2024 International Symposium on Sensing and Instrumentation in 5G and IoT Era (ISSI) | 979-8-3503-7868-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/ISSI63632.2024.10720473

Towards a Digital Twin for Vineyard Farms

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Abstract—**Smart systems have increasingly sought more applications in agriculture. With the advent of climate change and the understanding on the impact that intensive agricultural practices have on the environment, a more responsible and precise use of resources has gained focus on the farming community. The design of a Digital Twin for horticulture that may be able to monitor plants growth, plants physiology and control physical things in a farm is described in this paper. It includes a data repository for structured and unstructured data, different components for data acquisition, data communication, data storage, data modeling, data analysis and data visualization. The Digital Twin data sources, IoT technology for soil moisture and nutrients monitoring, and techniques for grapevine modeling are described in this paper.**

Keywords— Digital Twin, Soil Moisture, Soil Nutrients, IoT, Time-Domain Reflectometry, Virtual Reality, 3D Modeling

I. INTRODUCTION

Precision Agriculture (PA) is a rapidly evolving area of research that aims to make farming simpler, more efficient, and more productive, and to reduce costs and the environmental footprint of agricultural production (i.e., by decreasing the need for agricultural inputs like water, fertilisers, and pesticides) [1]. Although it was introduced in the 1980's (during the 3rd Agricultural Revolution) it was only during the 4th Agricultural Revolution (i.e., concept driven by the Industry 4.0) the technological development of the field took off [2]. Agriculture 4.0 represents the use of technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, Cloud Computing, and other smart systems and devices for automation in farming, ubiquitous agriculture sensing, and trustworthy food supply [2] [3]. These technologies have made farming simpler, reducing uncertainty associated to agriculture, improving efficiency and reducing the costs of production. Even so, with the increasing population, shrinking resources, the growing frequency of extreme weather events (i.e., intense drought, severe hurricanes and storms, and extreme floods), as well as other factors that affect agricultural production, such as vegetative diseases and the rising prices of seeds and fertilizers due to trade wars [4] [5], there are still many challenges to be overome using PA.

In the last decade, the Information and Communication Technologies (ICT) for Smart Farming as part of Agriculture 4.0 evolved and diversified. If initially information systems for farms have included functionalities for billing and invoicing, inventory management or inputs management, currently numerous information systems for farmers include features for production tracking, crop plans development, forecast and measures of farm profits, risk portfolios management, labour management, etc. Trends in technologies for PA, characterized by more automation, more use of IoT and AI technologies, arise from the increasing lack of human resources for agricultural labour, the need of farmers for extension services (i.e., the services that provide opportunities to acquire valuable knowledge regarding seeds, plant varieties, fertilizer, pests and plant diseases management strategies) and the necessity of user-friendly computer interfaces for farm process monitoring and control [6] [7]. The use of ICT in PA also cuts down the need for physical labour and improves productivity, enhancing the profitability of farming as a source of livelihood [1].

There are many existing applications to help farmers make more informed decisions and improve their operations by providing information on weather forecasting, crop growth, yields measurement, irrigation efficiency, plant diseases and pests management (e.g., AquaCrop, AgrometShell, Agrivi, AgVerdict, DSSAT, ExactFarming, FarmLogs, PrecisionHawk, SpiderWebGIS, Trimble, VitisFlower, Advanced Management Systems amssoftware). However, mainly big farms have adopted those technologies [6] considering their high costs (i.e., even for their acquisition, or for maintenance, or training or payments for trained workers). Nevertheless, these tools may provide great benefits to smallholder's farmers, mainly for those in developing countries (who constitute about 90 percent of all farmers worldwide), who may suffer from low farm productivity and yields, and are disproportionately vulnerable to shocks such as extreme weather events [1]. Mobile phones, remote sensing using satellites and unmanned aerial vehicles (UAVs), new sensors and IoT technologies, the growing mobile phone and Internet penetration, the falling costs of data communication, open-source software for data acquisition, storage and analysis, are making information systems for farms management increasingly affordable and accessible to even smallholder farmers in developing countries.

