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Distributed monitoring system for precision enology of the Tawny Port wine aging process

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ABSTRACT

Aging of Tawny Port wine is a multifactorial process critical for attaining the desired quality. Real time monitoring of important intrinsic and extrinsic factors that are known to affect the time and quality of the aging process are important to optimize and to manage the natural variability between wines aged in different long-used wood barrels. For this study, a distributed monitoring system was installed in sixteen oak barrels, placed in two adjacent wineries – one of them with controlled temperature – in the Douro Demarcated Region, Portugal. The monitoring process was performed using a RS-485 industrial network, which interconnects sensors that continuously measure wine temperature, pH, redox potential and wine's dissolved oxygen, as well as other sensors that measure parameters related to the barrels' environmental context, such as room temperature and relative humidity. This work presents the design, development and implementation of a remote distributed system to monitor such parameters, aiming to determine the existence of behaviour models for Port Tawny wine during aging in long-used oak barrels, depending on their storage history and to understand the evolution of wine pH, dissolved oxygen and redox potential in real winery conditions as well as their dependence on the wine's storage temperature. This approach is based on easy-to-use embedded systems, with the aim of giving a relevant contribution to other projects in the area of precision enology.

1. Introduction

Tawny Port wine is a fortified wine commercialized worldwide, produced from grapes grown and vinified in the Douro Demarcated Region of Portugal. After fortification with wine spirit to stop the alcoholic fermentation at the desired level of residual sugars, it is aged in long-used oak barrels from two years to many decades. Both the complexity and quality of the final product are dependent on several intrinsic and extrinsic variables. High quality grapes, although essential, do not ensure high quality wines, with the Tawny Port wine aging process of oxidative nature being the most important and critical process in its production. Extrinsic factors like the wine's dissolved oxygen levels, racking operations and the storage temperature are empirically known to influence the aging process. Moreover, wood barrels' usage time and the raw material used to build them are also variable. In addition, both wine pH and phenolic oxidation are key factors for a successful aging process (Mateus and de Freitas, 2001; Sánchez-Iglesias et al., 2009; Carrascon et al., 2015; Day et al., 2015; Oliveira et al., 2015). During the wine aging process a color evolution occurs, mainly due to anthocyanin reaction mediated by acetaldehyde and pyruvic acid: acetaldehyde is formed from ethanol by a coupled auto-oxidation of *ortho*-diphenolic compounds, resulting in H_2O_2 formation that oxidises ethanol to acetaldehyde. An increase in acetaldehyde concentrations increases the rate of anthocyanin-tannin polymerization (Singleton et al., 1964; Wildenradt and Singleton, 1974; Timberlake and Bridle, 1976; Chris Somers and Evans, 1977). Time required to reach both the sensory and chromatic profiles defined for this Port wine category depends on all of the aforementioned factors, which means that it is necessary to control the wine aging process. This is done based on highly subjective parameters, essentially through sensory evaluation. Such natural unchecked variability demands for control and process management, which results in high costs. Indeed, each and every one of the wine aging process stages must be carefully monitored, which is usually done by manual sampling and chemical and sensory analysis. This makes the monitoring operations time consuming and prone to variations. Furthermore, wood barrels are frequently stacked in the wineries during the aging process, which makes sampling operations potentially hazardous for technicians. Increasing the

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predictability of a wine's aging potential as well as of the final product's quality and consistency, can contribute decisively to improve stock management and to reduce costs.

The collection of comprehensive chemical and sensory analytical data can allow the development of relatively simplistic prediction tools to estimate a wine's future condition – provided its initial chemical composition is known – based on time and both extrinsic (e.g. temperature, dissolved oxygen levels) and intrinsic (e.g. pH, redox potential) factor profiles that it experiences. The establishment of a relation between parameters that affect the aging process, the final product's quality and the time for obtaining them, could represent both an economic and quality added-value for the Port wine sector. Hence, to optimize the production and quality management of the Tawny Port wine, Precision Enology (PE) is required. The monitoring of Tawny Port wine aging processes through technological solutions that provide real-time data of wine and environmental parameters are relevant to the development of decision-support tools for PE. Although there are some studies available, most approaches for wine aging processes' monitoring only address the temperature parameter, which is essential but insufficient to properly characterize what is known to be a complex process and to support the creation of wine aging models based on the monitored parameters. Few real-time wireless monitoring systems that consider other parameters besides temperature have been described in the literature. While Di Gennaro et al. (2013) monitors malolactic fermentation by measuring pH and temperature, Di Gennaro et al. (2014) acquires pH and temperature values for monitoring wine evolution and Zhang et al. (2015) presents a system that monitors wine's ullage and temperature in wood barrels, at two of the winemaking's stages: fermentation and aging. Notwithstanding, the monitoring of only the wine's pH and temperature in both Di Gennaro et al. (2013, 2014) is clearly insufficient to have a correct monitoring of the wine's evolution, by the authors' own words. Either Di Gennaro et al. (2013), as Di Gennaro et al. (2014) and later Zhang et al. (2015) propose monitoring systems focused on being suitable for large scale use in wineries: low-cost, flexible and with reduced energy consumption solutions. Again, only two of the wine's parameters are monitored in Zhang et al. (2015), despite the authors' claim that more sensors can be easily added. Yet by doing so, the proposed system's cost – estimated in about 20 €[1] for each sensor node and about 180 €[1] for the local base station – would definitely increase. Moreover, the other two main objectives – the solution's size and the energy consumption – will also be affected by adding more sensors to monitor other parameters. In what regards wineries' environmental parameters monitoring, there are only a few works that address it. From those, the large majority considers only the room air temperature parameter. While wineries' environmental parameters monitoring systems are proposed in Anastasi et al. (2009) (temperature and relative humidity) and in Zhang and Wang (2012) and Medela et al. (2013) (temperature and humidity), thermal studies based on gathered data sets are presented in Ocaña and Guerrero (2006), Mazarrón and Cañas (2009), and Barbaresi et al. (2014) and temperature models for improving wineries' construction or to deploy temperature monitoring networks are presented in Barbaresi et al. (2014, 2015).

