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Concept study of a Digital Twin of a Precision Agricultural Robot

By

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Abstract

When designing a digital twin, different properties are needed to be implemented so that the physical twin can be able to interact with the environment and fulfil the tasks that the physical asset was developed for. The methodology proposed in this thesis is of highly relevance when designing a digital twin solution, being simple to adapt to different necessities and with a clear architecture to utilize or to adjust to digital assets in different applications.

The digital twin developed in the case study, on which this thesis is based, is the foundation of the development and creation of an innovative table grape harvesting robot.

The main objective of this research is to review and identify potential methodologies that can be used in the design stage of a digital twin and to validate how the processes in the methodologies can support the system to fulfill the objectives of the project. The system involves the interactions between the robot, the environment, and the agronomical tasks that the robot needs to perform.

This thesis creates the methodologies that will assist different stakeholders in easily identifying the processes that streamline the testing procedure of different algorithms in the digital twin, saving time and resources by doing the development in the digital twin and not in the physical object.

The thesis assessed the challenges of limited testing time and transporting equipment and personnel difficulties to a fixed location, in this case, a vineyard located in Italy, defined later as the physical asset. It is of highly importance to incorporate the research structure to the digital twin development team early in the project's timeline. Based on the literature and discussion between stakeholders, the basic architecture was created, and from there, the cases defined in this thesis will allow the users and clients to test in a seamless way their products in the digital twin. The process gave the option to the users to select and use from a basic environment to a more complex and challenging one.

The purpose of the thesis was to present and document certain architecture and methodologies used in the research and present them as a base for future developments in the area. This method can be used for projects when physical assets need to be created and tested, when time periods

for testing are part of the challenges of the project, and the availability to allocate and integrate resources is complex.

The main results and conclusion of this thesis is the methodology proposed, on how a simple processes and methodologies can be easily adapted to the necessities of any digital twin solution, and how the architecture proposed can have the ability to modify different cases for specific objectives. And finally, how it is possible to use, prepper and export the information needed to train the Machine learning (ML) algorithms, and to add noise specific to allow the evolution of the algorithms.

The methodology proposed in this thesis can increase the quality and usability of any digital twin by proving how it can be successfully implemented during the planning developing process of a project. Furthermore, the methodology demonstrate that it can be easily adapted to the necessities of any digital twin solution and streamlined the progress in the future use of digital twins in any area.

In the case study, the methodology helped all different stakeholders to utilize the digital twin to develop, test, and improve different algorithms from different locations through Europe without the need to build the physical robot, or being in one particular place, and without the restrictions of seasonal harvesting periods.

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Juan Carlos Correa
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List of abbreviations

3D	Three Dimensions
DNV	Det Norske Veritas
FE	Functional elements
IMU	Inertial Measurement Unit
Lidar	Light Detection and Ranging
MAE	Mean Absolute Error
MB	Mobile Base
NASA	National Aeronautics and Space Administration
PLM	Product Lifecycle Management
RGB - D	Red, Green and Blue, Depth
ROS	Robot Operating System
RTK-GNSS	Real-Time Kinematic - Satellite Based Augmentation Systems
TCP	Transmission Control Protocol
UAV	Unmanned Aerial Vehicles
UN	the United Nations
URDF	Unified Robotics Description Format
USD	United States Dollar
WiFi	Wireless Fidelity
XML	Extensible Markup Language

1. Introduction

Different entities in varied fields are facing common challenges, all related on how to increase the research and explore the commerciality options for using robots in tedious, but at the same time complex tasks, aiming to achieve the goals and needs of the industry while keeping control on costs associated to research and development.

Digital twin is a common topic used or referred in different areas of the technology since 1960's and adapted to the new digital and information technologies since the 2002. The modern concept of digital twin as a term was introduced by Dr. Michael Grieves from University of Michigan while presenting the idea of a formation of a Product Lifecycle Management (PLM) center. The concept Dr. Grieves presented, was basically that the information in the physical system can have a "twin" digital information, and this twin can interact with the physical system in the entire lifecycle of the system (Grieves, 2016).

The concept in principle, as mentioned before, was used since the 1960's by NASA to simulate the environment and conditions of the apollo flights. The concept was used successfully in the Apollo 13 mission, where NASA used digital information in a physical twin to simulate, diagnose and provide solutions to a remote physical asset (Simcenter, 2020).

More specifically, in the robotics area, software simulation is usually presented as a digital twin and is a tool commonly used to mimic physics of movement in a physical equipment or to test different equipment in the robot or for testing its stability and compliance. Commercially, it is limited to robot design and/or to control joints and velocity of movement of the robot. The most common commercial simulators are Gazebo (OSRF, 2019), Webots (Cyberbotics.com, 2021), CoppeliaSim (Coppeliarobotics.com, 2022), and Marilou Robotics Studio (Anykode.com, 2019).

The Digital Twin area can be part of the solution, methodologies, and process to structure the use of a digital twin in a collaborative environment are going to be an essential part of this research work.

1.1. Topic Relevance

The case study presented in this work, is developed in the field of precision agriculture. Precision agriculture is a topic concerned on managing and controlling different stages of farming. Its approach is based on the use of technology and information technology to improve and optimize processes. Concepts of the precision agriculture are closely related to the UN sustainable development goals. The objectives of the precision agriculture are closely tied to concepts like: “fight against poverty and hunger (goals 1 and 2) by feeding the increasing world population without expanding the amount of land allocated to farming” (goal 15), and “improve the labor conditions to farmer workers by using technology to avoid human-unfriendly operating conditions” (goal 3 and 8) (Un.org, 2022).

Specifically, in the field of precision agriculture, the use of digital information is widely used to support management decisions, as well to assist the use of technologies in field operations. More precisely, the research on how to use robots is a topic where different organizations are working on with more research on some type of crops and specific agronomic tasks that are more easily adapted to the limitations of the present-day robots than others. Tasks like fruit cleaning or transportation, soil preparation, crops irrigation are somehow complex and tedious processes that can and are being replaced by machines (robots), but more specialized tasks, like harvesting or pruning, are still in research stage with very few in the commercial phase restricted to very specific type of crops like strawberries or tomatoes.

The case study used in this thesis is focused in a highly specialized agricultural task, harvesting, in a particular complex crop to be handled such as the table grape. Very few research has been allocated in this area, with no literature on how a digital twin can be used on the design of a robot for fulfilling the task.

A brief introduction to the table grape business and some basic information about it is presented next.

The global table grape market is around 28 million tons of fruits harvested yearly (Seccia, Fabio Gaetano Santeramo and Nardone, 2015), with nearly one million tons produced in Italy (Tradingeconomics.com, 2022). The total market size in 2018 was of US$50.636 billion with a forecast of US$86.115 billion in 2024 (Knowledge Sourcing Intelligence LLP, 2019).

The table grape marked is facing different challenges, related to climate change and workforce reduction . Loss of production affected the global production due to lack of workers, mainly for the seasonal nature of the work and the migration of workforce to more stable productive sectors exacerbated by restriction on migration during the pandemic in 2020 and 2021. Finally, changes on rain and temperature patterns altering the harvesting period during seasons added difficulties to maintain a labor force available.

Additionally, the process of harvesting is a complex and tedious processes, due to the specific requirements for picking and handling the grape, converting the harvesting in a very delicate process to avoid bruises on the grapes which can reduce the quality of the product and therefore its price.

For harvesting, the grapes need to reach a level of maturity that can be measured by the color of the grape and the sugar contained on the grape. Portable refractometers and grape color and size tables are used for this purposed. The farmer needs to be trained on how to utilize the tools to correlate the size and color of the grape.

Extreme weather conditions during the summer months, when the harvesting is carried out, make the working conditions difficult. Due to this, in some parts of Italy, harvesting is not allowed from 12:30 pm to 4 pm, reducing the production and extending the harvesting season period one third of the time.

These challenges can be overcome by the use of technology. Robots, in theory, can work longer hours and can have minimal assistance from farmers, reducing the exposure to unfriendly conditions to workers. Sensors for sugar and color detection are not based in human subjectivity but to fixed mathematical rules. Additionally, it can help to mitigate the labor shortages, reducing the need for seasonal workers and increasing the needs for permanent and qualified labor (Battistella and Quaranta, 2010).

1.2. Research needs and gaps

The main objective of this work is to propose a set of processes and methodologies for a digital twin common development platform, is to be used to promote and facilitate the interaction of different stakeholders while digitally developing the robot and its components. Addressing this topic is of utmost importance for the continuous research and development in the digital twin area, with continuous improvement on the technology necessary to create complex digital twins and to deploy them in areas where physical assets are difficult or expensive to prototype, for example, the possibilities for testing assets in distant environments, not just a vineyard in Italy for example, but in remote plain on Mars, or assets in industries subjected to extreme conditions where different type of materials, or shapes are designed and tested before an advance prototype is efficiently build.

The area of the digital twin is in constant evolution, with different processes and methodologies being on test continuously. Therefore, a framework that allows research and commercial enterprises to collaborate remotely and under a set of best practices and guidelines that can be used to simplify the coding time, algorithms development, and documentation, is of high relevance. This kind of methodology is of great benefit to any enterprise by reducing the risk of compatibility issues, the validation of different algorithms, and the speed-up of the integration process.

Recommended practices are being produced and shared to the community, while some others are in deployment, but as the digital twin being a new area, several topics are still far from being standardized. For example, the latest recommended practice from DNV related to digital twin is the DNV-RP-A204 named "Qualification and Assurance of Digital Twins" published in October 2020 and amended in September 2021, but it is just one of many themes that can be standardized.

The case study this work is based is a project that involve different stakeholders from the research community and commercial enterprises. All the actors are in different locations through Europe and are specialized in different activities and tasks that the robot will need to perform. The physical robot itself does not exist and is not possible to test the algorithms in the physical environment, a table grape vineyard in the Lazio region in Italy, outside the harvesting season (July - August).

For this reason, a virtual common platform is to be used to test the different algorithms . This will allow multiple actors to collaborate at the same time during all year with not restriction of agricultural seasons. This will also have an impact on reducing travelling costs, speed up the validation of the mechanisms and it will reduce the physical prototypes that need to be constructed.

1.3. Research Objectives

The purpose of the thesis is to define the methodologies and processes to be used in the creation of a digital twin for a precision agricultural robot. The system involves the interactions between the robot, the environment, and the tasks that the robot needs to perform to fulfil the objectives of the large project. The concept study will focus on the process necessary to validate the robot interaction in a simulated space before the testing of the robot in the field.

This work objective is to collect and present the processes and methodologies that will allow the project integration to be successful, describe the steps for testing the algorithms in the virtual environment, the list of requirements on how the robot should perform and the successful methodologies used to share the digital information and the shortcomings when multiple interactions of processes and rules are being validated at the same time. Finally, this study will help to amplify the knowledge around the topic and will add more information for a future standardization effort in this subject.