Another obstacle to the adoption of PA and ICT tools for farm management is the complex and less intuitive interfaces for data visualization. As the farmers should understand the data provided by the application in order to make informed decisions (i.e., when to increase water supply to plants, when to apply fertilizers or pesticide, or which plot of land requires additional agrotechnological intervention), the data visualization has great importance to the perceived usefulness of applications for farm management. Maps, pictograms, augmented reality, virtual reality or mixed reality may support efficient visualization of data for crop management.

The integration of such techniques in Digital Twin technology can provide a user-friendly interface for farmers as the interface may be a digital model of the farm (or part of the farm) that continuously updates information from physical world and provides easy to use tools for informed decision-making and remote control of different farming activities. The Joint International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC), the ISO/IEC standard 30173 - 2023 "*Digital Twin – Concepts and terminology*" has defined Digital Twin as "*the digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization*".

In this paper we present part of the work aiming to develop a Digital Twin platform for horticulture. In second section we present the architecture of a platform for Digital Twin for horticulture. The design of this platform may be used for scaling the developed vineyard management tool, described in this paper, for other horticultural branches (i.e., gardening; greenhouse horticulture; hydroponics; aquaponics; floriculture; olericulture). In the third section information on IoT technology for soil moisture and nutrients monitoring is described and in the fourth section the techniques used for the virtual modeling of a vineyard are presented.

II. Architecture of Digital Twin for Vineyard

A Digital Twin (DT) platform for a Vineyard Farm consists of several components. These include a data repository for both structured and unstructured data, as well as various components for data acquisition, communication, modeling, analysis, storage, and visualization. Additionally, the platform includes applications that enable the tracking of plant growth, plant physiology, and control of physical elements on the farm. (Fig. 1).

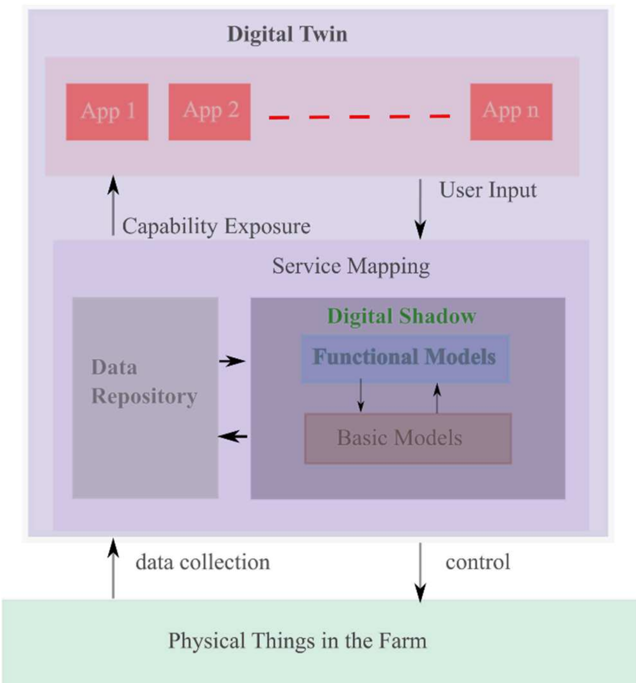

Fig. 1. Digital Twin framework for vineyard farm.

A data source for a vineyard farm could be data from on-site sensors or public weather stations. Weather stations can provide values on air temperature, air humidity, wind speed and direction, air pressure and UV index. Furthermore, on-site sensors can be used to collect data on light intensity, precipitation, chemical composition of water for irrigation field(s) topography, type of soil in different regions of the farm (using on site analysis of soil or public maps such as from European Soil Data Centre, EPIC WebGIS Portugal), chemical compositions of the soil (macronutrients, micronutrients, soil organic matter or humus, salinity), or soil water content, and the dynamic changes of soil moisture by precipitation, irrigation, or evapotranspiration. The system should acquire data that supports the understanding of plants physiology such as: photosynthetic carbon assimilation, chlorophyl content, stomatal conductance, intercellular CO_2 concentration, water release from the leaf, leaf area index, dry biomass, NBI (Nitrogen Balance Index), multispectral vegetation indexes, hyperspectral vegetation indexes, and evapotranspiration. Different sensing devices can be used for measuring plant(s) growth and physiology, namely: portable photosynthesis system, hyperspectral camera, multispectral camera, thermography camera, gravimetry devices, soil moisture sensors, soil NPK sensors, light intensity sensors, air temperature and humidity sensors, and remote sensing through satellites or drones.

