DIGITAL TWIN MODELLING FOR SMART FRUIT-GROWING: ECO-CYBER-PHYSICAL SYSTEM 4 + 1 ARCHITECTURE

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Abstract. The continuous evolution of technology and industrial revolutions provides new horizons for the application of smart solutions in every aspect of human lives. At the same time, it causes new social and engineering challenges, which require appropriate methodologies and solutions to overcome them. A smart orchard is an example of an eco-cyber-physical system. Modelling of an eco-cyber-physical system is more complex than simple software development because the complexity quickly grows together with the amount of interconnected components. The difficulties come together with various fruit tree species (in our case apples, pears, and cherries), related technologies and orchard systems. Such systems differ even in the frame of one species like apple trees (rootstocks effect on the tree size; planting density; tree canopy training systems, etc.) and some production risk-reducing technologies (rain and hail, against birds and insects protecting covering systems), as well as agricultural machinery movement in the site. An additional accelerator of complexity growth is the development of eco-cyber-physical and data-driven decision-making paradigms, which propose business-driven development considering ecological and technical aspects together within cyberspace. As a result, the product of synergy is a digital twin paradigm, which provides digital mirrors for artificial intelligence to monitor and manipulate the physical world considering environmental aspects. This article presents the digital twin "4 + 1" model of a smart orchard, which is described using modern visual notations like 4EM for project view, ARTSS for logical view, OPM for process view, IoT-adapted UML component diagram for physical view and spatial map for deployment view. The proposed methodology offers a roadmap for design and development of smart solutions in fruit-growing to predict the yield and potential of income generation in the early stages of the season.

Keywords: artificial intelligence; digital twin; decision-making; smart orchard model; UAV.

Introduction

Smart fruit growing nowadays is possible with application of appropriate decision support systems and artificial intelligence (AI) based solutions. Most of the solutions rely on predefined or historical data and scientifically proven models for crop development. However, it is important to follow crop conditions during the growing season in order to predict the yield or necessary application against pests or diseases. Eco-cyber-physical systems (ECPS) concept is a relatively new concept applied for describing complex systems. ECPS is defined as a "combination of the living and non-living components of the ecosystem in conjunction with the cyber-physical sensors and intelligent agents in the environment, interacting as a system" [1].

Digital twins as the simulation modelling paradigm supports ECPS deployment in practical applications including sensing environment with IoT devices or robots [2]. At the same time the digital twin concept can be considered the highest level of digitalization of crop production management and the integrity of physical and virtual systems allowing a user to control the physical system through its virtual representation [3]. Smart farming will be the next generation related to food-growing production automation in which management tasks not only are based on geospatial data but also on context data, situational awareness and event triggers using a digital twin approach constructing a cyber-physical system for farm management [4].

If a digital twin provides only the monitoring and data collection part, it is called digital shadow. The orchard monitoring can be completed using UAV, which periodically surveys the orchard. UAV is a tool combined with sensors and cameras to quickly collect data without subjective traits that humans possess. Considering that survey plan and UAV launch must be completed by ECPS considering weather conditions, it belongs to category "digital twin" not "digital shadow". With relevant mathematical models it can give answers to questions about the yield and its quality. As a result, it could be used for commercial planning of resources, financial assets, work flow and load, human, storage and processing capacity, sellings etc. Using the temporary and historic data, it is possible to forecast a fruit yield or to simulate its development to optimise agribusiness tasks.

The digital twins are promising to revolutionize the way the future cyber-physical systems will be developed and operated, which are becoming increasingly complex every day [5]. However, it is a fact that the development of cyber-physical systems is complicated compared to that of traditional software systems, especially in relation to requirements of engineering [6].

This article presents the “4 + 1” model of a smart orchard digital twin, which is described using modern visual notations like 4EM for project view, ARTSS for logical view, OPM for process view, IoT-adapted UML component diagram for physical view and spatial map for deployment view. The proposed methodology offers a roadmap for design and development of a digital twin in fruit-growing to predict the yield and potential of income generation in the early stages of the season.