1.4. Methodology

The methodology used for this work was outlined based on how much information and standard procedures are already available in the literature, and the gaps on them.

For the first part, an extensive search of articles on different science databases was carried out, investigating how much research was done in the digital twins in diverse areas of the precision agriculture. The second part of the research was to review the project reports created by different stakeholders in the case study, understanding the proposed tasks to advance in the project of creating a harvesting robot and how they are going to use the digital twin for that purpose.

The third part of the project is to review and understand the latest recommended practices related to digital twins, understanding the gaps and what can be proposed to the stakeholders.

The fourth stage is a survey to understand the stakeholder's approach, and which are the areas with common process between them and what are the topics that have not been considered and are possible areas of improvement in the implementation.

Also, it was evaluated how the stakeholders understand the basic setup of the common virtual environment, the advantages and limitations while using the digital twin and which processes can realistically be implemented. Based on the evaluation, the definition of the digital twin process was created.

Lastly, a final review on how this case study and the proposed design can increase the quality and usability of the digital twin and how successful the implementation of the planned process in the stakeholder's project development can be.

A discussion is presented at the end of the thesis on how this work can be expanded with a future work and a broad recommended practice for any collaborative initiative envisioned to use a digital twin.

1.5. Scope of the thesis

The scope of the thesis is to propose a methodology on how different stakeholders can interact with a digital twin, and to suggest a set of standard procedures and processes to more efficiently achieve the goals based on the methodologies used by the stakeholders.

The intention of standardize the procedures is to offer a clear path for a successful integration of the involved parties.

1.6. Project plan

The project plan is described below in Figure 1.

	Month																				
	FEB				MAR					APR				May					June		
Week #	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
TASK																					
Problem understanding and description																					
Literature review																					
Framework development																					
Data collection																					
Data analysis																					
Revise the framework and Case study description																					
Solutions generation																					
Data collection and analysis, Part 1																					
Data collection and analysis, Part 2																					
Data collection and analysis, Part 3																					
Verify the proposed solution																					
Writing the data and analysis chapter																					
Demonstrate the proposed solution																					
Discuss the proposed solution and the whole case study																					
Draw up the conclusions and further work																					
Deadline for first submission																					
Thesis revision, Technical and academic checks																					
Final submission to university																					

Figure 1. Thesis Project Plan

While collecting and working on the thesis research, different tasks with their deadlines were proposed as part of the plan. During the first month of the thesis work, the main task was to understand the problem and to search for the available information related to it. Based on the findings, a framework of the type of development was created. During the second month the task was to collect the information available and make an analysis of the findings and the process used in the project. During the third month it was carried out a verification of the solution proposed from the analysis done before, and the analysis chapter was written. During the final month, the proposed solutions was demonstrated and discussed, the document was completed and was ready for review by the supervisor. After the final review, the thesis document was ready for final submission.

1.7. Thesis structure

This work is structured in the following way. The chapter 1 is a contextual review of the concept of agricultural precision and the use of technology in it. The review is extended on how robots had been incorporated into the area and how the use of a digital twin can assist efficiently the process. The literature review provided a framework to understand the gaps in research in the subject and to understand how the findings from this case study can be used in future works, not just in the precision agricultural area, but in any area that uses a digital twin.

The second chapter is a review of the theoretical background, specifically a review of the theories about the general topics of these study, like precision farming, digital twin and robots in agricultural tasks. A review of the literature on theories on the methods used in the study and the methods used by different stakeholders of the case study to utilize the digital twin to fulfill their milestones was also carried out.

Chapter 3 is a review of the research methodology and design of the case study. The research objective is defined, and the approach and methodology are presented. The data sources and data formats are summarized, showing how the information will be used. The last part of the chapter covers the interpretation of the method and its limitations.

Chapter 4 collects the knowledge from the different stakeholders that participate in the case study by the use of a survey, analyzing the methodologies used to interact with the digital twin and identifying the areas that are well understood by the stakeholders and the level of confidence and the areas where gaps in the research exist and or are approached differently between stakeholders. Basic information about the robot and the environment was collected in this chapter, as well as a system analysis of the robot and the environment, an analysis on the scenarios proposed in the case study and the requirements and benchmarking of different tasks to be developed in the digital twin was also covered, analyzed, reviewed and discussed.

Chapter 5 summarizes a discussion on how the stakeholders interact with in the common virtual environment and the advantage and limitations of it. Follow by a review on how this case study and the proposed design can increase the quality and usability of the digital twin. This chapter also mention the recommended practice while using a digital twin and a discussion on future work.

Finally, chapter 6 collect the conclusions on how the method can be used in this kind of projects and why it can be an alternative to different methods used in the industry.

2. Theoretical background

In this chapter the reader can find a literature review of the different theories and the theoretical background of the different topics related to the case study, as well to the theories of the methods used. The main headings and topics mentioned in this chapter are summarized below.

- Theories and background for precision farming.
- Theories and background for digital twin.
- Theories and background of Robots in Precision farming.
- Theories about the used methods.

2.1. Theories and background for precision farming

Precision agriculture is a topic dedicated to improving the efficiency and the amount of agricultural production harvested per unit of land area. The main goal is to assist during the different managing decision stages of farming, with the assistance of information, data and technology gathered with agronomic sensors and other high technology tools.

As mentioned before, the concepts of the precision agriculture are closely related to the UN sustainable development goals. The use of technology in the farm management helps to control and reduce the use of water and minimize the use of pesticides (UNDP, 2021), as well, is a mechanism that can be used to increase the production of crops without expanding the amount of land allocated to farming, helping to fight against poverty and hunger. The implementation of different technologies allows the farmers and different workers to avoid unfriendly conditions, by predicting extreme weather events, managing the workforce to avoid overexposing to unhealthy work conditions or, in the case of the unmanned vehicles, to assist and alleviate the working conditions present in the field.

The use of technology in precision agriculture is a difficult topic, and it needs the collaboration between the farmers and researchers. The evaluation of the benefits should overcome the costs associated to the new technology added to the farming system and to the modification of the process. Each particular field and crop may need an assessment of which technology can be adapted better to the location, necessities and farming practices.

Different examples of precision agriculture like tractors adapted to sampling and analyzing the soil, will give valuable inside on the characteristics of the soil in the field, how is affected by different amounts of fertilizers and water used and its evolutions through time. Drones that fly over the fields searching for unhealthy plants, irrigation systems controlled automatically using data from weather forecast and soil measurements, can maximize the crop's yields and reduce water consumption. Automated vehicles can assist farmers in different type of crops to carry out the products of the harvest, or to help to harvest the fields itself.

2.2. Theories and background for digital twin

The origin of the digital twin concept can be traced to Dr. Michael Grieves from University of Michigan while presenting the idea of a formation of a Product Lifecycle Management (PLM) center (Grieves, 2016). The concept showed that the digital information would be an exact replica "twin" of the information contained in the physical asset or system, and that both, digital information and physical asset or system can be connected during the lifecycle of the asset or system.

Digital twins are used for monitoring, diagnostic and prediction of certain tasks to improve the asset operation and utilization and with the improvement of different technologies, this concept had been adapted to different industries and different applications.

Most common is the creation of digital 3D models of the physical assets, where different properties can be tested, from how the physical asset looks to different operating states of the physical asset. This digital twin can use different sensors, digital or physical allowing the developers and constructors to test the asset in real time and with different sensorial inputs. Different types of algorithms are added to the simulation and are feed with the digital information coming from the digital or physical sensors, allowing the digital twin to interact with it. This type of process is highly used in the urban planning and in the construction industry.

In the robotic area, the digital twin had been oriented on the software simulation of the robot or asset. Frequently, its use had been oriented as a representation of the physics and movements of the parts of the robot. Different commercial entities provide software or products for the simulation but are lacking the interaction with digital or physical sensors. The most common commercial simulators are Gazebo (OSRF, 2019), Webots (Cyberbotics.com, 2021), CoppeliaSim (Coppeliarobotics.com, 2022), and Marilou Robotics Studio (Anykode.com, 2019).

2.3. Theories and background of Robots in Precision farming

The global agricultural robots market size is composed by different type of equipment, from milking robots, UAVs (Unmanned Aerial Vehicles), drones, harvesting systems and driverless tractors between others. The estimated market of robots in precision farming in 2021 was of USD 4.9 billion, with an expectation of grow to USD 11.9 billion by 2026 (Marketsandmarkets.com, 2021).

As part of the precision farming, the labor shortage and labor cost are the main drivers of the development. The agricultural robots are created to assist the farmers with a wide range of operations with the goal of improving the quality and efficiency of agricultural tasks while increasing the overall productivity.

It is fair to mention that the global agricultural robots' market is not yet a consolidated market and multiple type of crops and environments allow different organizations to research for more beneficial tasks. The dominated players are specialized in different type of robots and areas of expertise, for example Deere & Company (Deere, 2022) specialized in improve tractors with an automated vehicle guidance system; AGCO Corporation (Precision Planting, 2022) developed vehicles with extensions tools to measure different properties in the soil to decide the seed delivery in a process called precision planting; Agribotix LLC (AgEagle Aerial Systems Inc., 2021) utilize drones to capture the farm's crop health; Agrobot (Agrobot: Agricultural Robots, 2015) create robots that can control insects or harvest specific type of crops (e.g. strawberries) and Blue River Technology (Bluerivertechnology.com, 2022) specialized on a robot arm that can spry chemicals where are needed based on inputs from the farmers and sensors in the robot arm.

In the area of table grape, part of this case study, different organizations are researching on solutions for complex tasks like harvesting and few commercial or precommercial products are available to work as assistance in the harvesting process.

In particular, in the case of harvesting assistance, few companies are working on autonomous and semi-autonomous vehicles, for example Vinergy (Vinergy, 2022) presented a semi-autonomous cart that can carry out the grapes harvested manually by the farmer, the same product was presented by Burro.ai (Burro.ai, 2022), an autonomous farming tech company using an small robotic farm vehicles that utilize sensor fusion, mapping, and machine learning methods to carry the handpicked grape to the storage place.

But in the harvesting area only research and no commercial products are present in the market and literature. For example, the "Istituto Italiano di Tecnologia Advanced Robotics" (Advanced Robotics, 2018) is researching on how to create a robot that using technology can achieve the harvesting in a satisfactory way, at this moment the prototype is a fixed arm with sensors tested in the laboratory but with no experience in the field.

Finally, the very specific topic of a digital twin utilized for the task of harvesting in the table grape area, very few research exist, unfortunately with limited or no literature in common databases focusing on how a digital twin can be used on the design of a robot for fulfilling the harvesting task.