Different models of plants (e.g., model of grapevine such as Grapevine XL) could be imported and used in the DT for virtual representation of plant growth or the plant's response to environmental conditions (e.g., leaf response to different levels of solar radiation or quantities of soil water and nutrients). The Quantitative Plant Platform (https://quantitative-plant.org/), as part of a long-term, distributed, pan-European infrastructure for state-of-the-art phenotyping (EMPHASIS), includes a grapevine model and also numerous other models that may be adapted for modeling the impact of environmental conditions on plants. DT may have capability to acquire relevant data from an open database on phenotyping for evidence-based recommendation on plant varieties and their required condition for growth and development. The virtual representation of a grapevine or vineyard may use photos, mathematical models and 3D models to build a basic model of vineyard as well as real-time data from sensors for building a functional model of vineyard. A digital shadow or replica of a vineyard may be obtained by integrating data repository and services for representation of different instances of the Digital Twin. Digital shadow (i.e., in several papers is defined as digital replica) was defined by the German Academic Association for Production Technology (WGP), in the context of manufacturing, as a sufficiently accurate image of the processes in production in virtual environment with the purpose of real-time evaluation of relevant data [8]. A digital shadow is created for specific uses at various points in time and the model is fed by a one-way data flow with the state of an existing physical object [9]. It should be understood as a pure assignment of the status data by a measurement to a specific asset in physical world at a specific instant in time. Therefore, if for a real physical object may be many digital shadows (replica), only one and no second Digital Twin may exist for one real physical object, including and combining all relevant properties for its purpose along the specific asset's lifecycle [10]. Digital shadow collects data from the physical world through sensors, Internet of Things devices or other sources. A change in state of the physical object leads to a change in the digital shadow. However, the digital shadow lacks bi-directional flow of information which characterizes the Digital Twin.

In addition to data on plant physiology (i.e., acquired by sensors on the fields or remote sensing) and plant phenotyping from open database, other data that may be supplied to DT are data from open databases on plants phenology (e.g., USA National Phenology Network). Phenology, the study of the timing of seasonal biological events, is currently studied both as a plant trait and an ecological process. The knowledge of phenology has been generated through combination of local scale observations, digital recordings from many sites or large and diverse geographical spaces, and experiments [11]. The data on phenology may improve modeling processes in DT associated with climate changes, which may increase prediction capability of different scenarios that may support decision-making for risks mitigation in farm.

Digital Twin should also include agrotechnological data (e.g., pruning, irrigation, fertilization, plant diseases and pests' surveillance). Smart sensors, Internet of Things devices, and vineyard robots may play an important role in the capturing and transmission of data on agrotechnological measures to the DT platform. Data collected from in-situ or machine embedded sensors regarding moisture, nitrogen (N), phosphorus (P), and potassium (K) can be utilized for real-time decision support in controlling Variable Rate Technologies (VRT), such as smart pumps [12] and fertilizer mixers [13], as well as automated section control (ASC) during irrigation, fertilization, and pesticide application.

Public data from national or international association related to agriculture (e.g., FAO – Food and Agriculture Organization of the United Nations; ISPA - International Society of Precision Agriculture; OFE-C – On-Farm Experimentation Community) may also be used to supply data on agricultural practice to the Digital Twin for horticulture farm.

III. IoT Technology for Soil Moisture and Nutrients Monitoring

As part of digital twin for smart farm implementation it was developed a wireless sensors network (WSN) that uses Time-Domain Reflectometry (TDR) sensors for monitoring soil content of N, P and K as well as other parameters of the soil such as moisture, electric conductivity (EC) and temperature (T). Air conditions such as relative humidity (RH) and air temperature (AT) are also measured using the designed and implemented sensing node. The data acquired from the sensors is integrated in a Digital Twin for vineyard. The proposed system follows an architecture as illustrated in Fig. 2. It includes four layers: a Sensing layer; a Network layer; a Data Processing layer; and an Application layer. The Sensing layer is composed of WSNs that follow a Star topology, where an aggregator node combines data from sensor nodes, which can be found at distances of up to 100 m from the aggregator node. Although the star topology introduces a single point of failure and has limited scalability when compared with other topologies such as tree and mesh, it is simple to setup and manage. Given the small scale of the study this topology was considered optimal. The combined data is sent outside the WSN to the Data Processing layer where it is stored in a Postgres database provided by Supabase cloud. The data is processed and used to update the Digital Twin, which is integrated in a web application based on Node-Red Dashboard 2.0, as Part of the Application layer. In the following subsections the components of each layer are explored in more detail.

