previous research experiences in the field of data gathering for WSNs, and implemented a customized version of our protocol for robust and energy-efficient data gathering on the nodes of both networks. As already explained, although the deployment of the nodes is statically set, both environments present dynamic characteristics, so that transmissions may still incur in losses.

Our previous work has proposed a network-layer protocol for WSNs based on the IEEE 802.15.4 standard [5]; the protocol was devised to provide reliable data gathering in latency-constrained applications, and exploited both the flexibility of the IEEE 802.15.4 MAC layer and features of data aggregation techniques, such as implicit acknowledgment of reception. The proposed protocol acts as a routing module and a control entity for the MAC layer and provides reliable communication, while managing power saving and synchronization among nodes. Without relying on MAC-layer acknowledgments, it implemented caching and network-layer retransmissions, triggered upon detection of a link failure. The performance of the proposed approach is studied through simulations, in which we evaluate the achieved reliability and the energy consumption with varying network settings.

A final consideration regards the connection between each network and the data storage server; in the case of the *VineyardWSN*, this was realized thorough a WiFi channel in order to allow for future extension of the same monitoring structure to nearby fields; the bridge between the IEEE 802.15.4 network and the WiFi one is realized by a Stargate board, equipped with both interfaces. On the other hand, the configuration of the considered environment allowed for a simpler cabled connection (via a Mote-to-Ethernet interface board) for the *CellarWSN*.

5 Experimental Scenario

As already mentioned, the project site was a winery in the countryside of South Italy, where Nero d'Avola, Cabernet Sauvignon, Merlot, Syrah, Chardonnay, Fiano, and other experimental varieties of wine are produced in about 110 ha of vineyards. The estates also include a rural building hosting the administrative offices, and a basement with the wine cellar; In the cellar about 4000 hl of wine may be contained in steel vessels; moreover, a separated area is dedicated to store up to 1500 wood barrels for bulk aging. In the following, the details of an actual deployment will be described.

5.1 Deployment Settings

Different types of nodes were deployed in the two main areas to be monitored, and the characteristics of their processors boards and radios are summarized in Table 2.

Figure 2 shows a picture of the actual deployment in the vineyard. Fifteen nodes were positioned so as to cover a representative portion of the field; they were arranged along every other hedgerow, and tied to the poles holding the canopy. The distance between the hedgerows is 2.20 m,

Figure 2. The WSN deployment in the vineyard.

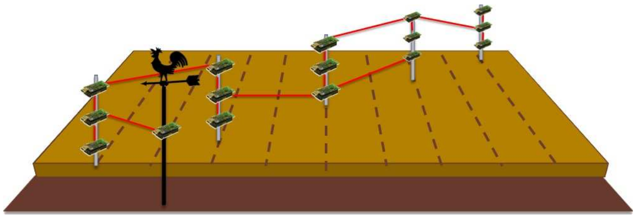

Figure 3. Schema of the deployment in the vineyard.

while iron poles are 80 cm apart from each other. Three nodes were positioned on each pole at different heights (namely, at 60, 90, and 120 cm), in order to obtain measurements about the micro-climate at the productive area of the grapevine, measurements about the micro-climate of the leaf-covered area, measurements from the top of the green canopy to be used as reference for the lower areas; all nodes were TelosB motes equipped with light, temperature, and relative humidity sensors.

The same set of sensors, except for the one measuring light exposure, was replicated in a node located externally to the monitored field, whose purpose was to provide indicative comparison values for the same parameters, but globally referred to the macroclimate of the whole field. Additionally, this node gathers measurements for two parameters, namely wind speed and direction, that influence the global equilibrium of the cultivation by affecting, for instance, soil transpiration.

A schematic description of the deployment of the sensor nodes in the vineyard is reported in Figure 3.

In the wine cellar, twelve nodes were deployed as shown in Figure 4; nodes were attached to the concrete columns in the peripheral area of the roughly 20 $\times$ 25 m room. The

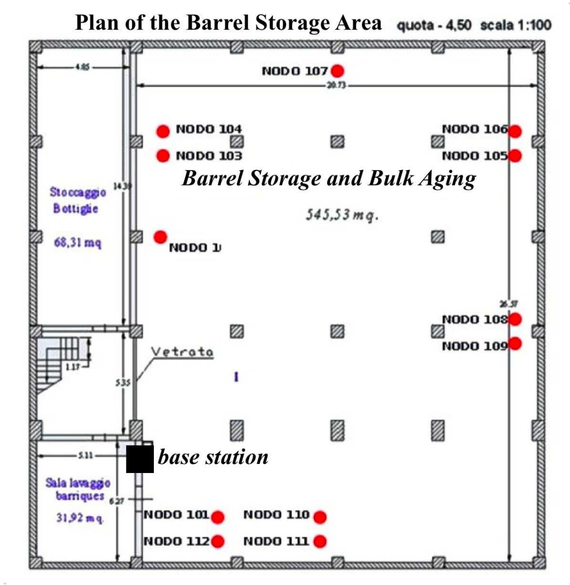

Figure 4. The WSN deployed in the wine cellar.

node with ID 107 (in the uppermost part of the figure) was placed in correspondence to the only exit of the air conditioning system; the system is regulated by an on-off switch triggered by a sensor also located close to this exit; this results in a controlled temperature only for the nearby area, whereas it is impossible to ensure homogeneous conditions in the whole room. The setting of the sensor nodes was thus chosen in order to investigate the more remote areas of the room, where barrels are also stored. The central area in the figure is where most of the barrels are kept, in metallic structures holding three rows of barrels on top of each other; as described earlier, it is periodically necessary to move them around so that the environment topology is not know a-priori. Sensor nodes that are shown in pairs in the figure were placed on the same column at different heights (50 and 100 cm) in order to obtain a more precise monitoring of the required quantities.

5.2 Project Assessment

As already pointed out, the prototypal tool developed in the context of this project is meant to provide some basic traceability to the wine producer. The specific application context, though, requires that an assessment of its validity may be done only after a significant amount of data is collected. At the moment, we are able to observe the correct behavior of the system in terms of its basic functionalities, such as fault resilience, limited energy consumption, and adaptability, although a more precise validation might only be possible in the short period (at the end of the next grape harvesting season). A first complete assessment will be possible in two-years time when correlations might be inferred between the quality of the produced wine and the data acquired during the process of grape growth, and wine aging in the barrels.

6 Conclusion and On-going Work

This paper presented the experience maturated during the design and deployment of a prototypal WSN-based system for monitoring the productive cycle of high-quality wine in a Sicilian winery. As has been discussed, the project is already functional and data is being collected and stored; some preliminary analysis on the collected measurements has already triggered the wine producers to perform corrective actions on the field (in particular, the values of temperature and relative humidity signaled the possible occurrence of a fungi infection, and corresponding measures were undertaken).

On-going work is being carried on in order to investigate the possibility of enhancing the existing prototype with additional sensors; for instance, to measure soil temperature and moisture in the vineyard, thus getting a more precise picture of the factors influencing the growth of grapes.

The project generated relevant feedback also for what regards the monitoring of the conditions of barrels in the cellar; in this case, the project will be expanded in order to provide more sophisticated visual tools that will allow the wine producer to remotely assess and control the conditions of the cellar room via an integrated system of sensors and cameras.

7 Acknowledgments

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