2.4. Theories about the used methods

The theory on the methodology used when describing the research question of how to create a concept study of a digital twin, is based on a general concept, that is divided in two main parts, (1) the digital model creation and (2) the digital twin enabling (Aivaliotis et al., 2019).

In order to create the digital twin, it is necessary to develop and deploy three parts; the physical object in real space, the virtual object in virtual space, and the flows of data and information that ties the virtual and real products together. When this is done, and the three parts are ready, a digital model is created, then the digital twin can be used to validate the systems to be used.

In this case study, there is a fundamental change on the methodology, because the physical real object does not exist, and is going to be created, designed, and modified at the same time as the digital twin tests validate the systems that will be used in the physical real object.

How the stakeholders are testing the different algorithms in the digital twin is a Model-Based Systems Engineering case, where the real object will be designed, tested, and improved throughout their lifecycle (BAE Systems | International, 2021). The exact methodology is based on a testing loop between an ideal scenario and a non-ideal scenario where complexity is added to the digital twin in form of noise, based on the requirements from the stakeholders. Once the algorithm is tested and validated under a particular threshold, the developed algorithm may be used in the real physical object for a testing.

3. Research methodology and design

The research objective is to review and identify the process necessary to validate the system in a digital twin. The system involves the interactions between the robot and the environment and the tasks that the robot needs to perform to fulfil the objectives of the large project.

In principle, the philosophy of this case study is to assist different stakeholders to easily identify the methodology that streamline the process of testing different algorithms in the digital twin, without the need to spend time and resources in doing the development in a physical object.

The final approach utilized in this case scenario will be explained in detail in the chapter 4 "Data collection and Analysis", but a simple description can be found next. The digital twin needs to be created following the input data of a case farm and information about the robot. Different versions of the digital twin will be created based on the basic information shared by the stakeholders and followed requests of more complex environments after the stakeholders interact with it. Different scenarios will be created and utilized by stakeholders and final users, to test different algorithms and to test the feasibility of reaching the goals for agricultural tasks. After the test is completed in the digital twin and the integration is tested in different scenarios, an analysis loop between the physical object and the digital twin will be needed to optimize and confirm the efficiency of the system.

The methodology used was to divide the different scenarios in multiple work packages. The first step was to proceed to collect the basic information of the test vineyard and the information about the robot, both the mobile base and the upper part. Based in this information, the scenario where the digital twin will be placed was created.

The whole digital environment was created in a 3D simulation and an architecture using a Unity 3D engine (Unity Technologies, 2022). A bridge between users to the simulation was created using a ROS interface (Ros.org, 2022c) allowing different clients and spectators to interact in the simulation.

The interaction is both ways, from the clients using the algorithms inside the simulation, but as well from the simulation to the client, where the simulation generating synthetic data to train the machine learning developed by the clients. The synthetic data is a homogeneous and perfect data generated by the sensors attached to the robot, or the exact configuration of any object build in the simulation, like structures position and coordinates, grapes colors, sizes, and distance from the robot end defectors between others.

In order to integrate the different clients and stakeholders, the system allows a dynamic interaction among actors and objects. These interactions will be synchronized to all other clients such that they will be able to see and respond to the results of these interactions. The simulation supports dynamic interaction between different clients across the network, like a human client manipulating the arms of a robotic client, or a robot client receiving different tasks from outside the simulation, or a human avatar client communicating with gestures or voice commands with a robot client.

Different data from different sources and formats were needed when building the digital twin and when creating the process and protocols to validate the system. Data from the physical vineyard including pictures with measurements for easy sharing the dimensions of the vineyard, different videos to create a look alike representation of the physical vineyard, pictures of the grapes with different colors, color code tables for grapes labeling the optimal color for harvesting, several density tables with looseness and compactness samples for harvesting. The measurements and the dimensions of both, mobile base and upper part of the robot, were provided in URDF (Unified Robotics Description Format) files by the stakeholders responsible of them. Additional XML macros were provided in case some information may be lost when importing the URDF files or if there is necessity to edit the file when adding different equipment to the robot.

For testing or calibration of the models, a set of ROS bag files from physical sensors (lidar, depth cameras, etc.) is shared and used in the simulation. A bag is a file format in ROS for storing ROS message data (Ros.org, 2022).

The sensor equipment (Lidar, IMU, depth camera, RGB camera) brands and models were determined, and their output data specifications were obtained from their specific manufacturer. This step was necessary to compare the specifications of the synthetic data and modify it if necessary to match the original output description from the equipment manufacturer.

A summary of the different data sources can be found below in the Table 1.

Data Source	Object	Data Format2	Quantitative	Qualitative	Original	Modified
Digital Vineyard	Structure dimmension	picture	✓		✓	
	Vinyard view	video		✓	✓	
	Grape color	Excel table	✓		✓	
	Grape color	picture		✓	✓	
	Bush density	Excel table	✓		✓	
Robot	Mobile base	URDF	✓		✓	
	Mobile base movement	video		✓	✓	
	Upper part	URDF	✓		✓	
	Upper part	XML macro	✓			✓
Equipment	Sensors	ROS bags	✓		✓	✓

Table 1 Data sources summary

The project was divided in different work packages, the first package was to develop the robot platform for integration and testing. In this package the basic architecture was designed and created and the methodology for testing and integration was defined.

The second work package focus on implementing the simulated farming environment and the basic robotic components supported from the information shared by the stakeholders.

The third work package objective was to develop in the simulation the agronomic oriented perception components necessary for the navigation and for the agricultural tasks.

The fourth and last work package was to finalize the components for the digital robot, and the interaction between the multi-human clients, multiple robot clients and spectators.

The case study was carried on by using an Agile methodology with two-week sprints. After the initial milestone was concluded, multiple interactions with the stakeholders were necessary to increase the capabilities of the digital twin.

However, there are certain limitations on how the case study was created. In order to achieve the level of complexity to simulate the real environment, multiple interactions between the stakeholders and the digital twin developers needed to be planned after the work package was delivered.

Verification of the algorithms in the physical robot tested successfully in the digital twin, but it was just possible to test only in the mobile base of the robot. The upper part and the agronomical tasks were not tested due to the lack of the physical upper part of the robot.

The case study of the digital twin is just a part of a macro project with the objective to harvesting table grape. Scaling the digital twin will need the cooperation of the different stakeholders to adapt their own methodologies to the inclusion and use of a digital twin in future assets developments.

4. Data collection and Analysis

In this chapter, the systems analysis of the robot and the case farm, the designed digital twin, the operating scenarios, and the stakeholders' requirements will be provided and discussed. Additionally, the data collected necessary to simulate the robot, the equipment and the environment is presented.

In order to answer the research question "how to create a concept study of a digital twin for a precision agricultural robot focusing on the process necessary to validate the robot interaction in a simulated space before testing in the field.", the following analysis methodology and steps (described in chapter 3) are performed:

1. Systems analysis of the robot
2. Systems analysis of case farm
3. Systems analysis of the designed digital twin
4. Use case scenarios analysis
5. Stakeholders' requirement analysis
6. Testing algorithms analysis

4.1. Systems analysis of the robot

The robot to be used in the project can be described by the sum of different elements. The robot main components are the Mobile Base (MB), the navigation equipment, the dual arm robot and the Sensorial equipment for agronomic perception. Below is a detailed description of the physical elements of the robots and its capabilities.

4.1.1. Mobile Base (MB)

The mobile base (MB) is a crawler carrier vehicle platform that is used to support the equipment required for the agronomic activities. The MB to be used in the project is the commercial equipment Alitrak DCT-350P as presented in Figure 2. This mobile base was selected due to its stability and capability for carrying weigh, and the platform space. The URDF and the XML macros were provided in order to import the mobile base into the simulation.

The MB can stand dust and water and is able to be used in irregular terrain without losing stability. Other functionality of the MB is the option for customization using the multiple mounting points in its chassis, making it possible to integrate the different equipment to be used in the robot.

Figure 2 Alitrak DCT-350P Mobile Base Robot

4.1.2. Navigation Equipment

The equipment needed for the robot navigation consists in a set of sensors. The sensors were selected due to it robustness and the option to work together.

The robot uses a localization system RTK-GNSS that reports a georeferenced location of the robot position with great accuracy. The robot integrated the Septentrio AsterRx-m3 Pro+ (Septentrio.com, 2022) in a vehicle configuration and the Septentrio AsteRx-U (Septentrio.com, 2022) in a base station configuration. The high accuracy provided by the sensors, 0.6 cm horizontal and 1 cm vertical, is better than the project requirement of 1.5 cm for both vertical and horizontal. The specifications of the output data were obtained from the manufacturer and ROS bags with sample data was reviewed and compared with the synthetic data generated by the simulation.

As part of the navigation and localization (equipment/module), the robot uses an IMU sensor. The sensor provides the information about the platform's inertial state, orientation, and tracking potential changes of its 3D orientation. The IMU is placed in the center of rotation of the MB to provide the most accurate information about the inertial status of the robot.

LIDAR sensors are installed in order to sense a three-dimensional representation of the environment around the robot as presented in Figure 4. The sensor capabilities are based on the long range and peripheral detection of obstacles while allowing the creation of maps of the environment and defining fixed anchor points for the detection of state changes in the movement of the robot. The LIDAR sensors are placed in a diagonal configuration where they achieve a full 360-degree coverage. This configuration, as presented in Figure 3 allows each sensor to cover 275 degrees despite the occlusions from other sensors and equipment, and the dual arm robot on the base.