A. Specificities of the Study Field

For a preliminary study of the implemented DT, a row of vines from a field in the region of Lezíria do Tejo, in Portugal, has been chosen. The region has unique climatic conditions, characterised by hot, dry summers, with little rain and mild, wet winters. It is also well-known, that this region can reach temperatures as high as 40°C in the summer. This factor coupled with the reduced rainfall, the sandy-clay texture and granular structure of the soil, results in the loss of water in the soil and plants through evapotranspiration, as well as reduced organic matter and micro-organism activity in the soil. The vines are also located in an inclined terrain, with slope of roughly 35º which further contributes to the poor nutritional conditions of the soil, as N and P are more easily lost through leaching and surface runoff. As a result, N and P can be found in very low and low concentrations in the area respectively. Even so, as in most soils, K can be found in very high quantities. The unique edaphoclimatic conditions in the area makes it a great case study for precision nutrient management.

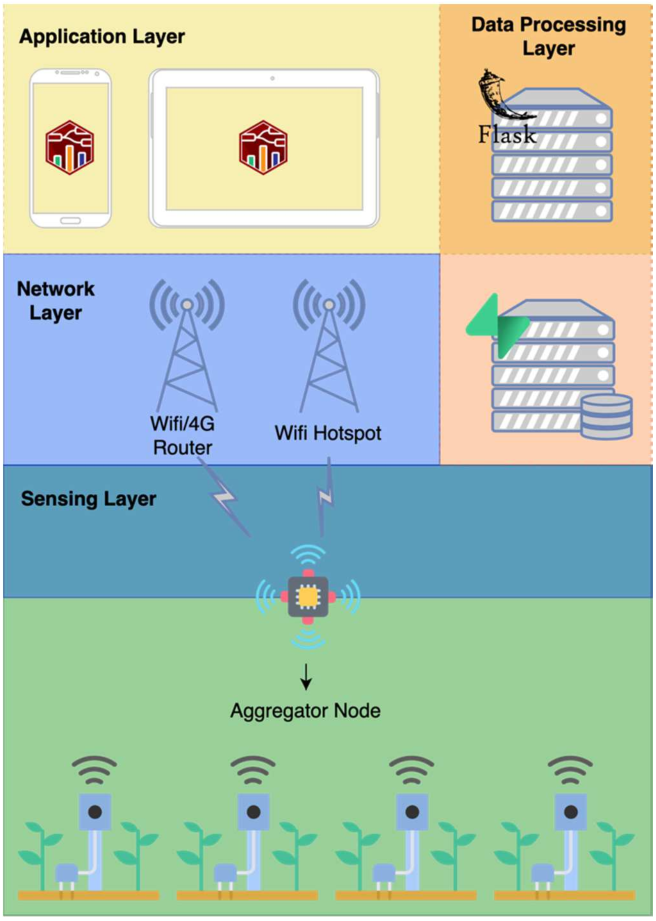

Fig. 2. Architecture of nutrient monitoring system, including 4 tiers and wsn in sensing layer.

B. Sensing Node Design

Sensor nodes are a key component of the Sensing layer. They are responsible for reading data from various sensing channels and sending it to the aggregator node. In Fig. 3 can be seen a block diagram of the components in a sensor node.

Each sensor node includes sensors for soil and air parameter measurements.