This study presents the design, development and implementation of a remote distributed system to monitor parameters known to influence the aging process of Tawny Port wine. A set of 250 L long-used wood barrels were instrumented in two adjacent wineries – one of them with temperature control – in the Douro Demarcated Region, Portugal. Sensors placed in each wood barrel and in the wineries are connected to communication networks that collect data for local and remote storage. A remote IoT-based agroforestry management platform (mySENSE) is responsible for receiving sensors' data every 15 min and act as a decision support system for the management of the Tawny Port wine aging process through PE. Extensive tests were also performed to evaluate both the monitoring system's reliability and robustness.

The purpose of this work was to investigate the existence of behaviour models for Tawny Port wine aging in long-used wood barrels and its dependence on the storage history and to understand the evolution of wine pH, dissolved oxygen and redox potential in real winery conditions and their impact on the aging process as well as their dependence on the wine's storage temperatures.

2. Materials and methods

2.1. Monitoring system's architecture

The monitoring of the Tawny Port wine aging process is carried out in two identical wineries – one of them with temperature control – in Vallegre, Porto S.A Wines farm, located in Pinhão, Portugal (N 41°10′30.7″ E 7°33′39.9″). The wine was placed inside wood barrels in February 2016. Eight wood (oak) long-used barrels were arranged in each of the two wineries. Each barrel was instrumented with sensors to measure relevant parameters in the wine's aging process, namely: pH, redox potential, dissolved oxygen and temperature. Moreover, two of the environmental parameters of both wineries – temperature and relative humidity – are also monitored. Fig. 1 represents the monitoring system's general architecture.

Given the environmental and physical contexts in which this study continuously takes place during about two years (2016 and 2017), as well as the economical and social potential relevance of its outcomes, the option was to use industrial range sensors with a RS-485 connection. Thus, the sensors in each barrel are connected to a RS-485 bus that starts at an hub element and runs through a set of IP68-graded junction boxes, covering both the wineries. In what regards the aforementioned environmental conditions sensors, they have a RS-232C direct connection to the hub.

The concentrator or hub consists on a low-cost single-board computer (SBC) solution – a Raspberry Pi (model 2) – that is responsible for: (i) managing communications with both the RS-485 network' sensors and with the RS-232C sensors and (ii) transmitting the acquired sensors' data to a remote agroforestry management platform based on the IoT concept named mySENSE (https://mysense.utad.pt), which is being developed at the University of Trás-os-Montes e Alto Douro (UTAD), Portugal. As a way to minimize the loss of data due to the possible unavailability of communications with the farm's exterior, which prevents data transmission to mySENSE, the hub implements a temporary storage system based on a data manager application and a local MySQL database.

As for exterior communications/Internet connection, the hub was initially equipped with a General Packet Radio Service (GPRS) modem (GL865, Telit, London, UK). However, to ensure greater reliability and to increase quality-of-service (QoS), two wireless routers (BR-6478AC, Edimax, Taiwan) were installed: one about half-way between the wineries and the farm's main house in repeater mode and one in access-point mode in the wineries' control room. This enabled the extension of the farm's wireless 802.11b/g network to the wineries and the consequent use of the farm's wired Internet connection to transmit data to mySENSE. Moreover, at an early stage there were also some exterior sensor stations that relayed environmental data through a 802.11b/g connection (RN171XV 802.11b/g Wireless LAN Module, Microchip, USA) to the hub, which is equipped with a 802.11b/g/n USB dongle (EW-7811Un, Edimax, Taiwan, ROC). Thus, if the need arises to migrate to or to integrate wireless sensors in the monitoring system, there is available an implemented and tested solution.

2.1.1. Sensors and interconnections

The monitoring of wine parameters which were considered relevant to its aging process is done through the use of two specific sensors. While pH, redox potential (mV) and temperature values are measured using PHEHT sensors (SN-PPHRB, Ponsel, France), dissolved oxygen

[1] AUD to Euro exchange rate on 1st March 2017.