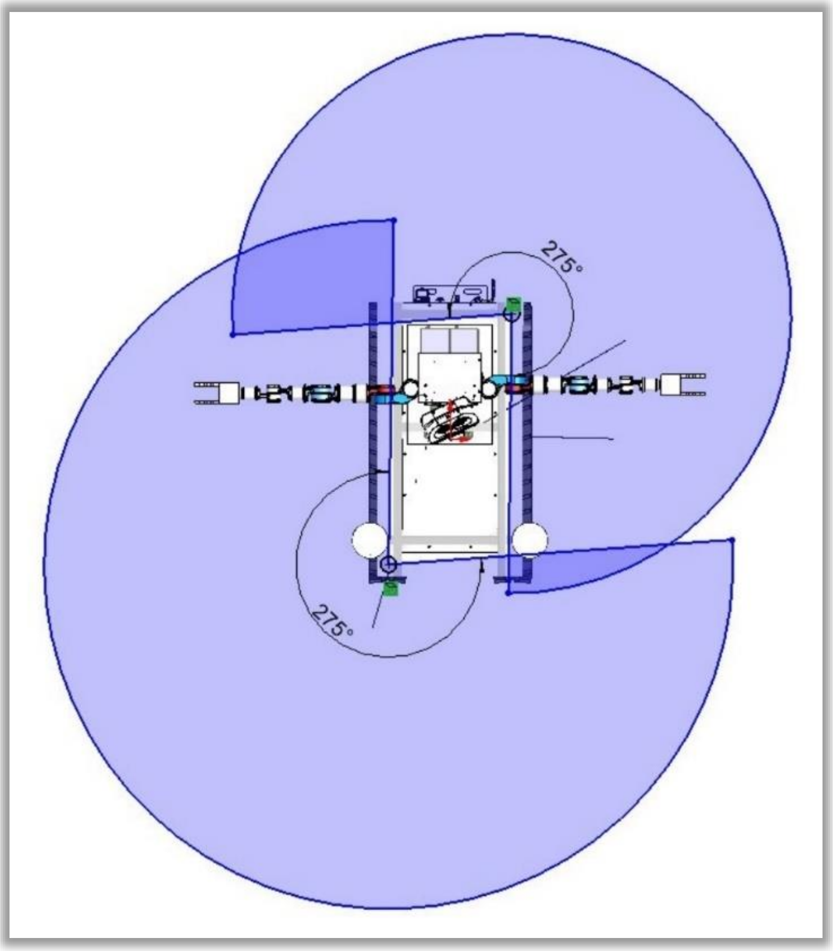


Figure 3 LIDAR sensors placement

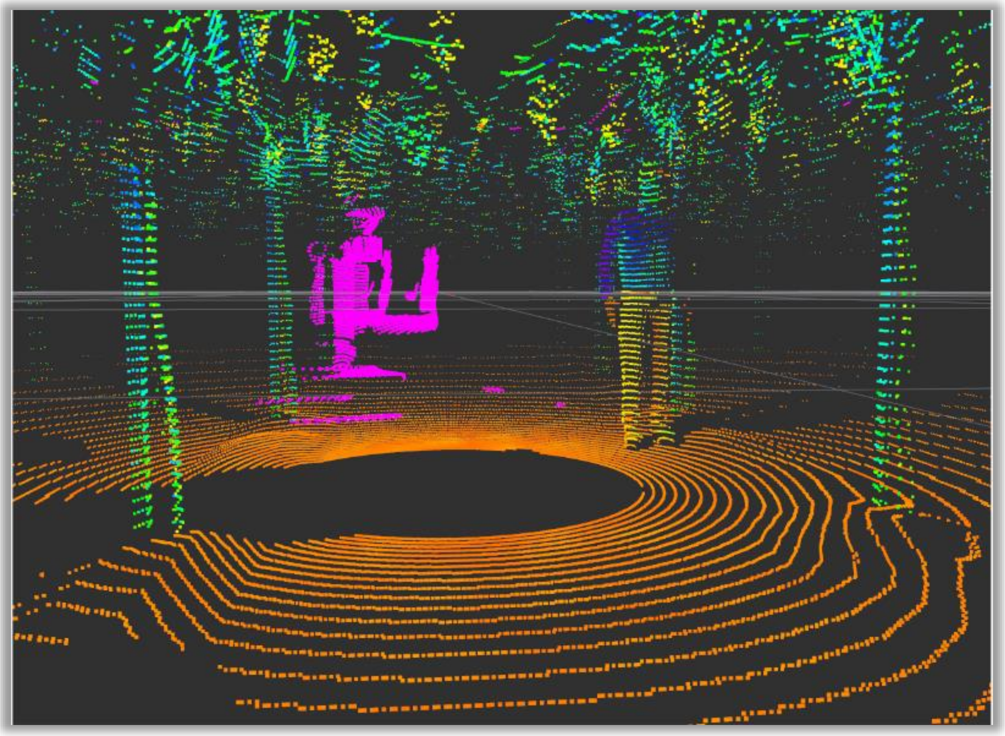


Figure 4 LIDAR three-dimensional representation

For the sensors (LIDAR, RTK-GNSS), other systems (dual-arm) as well as communication between robots the main source of communication will be a local network with also WiFi connectivity.

4.1.3. Dual-arm system with actuated torso

The dual arm robot will be adapted from the TIAGo++ commercial robot created by the company PAL Robotics (Viladomat, 2019) as presented in Figure 5. The different specifications and customization for the dual arm robot will provide the capabilities needed for the agricultural task of harvesting. An URDF with the information about the robot was shared by the manufacturer including the modifications done to fulfil the requirements of the project. An XML macro file was provided in order to modify the URDF when adding additional equipment and sensors to the simulation.

The dual-arm robot will have a minimum rotation range of 300°, the arms payload will be of 3 kg (without end-effector cutting tool), and it can be totally extended parallel to the ground. The maximum reach of the arms is of 90 cm and for safety regulations, there are brakes in the first 6 joints of the arms.

The agronomically adapted dual arm design will be accompanied by custom gripper designs (end effectors) that will allow the execution of the harvesting and pruning tasks.

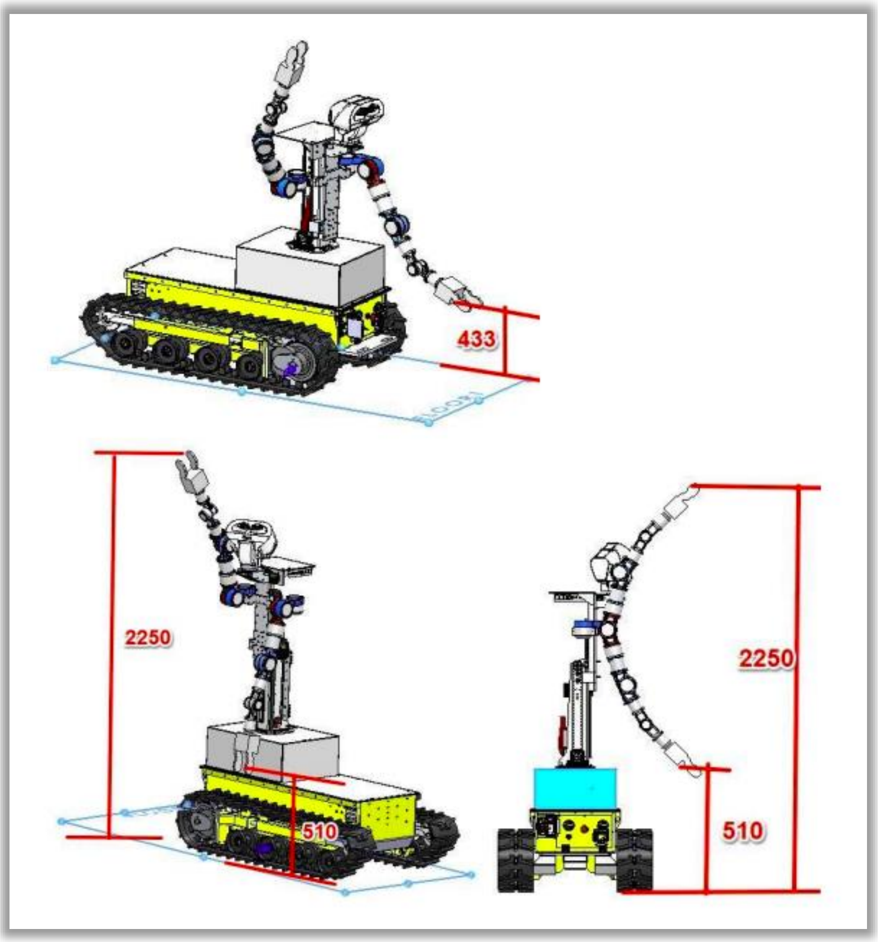


Figure 5 TIAGo++ robot and reach of the arms measurements

4.1.4. Sensorial equipment for agronomic perception

Different sensors can be adapted to the robot to sense the environment and to detect and locate the objects of interest. The specifications of the output data were obtained from the manufacturer and ROS bags with sample data was reviewed and compared with the synthetic data generated by the simulation.

RGB-D sensors will create RGB images and 3D point clouds as part of the vision-based system. This data will be used as input for training the developed agronomic perception algorithms. The equipment to be use is a Realsense D435i (Figure 6) (Intel® RealSenseTM Depth and Tracking Cameras, 2021).

Figure 6 Intel® RealSense D435i Depth and Tracking camera

Cameras and RGB-D sensors will be placed on the head of the dual arm manipulator to be able to observe a good portion of the grape clusters at a horizontal level. Additionally, two cameras will be placed on the robot arm, wrists, near to the end-effector.

4.2. Systems analysis of case farm and Environment description

The site identified to experimentally validate the capabilities of the integrated system developed is a vineyard of approximately size of 114 m x 51 m (0,58 ha). The vines are mature and in full production and health, representing a typical working condition for the validation of the agronomic activities like fruit harvesting.

The table grapefruit develops as clusters (bunches) with each berry attached to the bunch stem (rachis and branches) via a pedicel, which contains vascular bundles (also known as the cap stem) as presented in Figure 7. The grapes are no climacteric fruit and do not continue to ripen after collection, so harvesting timing is critical.