For measuring soil parameters the JXCT 7-in-1 Integrated Soil Sensor was selected, which can simultaneously measure N, P and K concentrations with a fairly reduced error rate (±2% of the full scale (FS) of values ranging from 1 to 1999 mg Kg^{-1}). Monitoring the concentration of these nutrients is important as they often limit plant development and consequently the productivity of the crop. In addition to these parameters, the sensor is also able to measure soil moisture content, temperature, pH, and electric conductivity (EC), factors that can influence the availability of these nutrients for plant intake, where EC is a great indicator of the salinity of the soil. The sensor also provides accurate values for these parameters, with: ±0.4% of FS for values ranging from -40ºC to +80ºC for temperature; ±2% of FS for values ranging from 0–20 mS cm^{-1} for EC; ±2% and ±3% for values ranging from 0–50% and 50–100% of moisture content respectively; and ±5% of FS for values ranging from 3-9 for pH. The sensor is factory calibrated, requiring no additional setup in the field.

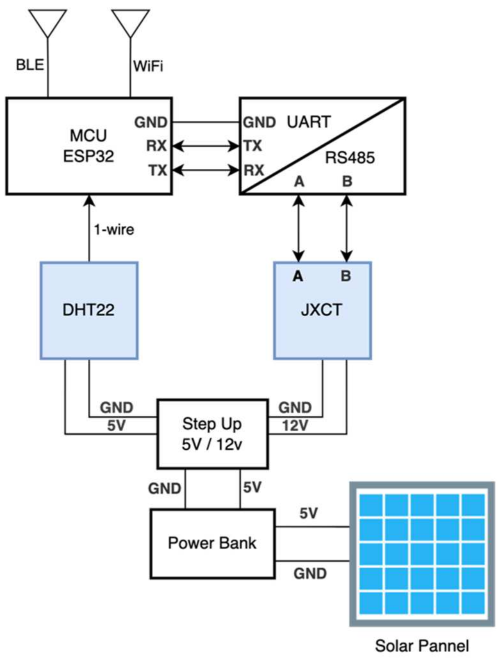

Fig. 3. Block diagram of components of sensor node.

High temperatures lead to increased evapotranspiration in plants, which, if not controlled, can affect metabolic processes in plants resulting in a reduction in plant nutrient intake [14]. Hence, it is important to take this parameter into consideration when scheduling fertilization. With an accuracy of ±0.5 ◦C for temperatures between -40 and +80 ◦C and ±2% for relative humidity, the DHT-22 sensor is a reliable component for detecting both ambient temperature and relative humidity.

The system is based on Heltec WiFi LoRa 32 (v3) board. The board was selected for its small size, low power requirements, as well as the support for various wireless communication protocols, including Bluetooth LE, Wifi and LoRa powered by an integrated SX1262 chip. Additionally, for the microcontroller to communicate with the soil sensor it was necessary to include an RS485 to UART converter based on MAX485 chip.

The components of the node are powered by an 5V, 10 Ah power bank, charged by a 27.5 cm × 19 cm, four cell solar panel which provides 13.2W input power. Additionally, due to the power supply requirements of 12V, an additional 5V to 12V step-up converter was included as part of the sensor node.

C. Acquisition software

A typical acquisition flow is illustrated in Fig. 4. After the microcontroller starts up, it initially verifies if there is any saved configuration, which must be given by the user during sensor installation through the mobile application. During this setup phase, the microcontroller receives the details (SSID and password) for the network in which it is included in, its own identifier, sensor types and IDs, and measurement intervals. Afterwards, the microcontroller establishes a connection to the Wi-Fi network using the provided login information and initiates the process of collecting data from the sensors that are connected to it. The node reads the sensors every 5 minutes. The data read from the sensors is converted to a JSON object containing the values measured, as well as the identifier provided in the configuration, the location of the node and the current timestamp. The data is then sent to the aggregator node in the network via MQTT protocol with the topic "measurements".

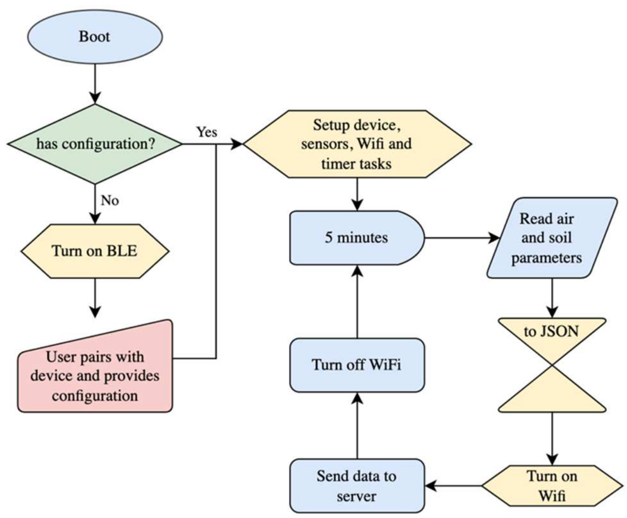

Fig. 4. Microcontroller embedded software flowchart.