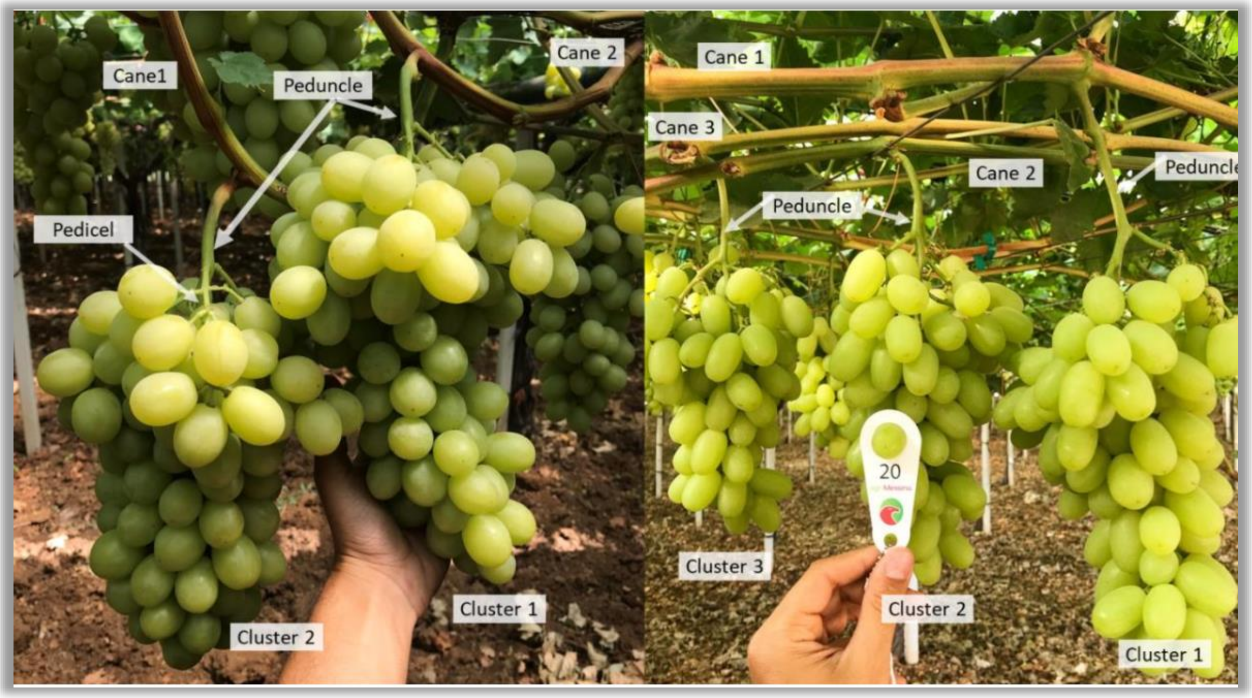


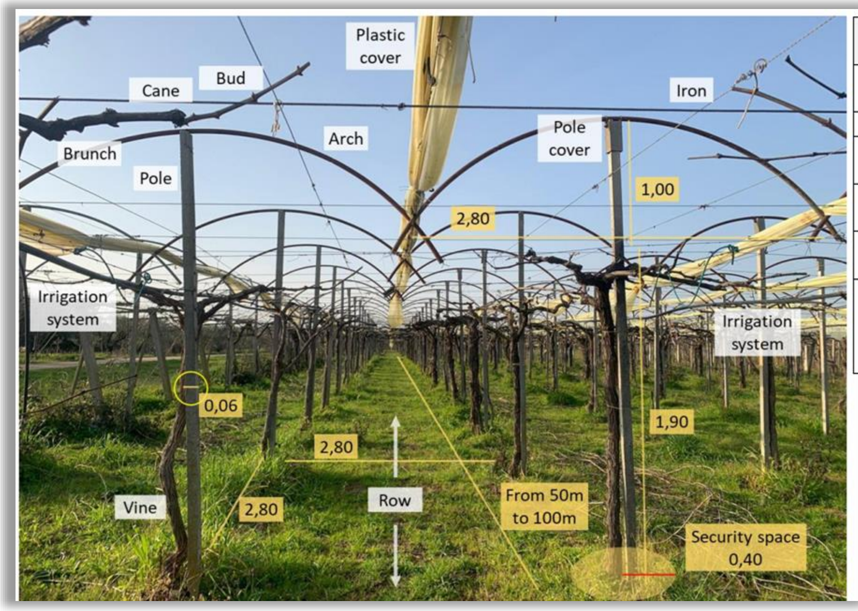
Figure 7 Cluster description

The soil where the vineyard is located can be considered standard for table grapes production, with a lower percentage of stones and higher percentage of sand, that will allow tests of the robot under most weather conditions, even after heavy rain, thanks to the excellent draining capacity of this type of soil.

The vineyard structure is a traditional trellis system “Tendone” with a wide distance between each plant of 3m x 3m. The support structure is a permanent structure Flat-Roof Pergola to support the growth of the vines as represented in Figure 8, Figure 9 and Figure 10 (Figure 10 from EastFruit, 2021).

The vineyard structure consists of the following components: (1) Vertical and diagonal concrete poles to guide the vine trunks and support for the next items; (2) Iron wires to support the vine’s branches, the irrigation system, and the cover structure; (3) Tunnel shaped plastic cover supported by the arches; (4) Irrigation system.

All structures are traditionally covered with plastic and net to protect grapes from rain and hail.



Name	Flat-roof Pergola system (*Tendone*)
Plant distance	2,50m x 2,50m to 3,00m x 3,00m
Plant density	1.100 – 1.600
Structure height from the ground	2,00m
Grapes distance from the ground	1,70m – 2,00m
Min grapes distance from plastic cover	0,30m – 0,50m
Grapes and canopies area	Canopies and clusters are on two different level, but not structurally divided

Figure 8 Table grape "Flat-Roof Pergola" structure overview

Figure 9 Outside view of table grape structure

Figure 10 Inside view of a table grape vineyard

All these components will be modelled as objects in a static structure. This means that it is a permanent, unmovable structure, and it will stop the movements of any object colliding with it. This includes collisions with the mobile base, the dual arm, humans, grape vines and/or grape clusters (AGRIMESSINA, 2021).

4.3. Survey to stakeholders

With the objective to understand how the key stakeholders were preparing the algorithms and what is the best options for them to use the simulation, the following questions were asked, and a collection of answers were analyzed.

From the analysis, the hierarchy and methodology were modified and adapted to their needs.

The questions in the survey are below.

- How are you running the simulation?
- Is there a particular procedure that you are using while testing?
- How useful is the simulation?
- Is the simulation used for basic test of algorithms or training the machine learning algorithm?
- What is the procedure for testing the algorithm in the simulation, if any?
- How do you measure or validate that the algorithm version works?

- How do you determine if the algorithm reaches a “good enough” stage?
- Is there a set of algorithms to test for the same goal? Or just one for a task?

The analysis from the answers gave a clear view on how the stakeholders were adapted to the simulation. Understanding the needs for multiple and different scenarios, and a standard “homogeneous” simulation to test in perfect conditions the initial algorithms and to collect data to train the machine learning.

The benchmark validation from the stakeholders were measured from the described in the benchmark chapter 4.6 below but adapted to near zero error when the algorithm was tested in standard ideal scenario.

4.4. Digital System Hierarchy

The digital system is composed by different elements all interrelated to achieve the agricultural tasks defined for the robot, the summary of the system is represented in the Figure 11.

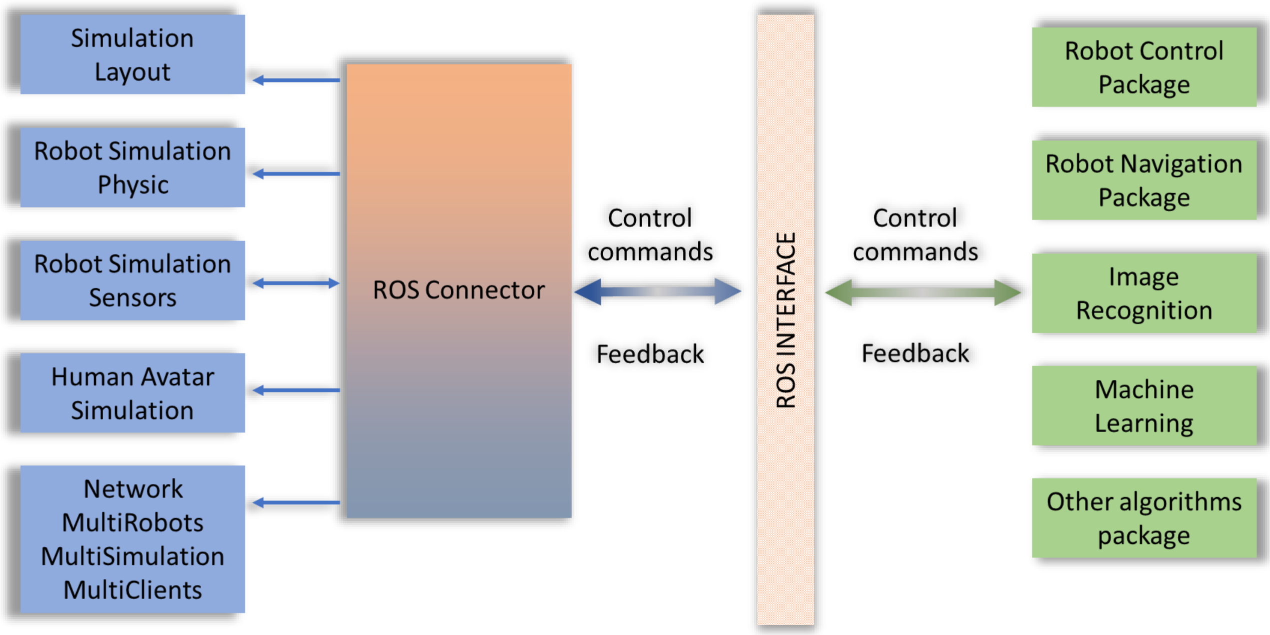


Figure 11 Determine the capability level of the digital twin

The digital twin is an important part of the digital environment. It is the sand box where the machine learning is trained, and the algorithms are tested. The digital twin, consist of two different concepts scenarios. The first one, is an ideal simulation where pure mathematical environment is simulated, allowing machine learning to be trained with clear depiction and defined representation of the environment, allowing the algorithms and the control commands to be tested in a closed environment where error needs to be close to zero.

A second concept where the simulation recreates an environment with added noise to make the simulation more "realistic". This simulation will be used to test the algorithms in a more challenging environment trying to imitate the real-world environment helping the algorithms to adapt to it.

The algorithms are prepared as packages by the stakeholders and are fed to the simulation through the ROS interface. The different packages can be structured in a particular order to fulfil different tasks.

The basic package is the control of the MB. The algorithm contained in this package is the code that controls the amount of power on the engines in order to move the MB in the desire direction and velocity.

On top of the control message package is the navigation package. The navigation package is an algorithm trained with machine learning that identify and avoid the obstacles (vines, pole structure, humans, robots) sensed with the navigation equipment (Lidar, depth camera, RGB camera), and to move in the direction specified to the robot.

The image recognition package is an algorithm trained using machine learning that is used for different tasks. As mentioned before, it is trained to identify obstacles for the navigation algorithm which allows the robot to navigate through the vineyard achieving its goals. This package is used to identify gestures from the humans related to the human robot interaction. The identification of these gestures can orientate the robot to select a particular bunch of grapes or to skip a vine or to cancel a task. An additional main task for the image recognition is to train the machine learning to identify the clusters of grapes and to decide, based on the color, which of them are ready for collection or not.

This diagram presented in Figure 11 is the representation of how the physical and digital system works. The first blocks at the left are the simulation blocks. The layout represents the vineyard, weather, light and soil, pole structures, plant's location, etc. The robot simulation consists of two parts, the physical behavior of the robot and the sensors input from the devices measuring the environment. The human avatar can be considered an object controlled by a client, the object can interact with the robot and is an obstacle that needs to be avoided. The last part of the simulation is the network environment, where different robots, simulations and clients interact inside the simulation. An additional algorithm is used for the robot arm to reach the bunch of grapes after the robot identify the target and to place into the box after cutting them from the branch.

4.5. Scenarios

The digital twin has two main scenarios where different simulations are tested, one scenario where the simulation recreates an environment with the most ideal layout and other scenario with a simulation where noise is added to make the simulation more “realistic”.

The main concept of having an ideal simulation is to train the machine learning algorithms and test the control commands in a closed environment with synthetic data where the testing error results need to be zero or close to zero. The ideal simulation means that there is no noise in the information detected by the sensors, the color of the elements in the simulation is not affected by lights or shadows, so the representation is the true color defined in the simulation, in that way the early versions of the machine learning of the image recognition can be trained with in a controlled environment and with plenty of labeled data. The depth camera measures the exact distance to the object, the soil texture and level is a flat representation where there is no additional friction, and the robot velocity and turning angles are exactly as commanded by the algorithm that will be used by the control and navigation, forcing them to have a near zero error in order to be accepted.

Different versions of the ideal scenario are created for testing related by stakeholders needs. An ideal scenario for control and navigation, as presented in Figure 12, is simulated based on a fixed environment, with a controlled environment and defined structure measurements. Fixed and known coordinates of the pole structures and the vines with exact measured distance from every structure with no deviation between them. Under these assumptions, the simulation synthetic data will be used to train the machine learning algorithms for navigation on perfect conditions. When the algorithm is evaluated, the expected error needs to be closer to zero before being approved and tested again in a different environment with noise that make the simulation more realistic.

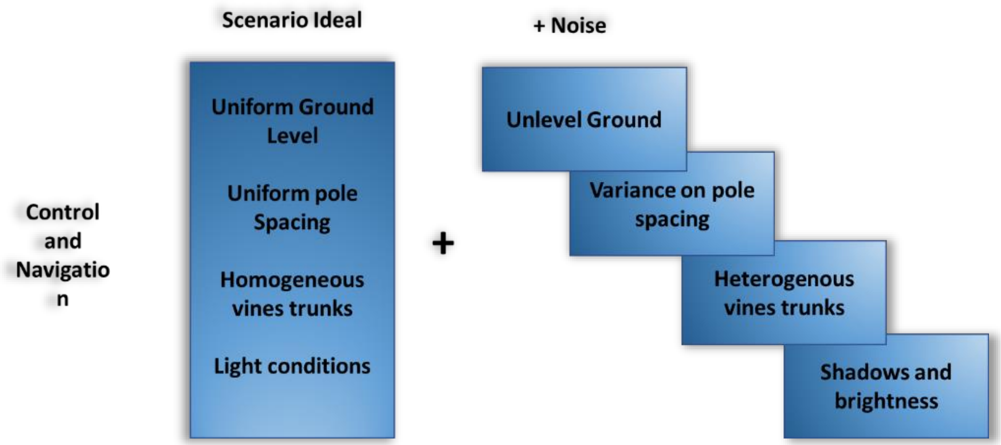


Figure 12 Scenario for control and navigation

Another version of the ideal simulation will be used for the grape's recognition. The vines will have a clear view of the grape's clusters with no obstruction of the view by leaves or any other visual obstacle. This will help the machine learning to spot the target objects and to learn to differentiate from different elements on the simulation. The first version of the simulation has the color of the grapes mathematically fixed with just two or three different set of colors with no random variation between the grapes to help the training of the algorithm. Different versions of the simulation will be added with more variation of color between clusters but keeping the elements visually unobstructed and with not light interference of shadows or brightness.

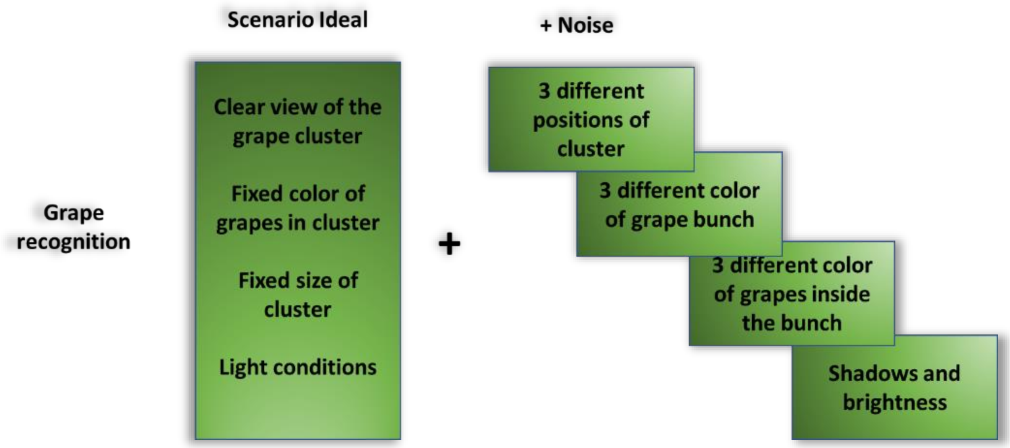


Figure 13 Scenario for Grape recognition

A different version on the ideal simulation scenario will be used for the algorithm in charge of moving the arms of the robot, described in Figure 14. The simulation version will have a constant distance from ground level to the peduncle as described in Figure 7, where the end effector will make the cut and grab the grape cluster. In this version of the simulation the peduncle will be unobstructed and with enough available space to be cut. In additional versions, randomness in the placement of the grape cluster will be added in a determined range to allow the algorithm to test how close the arm got to the desired location.

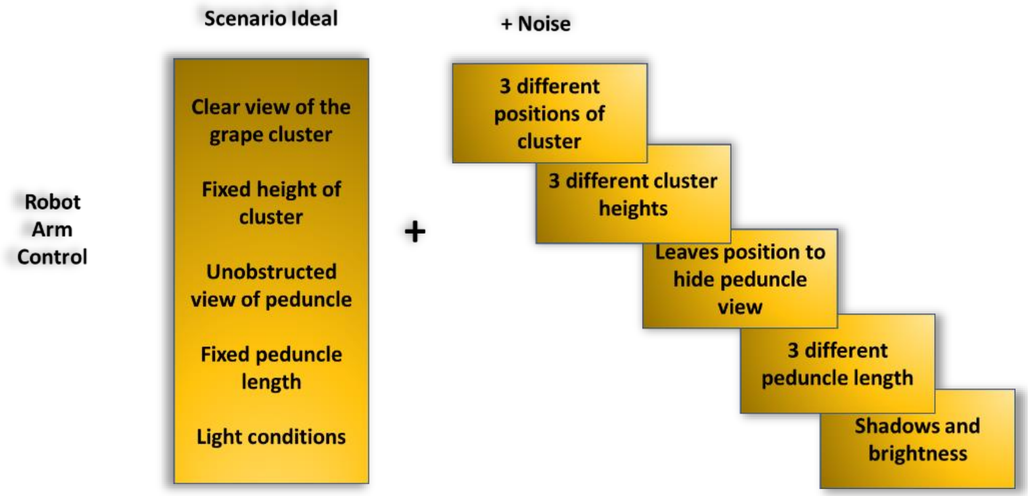


Figure 14 Scenario for Robot Arm control

In order to test the interaction between the humans and the robot, as presented in Figure 16, a version of the simulation from the ideal scenario will be used where the human avatar will present a set of gestures and verbal communication already labeled by the developers. These gestures and verbal communication will indicate the robot a specific command that need to be performed. Different versions will increase the amount of command gestures and the randomness in speed, position and orientation of the human performing the gestures to challenge the training of the machine algorithm (Figure 15). An example of the system for tracking commands can be found below in Table 2.

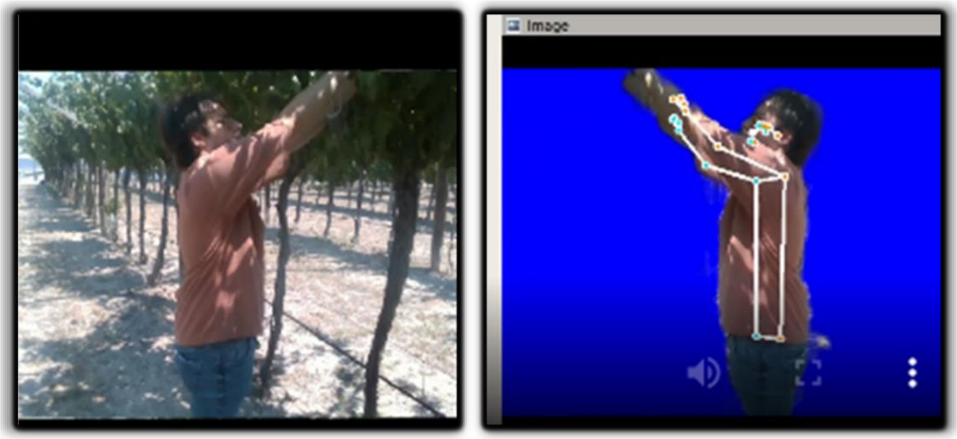


Figure 15 Human tracking software

Comand	Alert	Request
Harvest this grape bunch	Cannot reach it	Can you move away from me
Stop	Cannot recognize the color	Can you help me
Go forward	Cannot find the peduncle	
Go backward	Battery levelo is low	
Move left	The box is full	
Move right	I am listening to you	
Turn 90 degrees	Attention	

Table 2 Verbal command list

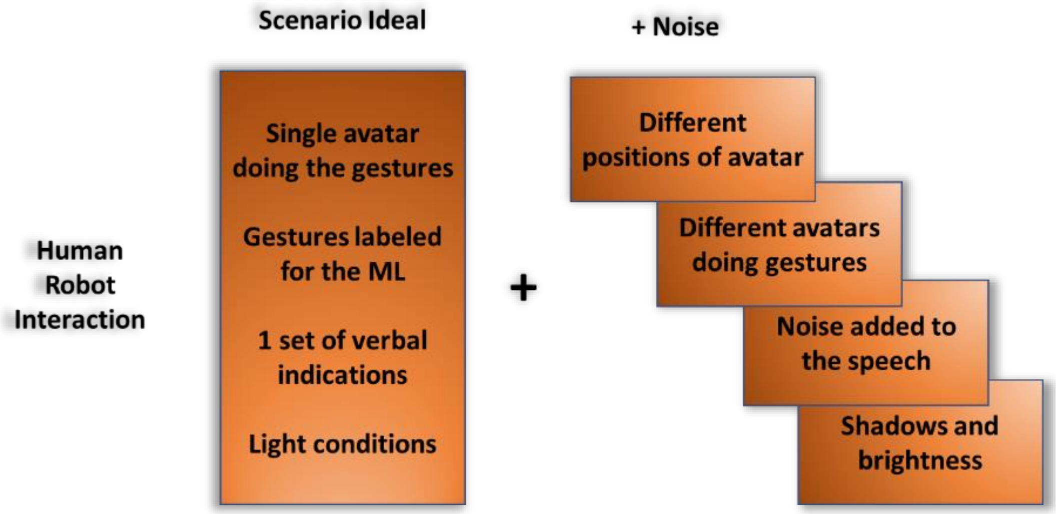


Figure 16 Scenario for Human Robot Interaction

When the stakeholder consider that the algorithm and the training process is acceptable under the different versions of the ideal scenario, the knowledge learned from the ideal simulation can be tested in different versions of the "close to reality" scenario.