D. Aggregator node

The aggregator node is the central connection point within the WSNs that makes up the Sensing layer. It acts as an MQTT broker, thus all communications in the network revolve around it. For the development of these nodes, the Raspberry Pi Zero v2 was considered because of it tiny form factor, low power consumption board with WiFi capabilities and enough processing capacity to run an MQTT broker behaviour. However, through experimentation, it was concluded that specifications of this microcontroller were insufficient. It was observed that under 10% of the memory remained available even with only one sensor node connected. This would limit the scalability of the system and would restrict the processing that could be performed on the aggregated data. As such the component was replaced with a Raspberry Pi 4 model B, which although has a larger form factor and requires more power, includes more memory (8 Gb) and more ports, allowing future extensions of the system.

Because Mosquitto is a lightweight, open-source broker implementation that works with Raspbian OS, it was used to implement the broker behaviour. Furthermore, aggregator nodes are also configured to have a static IP, for nodes to send data. A Node-RED flow also runs on the aggregator node side that subscribes to the "measurements" topic and combines their values before sending them to the data processing layer. If for some reason the node fails to send the data then it is stored in a local SQLite database. Once connection is established again the stored data is sent in batches of 6 rows. Last but not least, the aggregator node is powered by a solar panel equivalent to the sensor node's.

E. Data processing layer

The data processing layer includes two components: (a) a database for storing sensor data, (b) a data processing web application. In the following subsection these components are detailed.

1) Database

In order to avoid inconsistencies and redundancy in the data, as well as to enable more complex queries and data manipulation, a relational database was considered best suited for storing sensor measurements. As such, the data from the sensors is being stored in a Postgres database provided by Supabase. Supabase is an open-source Backend as a Service (BaaS), providing many features out of the box such as a database, authentication, file storage, support for real-time data synchronization (via Websockets) and edge functions (serverless web applications). Moreover, the platform also allows the integration of Postgres extensions, such as Postgis, an extension that adds GIS functions to the Postgres database. Lastly, Supabase also provides an easy to use API for accessing and modifying data, with client libraries for multiple languages, such as Python, Javascript and Kotlin. Hence, considering all the features as well as the scalability provided by the platform, Supabase was selected for storing and managing sensor data.

2) Data processing application

In order to monitor soil nutrients, it is necessary to analyze the data collected by the sensors. First, it is necessary to check if water, N, P, and K are available in concentrations adequate for plant development. The recommended concentration depends on the crop and its development stage. Furthermore, parameters such as soil pH and salinity (determined by EC) can limit the availability of nutrients for plant consumption, while soil moisture and temperature can limit plant nutrient uptake. To automate this process, a Web application was developed using the Flask, which is a Web framework written in Python. Flask is a simple yet flexible framework, with a wide array of extensions developed and maintained by its large community. Moreover, for being written in Python it benefits from an extensive set of libraries that simplify the implementation of data analysis and automation. Nevertheless, the web application also extracts additional metrics such as average and standard deviation for the values of each measured parameter. Also, the web application includes a REST API in order to provide measurement data and computed values to the mobile application.

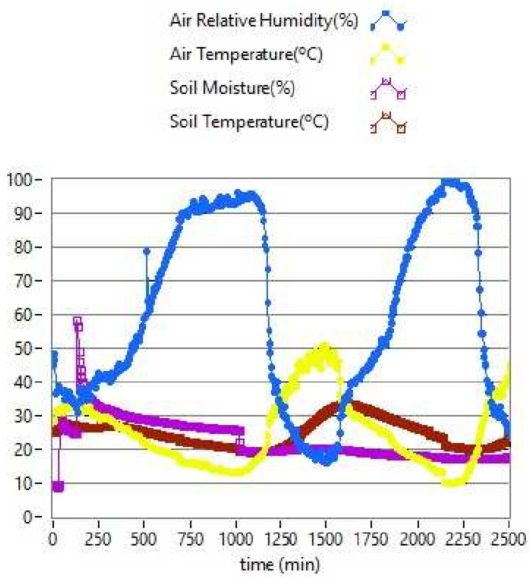

Fig. 5. Two day soil and air parameters variation. Air Relative Humidy and Soil Moisture in %, and air and soil temperature in ºC