At this stage the scenario is a mix of the ideal scenario with noise added to simulate a more real environment. As in the previous phase, the noise will be added to challenge the algorithm and to test it in conditions similar to the ones the robot will encounter in the real environment.

To test the control and navigation algorithms, the simulated robot will be placed in a simulated ideal environment with a structure following the measurements from Figure 8, but in a range between 275 to 285 centimeters between the poles. The vines trunk will not be uniform with differences in the form and sizes.

At the same time some testing of the initial versions of the algorithm are going to be tested in early prototypes of the robot, for example on the mobile base. The mobile base is the ground vehicle platform that enables the robots to achieve their agricultural tasks. In this early phase control algorithms for the mobile base can be tested including velocity and differential movement.

Once the versions are being tested in the "close to reality" simulation, an error percentage similar to the objective benchmarks needs to be achieved to be accepted by the stakeholders and to be integrated to the different layers of commands.

As the real-world vineyard plot is closed to the requirements of grapes and foliage, hybrid tests of the algorithms can be tested, or additional data can be measured and retrofitted into the digital twin. At any point during the testing, the feedback from the stakeholders that run the algorithms will be important for improving the digital twin, described in Figure 17.

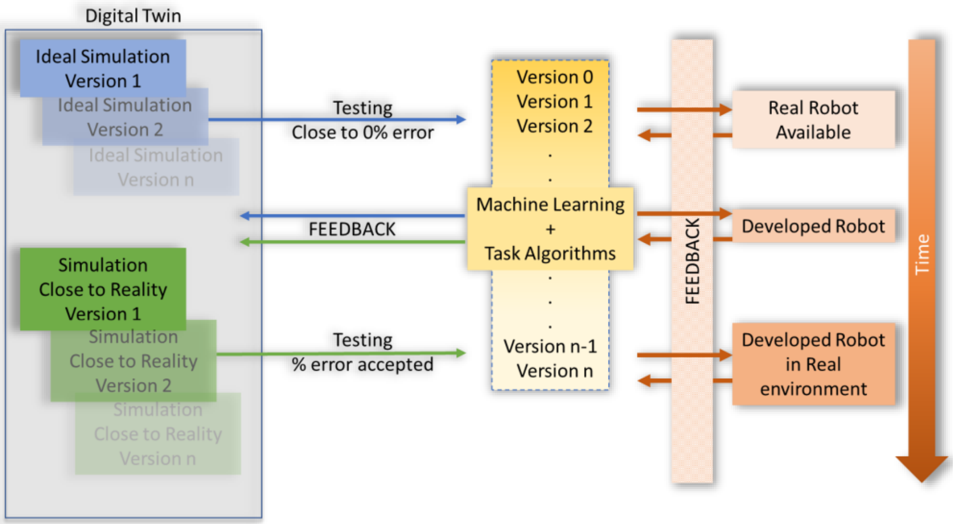


Figure 17 General scenario of the digital twin

4.6. Stakeholders Requirements and benchmarking

4.6.1. Robot navigation.

The stakeholders had setup some benchmarking objectives for the robot control. When navigating through the vineyard, it needs to have an accuracy of 15 cm regarding the position (x,y) and 20° regarding the orientation when executing a command. It needs to have an accuracy of 15 cm when identify the structure (vertical poles with the vine trunks tied up to them) and 20° accuracy identifying the row orientation. The main objective is that it needs the capability of safely navigating by keeping its localization accuracy within 15 cm regarding the position and 20° regarding the orientation along the trajectory.

4.6.2. Dual-arm manipulation and human safety.

The benchmarking when manipulating the dual arm is the capability of planning cooperative trajectories without violating kinematic and dynamic limits and avoid collisions (given perception) with external objects and/or self-collisions with the torso, arms and mobile base.

For the evaluation of agronomic operations, the benchmark is to reach a success rate of at least 70% when collecting cluster in single arm or dual arm mode and a success rate of at least 90% when placing the cluster in single arm or dual arm mode and a capability of the end effector of holding 2 kg of payload.

When physical interaction is allowed, the benchmarks for basic human safety features is the capability to adjust the arm and end-effector configurations according to human exerted wrench with a success rate of at least 90% and without instability phenomena.

4.6.3. Agronomic target detection and localization.

The targets related to detection are an accuracy in cluster detection with a success rate of at least 70%, and accuracy of 80% on selection of grape clusters to harvest according to specific quality parameters. Regarding the berry size estimation, it needs to achieve a mean absolute error (MAE) less than 30% of berry size on benchmark data from the size grape tables.

When classifying the grapes by color, it needs to achieve at least 80% of accuracy on grape bunch color classification on benchmark data from the color grape table.

Additionally, it needs to achieve at least 80% of accuracy on defects and sickness identification on benchmark data from the defects and sickness identification table.

4.6.4. Communication

On the communication between Human client and Robot client, the benchmark is a percentage of correctly detected acts between 70% and 100% according to the cruciality of the communication act itself.

A summary of the needs and acceptance criteria from the stakeholders is presented in the Table 3 below.

Topic	Stakeholder	Needs	Acceptance criteria
Robot Navigation	Organization 1	Position accuracy	15 cm from position
	Organization 1	Orientation accuracy	20° from real orientation
	Organization 1 & 2	Object identification	Identification when an object is at 15 cm
	Organization 1	Navigation	Secure navigation
Dual Arm movement	Organization 2	Arm movement	Move arm in physical positions
	Organization 2	Avoid collisions within the robot	Move the arm without collide with the robot
	Organization 2	Avoid collisions with objects	Move the arm without collide with objects in the environment
	Organization 3	Collection of objects	Success rate of at least 70%
	Organization 3	Arm placing in cutting point	Success rate of at least 90%
	Organization 3	Allows human to adjust arm safely	Allow human to exerted wrench with a success rate of at least 90%
Dual Arm end effector	Organization 4	Payload holding capability	Capability of holding 2 kg of payload
Agronomic detection	Organization 5	Cluster detection	Success rate of at least 70%
	Organization 5	Cluster selection according to specific quality parameters	Accuracy of 80%
	Organization 5	Grape size estimation	Mean absolute error (MAE) less than 30%
	Organization 5	Grape color classification	At least 80% of accuracy
	Organization 5	Grape defects estimation	At least 80% of accuracy
Communication	Organization 6	Communication detection – Gesture and verbal	Between 70% and 100% according to the cruciality of the communication act itself.

Table 3 Acceptance criteria summary

4.7. Concept planning for testing the algorithm

Different stakeholders will have the option to run the simulation build consider as ideal and activate or deactivate different features for testing the algorithms. Feedback on additional features will be communicated to the developers of the digital twin simulation in order to include or modify objects or features.

The different types of actors that interact with in the simulation are controlled using the ROS interface. The farming robot (robot actor) implements the functionality for navigation and harvesting, the Farmers (human actors) are real people who control 3D avatars and Spectators (human actors) are real people with some sort of interaction, for example voice interaction using a microphone and speaker, without the need of using avatars.

The development environment is done using a 3D simulation environment using a Unity 3D engine with a ROS interfacing for the robotic clients.

The networked multi-user environment supports multi-user training environment for users to share the environment to execute tasks together. The users are represented with full-body avatars and with voice-interaction for communication. This environment supports dynamic interaction between the users which makes it possible to manipulate objects in a realistic way. All movements of the users and relevant objects are synchronized across the network such that all users will experience the same situation at the same time.

The simulation communicates via an ROS interface allowing the users to send and receive ROS messages via a TCP connection to a specific interface between the simulation and ROS. ROS topics, actions, states, and parameters can be realized in this way enabling the option to simulate components like sensors which communicate with other ROS components in the same way as the original hardware devices do.

The simulation and the ROS package are shared with the stakeholders as an executable file in order to connect with the simulation from different clients sharing the same space in real time. For this, the movements of the robots and humans will be synchronized across the network.

The simulating computers for the robot and human clients can be distributed over the world. It is possible to join or leave a simulated environment at any time.

Dynamic interaction among actors and objects will always be calculated on the local computer to minimize latencies. The results of these interactions will be synchronized to all other clients such that they will be able to see and respond to the results of these interactions. The simulation supports dynamic interaction between different clients across the networking like a human client manipulating the arms of a robotic client as showed in Figure 18.

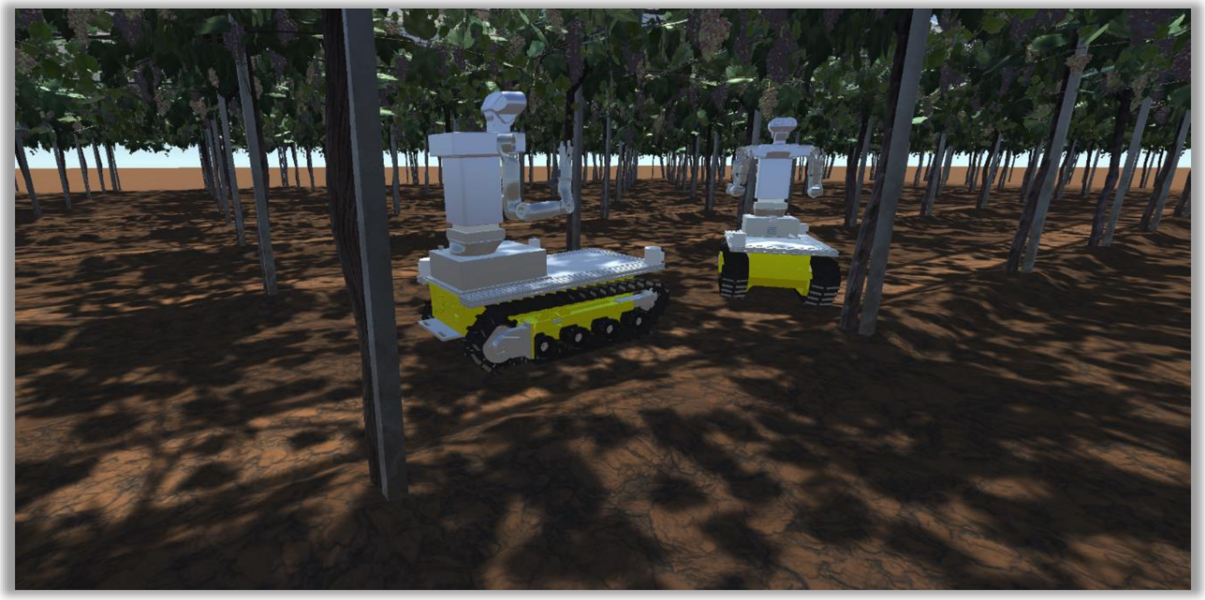


Figure 18 Multiple robots in the simulation

4.8. Capability Levels for functional elements

The recommended practice from DNV "Qualification and assurance of digital twins" DNV-RP-A204 (DNV AS, 2022), described the capability levels of the functional elements (FE) in a digital twin from standalone (level 0), descriptive (level 1), diagnostic (level 2), predictive (level 3), prescriptive (level 4) and autonomous (level). The levels are described in function of the maintenance topics. In this analysis, the capability levels will be evaluated based on how the digital twin operates.

Based on the functions of the digital twin, a set of functions based on the capability are defined describing its current capabilities and the designed intention (DNV AS, 2022). The summary can be found in Table 4.

Level	Capability	Function
0	Standalone	• The physical asset may not exist, no data streams are available from the asset. • The FE can describe and predict system behaviors based on synthetic data. • The asset information model has been developed and matured with the ability to provide a detailed description of the asset. It may contain

		contextualized and structured information, such as master data, graphical models, bill of materials, multidomain modelling (system-of-systems), etc.
1	Descriptive	• The FE can describe the current state of the system or asset. • Real-time data streams are available from the asset. • Describes the real system and provides status, alarms and events. • Ability to interrogate and provide information about the current and historical states.
2	Diagnostic	• The FE can present diagnostic information, such as object detection indicators.
3	Predictive	• The FE can predict the system's future states or performance and remaining useful life. • The FE can predict which element can be selected.
4	Prescriptive	• The FE can provide prescriptive or recommended actions based on the available predictions. • The FE evaluates the implications of each option and how to optimize the future actions without compromising other priorities.
5	Autonomous	• The FE can replace the user by closing the control loop to make decisions and execute control actions on the system autonomously. • The user may have a supervisory role over the FE to ensure that it performs as intended.

Table 4 Function level capability

At the current stage the Digital Twin is between the second and third level. The algorithms used can diagnose and predict the activities the digital robot need to perform. At a later stage, the intention is to reach a functionality of autonomy with supervision from a user.

4.9. Criticality and confidence level

One important analysis to assess the potential consequences of decisions by using a matrix based on three inputs, (1) how the decision is made, (2) the FE capability level discussed in the previous paragraph and (3) a confidence level qualification from 1 to 3 to each FE, where 1 is low and 3 is high. The potential consequences are based in the access to information from different sources that can help the system to corroborate the information, and the time availability to evaluate the information available. This analysis is based on the analysis performed in the DNV-RP-A204 (DNV AS, 2022), but adapted to the decisions on the digital twin used in this study.

The confidence Matrix is presented in Table 5 below.

Basis for key decision	Typical FE capability level	Potential consequence of wrong decision		
		Limited impact	Can cause delays, downtime or financial impact	Can cause major failures, accidents or environmental impact
The FE is one of several source of information and decision making is not time constrained.	0, 1, 2	**1**	**1**	**1**
The FE is the primary source of information and decision making is not time constrained.	3	**1**	**2**	**2**
The FE is the primary source of information and decision making is time constrained.	4	**2**	**3**	**3**
FE with automatic or autonomous functionality	5	**2**	**3+**	**3+**

Table 5 Determination of required confidence level for a functional element

It is important to point that the consequences of the functional elements are based on their use and testing in the digital twin, making the delays and downtime the more potential consequences. In case of the not having the option of testing the different algorithms, major failures, accidents, and environmental impact situations can occur.

4.10. Critical innovation big picture matrix

Any methodology has positive impacts but as well negative impacts, and this research is not absent of those. Furthermore, it is of highly importance to identify if not all the dependencies, at least the most important in order to increase the advantages on the use of the methodology.

The matrix presented in the Table 6 below gives a big picture of the dependencies and positive and negative impacts in terms of time, from short term, medium term, and long term. The matrix idea and structure are based on the work done by Tolstow, Beiky and El-Thalji (Tolstow, Beiky and El-Thalji, 2021).

	Short-term, immature	**Medium-term, Mature**	**Long-term, Lifetime**
Positive impacts	Understanding of the tasks need to be performed. Ability to test different version of algorithms.	Reduce the development time by testing different versions of the algorithms in a digital twin. Training data for ML.	Reduce the need to different versions of the physical asset. Saving costs and time.
Dependencies • Environment • Physical asset • Algorithm development • Data management • Integration	Not need to be in a physical place to test the algorithms. Use of the cloud to input variables and load algorithms in the digital twin.	Reduce the dependency of the physical asset for the development of the project. Data quality. Training data for ML.	Integration of processes.
Negative impacts	Multiple interactions for understanding the needs. Inaccuracy in the digital environment.	Cyber security. System upgrading (sensor, software. Difficulty to support additional changes.	Difficult to adapt to different needs.

Table 6 Innovation big picture of the proposed methodology

In the short term, when the methodology is being prepared and shared with the community, challenges and difficulties will appear. The understanding on what the digital twin needs to contain is missing at the beginning of the process, just the basic initial requirements. As the methodology is understood and the objectives are clear, more information and different versions can be added to the cases, resulting in a more complex environment, with multiple interactions to add to improve the product.

As the methodology is mature, the results are more palpate with a lot of time save by testing different versions of the algorithm without the need to have access or to modify the physical robot and without the need to be present in the physical location to do the tests. The successful environment will allow the clients and users to generate exact and labeled data with the purpose of training the machine learning algorithms.

In a long term, the need to build physical assets will be reduced to few prototypes for loop testing, with a high confidence that the algorithms that need to be used are going to achieve the objectives setup when developed, with the additional cost and time saving.

There are some negative impacts with the methodology, as mentioned before the multiple interactions to add different or complex environments that the users can think about or the inaccuracy of the digital environment that creates a set of algorithms with no use in the project. In the medium-term challenges regarding cyber security because the heavy dependency of cloud integration, and the issues related to upgrades on the software used in the platforms, or additional or replacement of sensor equipment. And in the long term the difficulty to adapt the methodology to different digital twin, made it obsolete and with not clear advantage.

5. Discussion

5.1. Discussion

The main objective of the thesis is to define the methodologies and processes to be used in the creation of a digital twin for a precision agricultural robot. The system involves the interactions between the robot and the environment and the tasks that the robot needs to perform to fulfil the objectives of the large project. The concept study will focus on the process necessary to validate the robot interaction in a simulated space before the testing of the robot in the field. The discussion below is to understand what was successful and what needs additional review.

The digital twin is a necessity due to the multiple tests needed to optimize the algorithms before the robot can be in the field to be tested. In addition, the period when the grapes can be harvested is no longer than two or three of weeks during summer months, and in the case the robot may need to be altered, the new test will need to be deferred until the next harvesting season, while if the solutions are tested in the digital twin, the physical robot can be designed with the latest updates and the algorithms can be tested in a loop between the digital twin and the physical asset.

As an overall, it is of great benefit to have the option of using the digital twin to simulate the entire robot and its capabilities. While in real world the modifications on the physical asset are entirely possible, it takes a long time to build, rebuild and/or modify the robot to include or remove a piece of equipment, or to test how efficiency the equipment works in different segments of the robot, allowing to select between different options based on how to avoid interferences and how the mechanical physics of the robot works. These type of process in the digital twin requires less effort and consume less time. This is not just true with modifying the physical robot, but for the testing of different algorithms, for example for navigation, it is not necessary to locate the physical robot in the vineyard for a test, but just in the digital twin controlling the digital robot in the simulated environment and test how is the performance of the navigation algorithms and modify them if necessary.

Another benefit of the digital twin is the option to modify the structures of the vineyard and to add additional elements to the structure that could be of highly important when testing the algorithms. Adding noise to the environment simulation by adding different type of terrains, adding, or removing foliage of the vines, increasing the foliage density, hiding or resalting the grapes bunches or using different light conditions is basic for the increase the confidence in the algorithm testing and to create sandboxes where different options can be tested.

Navigation of the robots can be adapted to different conditions, from basic navigation with mapped objects in fixed coordinates to avoid collisions to complex navigation with algorithms detecting static and dynamic obstacles.

The system analysis of the digital twin design present different opportunities for the development of the robot. Synthetic data gives a perfect representation of the environment that can be used to test the machine learning algorithms in different activities and tasks, giving the option to use large amount of data with different levels of complexity by adding noise related to what is needed to test. In addition, the data recorded in the physical world and real interaction between the physical asset with the digital environment can be added to the simulation to be tested as a whole by different algorithms.

As presented in the methodology in this research, the use of case scenarios analysis gives the option to increase the complexity of the simulation environment by adding layers of noise allowing the testing to go from an ideal scenario of different properties to complex simulations when noise is added. The ideal scenario and the added noise are different depending on the machine learning training or the algorithm that need to be tested.

The benchmarks and stakeholders' requirements can be supported using different environments and be used for different analysis. Different needs based on accuracy, object identification, payload capabilities, color and size estimation of grapes can be modified in the digital environment as the algorithm is developed, and additional requirements from stakeholders can be added to the simulation to understand how the algorithm may behave under different circumstances.

Package of data can be generated by the simulation and used by different stakeholders or final users, and data generated using different physical equipment can be added to the simulation by using the concept of the testing in this document. ROS packages can dynamically be exchanged and reused in different environments and tested independently by different users, giving a more robust quality control of the final product.

5.2. Future work

As an important part of future work, the validation of the scenarios will be crucial when the project is finalized. The need to understand what worked according to the expectations and what was technically difficult to achieve needs to be used to modify the methodology.

And before the case study is finalized the topic of integration will need further attention due to its complexity and importance. The integration will be a fundamental part of the case study because after all the algorithms are tested individually, there will be the need of grouping different packages and feed and test in the digital twin, in order to achieve a particular task. For example if the task is to harvest a particular bunch of grapes, the robot need to use the navigation algorithm to reach the next vine, then it will need to use the agronomical sense package to identify the grape bunch that needs to be harvested, it will need to be closed and to operate the upper arms and the end defector to get in position in the peduncle and proceeded to cut it and laid it on the collecting box.

Integration will need a methodology review based on the needs from the stakeholders and the capability of the process to be used and adapted.

This work can be expanded with a future work oriented on how to envision a collaborative initiative by using a digital twin.

6. Conclusion

The use of this case and the methods defined and elaborated can be used for projects when physical assets need to be created and tested, and when time periods for testing are part of the challenges of the project and the availability to allocate and integrate resources is complex.

As part of the introduction of Industry 4.0 to many industries, new technical updates are being integrated to most of the projects including progress in machine learning, with the increased necessity of high volumes of data, most of the time these data including label to train the machine learning algorithms. The methodology used in this case study provides, as part of the user cases, a simple process to prepper and export the information needed to train the ML algorithms, and to add noise tailored when the evolution of the algorithm required.

The methodology can be adapted to the necessities of any digital twin solution, being able to use the same architecture as proposed and the ability to modify the different cases defined in this document in order to complete the general and specific objectives of the algorithms or tasks.

This proposed methodology can increase the quality and usability of any digital twin and can prove how successfully can it be the implemented while planning process when developing a project.

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