An example of acquired data from a sensor node during two days is represented in Fig. 5. The data was collected in June with high daily temperatures, and the TDR sensor from the node was buried at a 5 cm depth. It can be observed a high increase in air humidity during nights. It is also observed that the soil temperature increased after an increase in air temperature. The TDR sensor was also previously buried at 20 cm depth however given the low variability that was observed due to the soil structure, the depth was reduced. The data on air temperature and humidity collected using in-situ sensors is perfectly matching with data from local weather station.

3) Dashboard

A web application was developed using Node-RED Dashboard 2.0 as the entry-point to the system. Its main features are the integrated analytics dashboard, and the "Virtual Farm", a Digital Twin of the farm. The app was developed using Node-RED for its ease of use being a low-code visual programming language, enabling fast prototyping and the development of complex flows in a fairly manageable way. In the following subsection is presented the "Virtual Vineyard" component of the application.

a) Virtual Vineyard

The "Virtual Vineyard" component of the web application is characterized by a Digital Twin of the vineyard including a digital model of the study field, with a skybox and directional light matching the sun position during the day. On the 3D model of the vineyard are also boxes marking the location of the sensor's nodes in the vineyard (Fig. 6). When it is detected that some of the measured parameters are deficient the sensor box turns yellow, and the user can get more details on the current values of each parameter by clicking the sensor node.

Fig. 6. 3D model of grapevine obtained with SfM technique

Structure-from-Motion (SfM) technique was applied to obtained 3D digital model of grapevines. To collect images the DJI mini 3 Pro drone was used. A flight pattern of three concentric circles around, at different distances from the target (3m, 10m and 30m) and heights (1m, 2.5m and 5m), was performed around a row of grapevines. By circling the target area at different diameters and heights it was possible to collect images on the area from different angles, allowing for more overlapping pictures, which may be used to generate high-density point cloud.

The Reality Capture software from Unreal was used for performing photogrammetry. Reality capture was selected for its comprehensive set of features such as picture alignment, point cloud extraction and editing, and mesh generation while being free for personal non-commercial use. Additionally, when compared with alternatives at the same price point, such as Meshroom and OpenDroneMap, it is easier to use and provides more features. Neural Radiance Fields (Nerfs) from Nerf Studio was used to obtain a 3D model of grapevine, but the resulting model was not considered satisfactory.

The Virtual Environment was developed using the Unity game engine. Unity provides an extensive set of features, with an easy-to-use interface, and great community. Additionally, when compared with its direct competitors, such as Unreal Engine and Godot, Unity provides better performance than Godot, and enables building for the web using WebGL. Since the Digital Shadow is to be included in a Node-RED dashboard, being able to export for the web is very important and Unreal Engine does not provide this option.

In order to include the developed virtual model in the dashboard, the scene was built for WebGL. As a result of this process, it is obtained code that can be used to display the scene on any modern browser, provided it is WebGL 2 capable, HTML5 compliant, and supports WebAssembly. Nevertheless, the code for the scene was deployed separately from the Dashboard. Moreover, a ui-template node from Node-RED dashboard 2.0 with an HTML iframe (inline frame) is being used to embed the scene in the dashboard.

IV. Conclusions

The paper presents a proof-of-concept for Digital Twin for vineyard farm. The DT data sources, IoT technology for monitoring soil moisture and nutrients, and the techniques for modeling the grapevine were described. The preliminary testing findings and the produced virtual model of a grapevine demonstrate the effectiveness of the developed technology in a small-scale setting. Future works will be focusing on synchronization of different acquired data with the virtual model of the vineyard, 3D modeling of a large vineyard, automation of irrigation and development of Variable Rate Technologies embedded in Digital Twin for vineyard.

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