Material and methods

ECPS design: the 4 + 1 architecture was presented by P. Kruchten (1995) [7]. The architecture presents multiple views for various stakeholders and handles the functional and non-functional requirements separately. In this article, the modern visual notations were applied to describe the digital twin of a smart orchard intended for autonomous yield estimation using UAV considering the 4 + 1 architecture.

Logical view: ARTSS methodology and ideas are applied to define capabilities in the form of requirements for digital twin solution. ARTSS methodology is developed as an extension of the Capability Driven Development with emphasis on data and services provided as resilience within the system as a response to external challenges. The methodology is deployed for development of a data-driven digital twin [8] where data can be collected from various data sources and devices. From the methodology perspective, models incorporate capabilities and services supporting their delivery as well as capability goals, delivery context and adjustment applied to adapt capability delivery in the case of unexpected events or real-life situations. Capabilities defined within ARTSS are used as a basis for further development of secure and resilient services, digital twins and knowledge sharing.

Project view: the 4EM Enterprise Modelling method consists of six sub-models for modelling goals, concepts, business rules, business processes, actors and resources, and information system technical components and requirements models [9]. They are designed to be for various purposes and can be applied to capture and represent most modelling problems related to the organisational designs [2]. Application of a methodology for particular context means identifying main goals for the particular case and identifying key aspects and features needed to be incorporated for smart fruit growing.

Process view: Object Process Methodology (OPM) is a conceptual modelling language and methodology for capturing knowledge and designing systems. OPM can be used to formally specify the function, structure, and behaviour of artificial and natural systems in a large variety of domains. It integrates the object-oriented and process-oriented paradigms. OPM graphical elements are divided into entities, expressed as closed shapes, and relations, expressed as links that connect entities. Object Process Diagram (OPD) is the one and only kind of diagram of OPM. An OPD graphically describes objects, processes and links among them. Entities are the building blocks of OPM. They include objects and processes, collectively called things, and object states. Links provide relations between entities [10]. OPM can be applied to depict the processes and related entities of a cyber-physical system to explain the system design to developers.

Physical view: IoT Visual domain specific modelling language has been designed with UML, IoT systems and technical/non-technical end users in mind. The language is built from several parts. The Thing is a basic element of the IoT system that is represented as a Rectangle labelled with the name of the device that matches the domain of the thing. There are two types of things that are composed of several items (inputs, outputs and components): besides a normal thing that matches a real device there is also a second type of thing with the stereotype < < virtual > > that does not exist in the real world and it is just a virtual collection of items. Besides the < < virtual > > stereotype, a < < subsystem > > stereotype is available that specifies a collection of things on a higher level. One thing can contain zero or more items. The items can be divided in three groups: inputs, outputs and components (log services, software components). The required interface is represented as a Semicircle, while the provided interface is represented as a Circle. The provided and required interfaces can be represented as UML classes with the stereotype < < interface > > . The most compact way to display the provided and required interface of an item is to use a property list inside the item. In order to show that an item that has a required interface is dependent on another item in the system that is providing the interface as dependency, a line has to be drawn from the semicircle symbol to the circle symbol of the item that is providing that interface. The internal structure displays the parts of the system that contain the things, items and the relations between them. This enables the representation of the relations in the specific context. Rules are represented as UML methods inside a UML Class block, and they are closely bound to ports and items [11]. IoT modelling language presented by Eterovic et al. (2015) [11] can be applied to depict the components of the cyber-physical system, their technical and non-technical parameters, as well as interfaces for developers.

Deployment view: it is strongly important to make geospatial analysis of the ecosystem to select optimal devices and their allocation places. The constraints can be starting from security aspects, non-functional requirements like Wi-Fi and power availability until aesthetic and land use issues. The geographical information systems (GIS) are applied to make geospatial analysis and draw maps.

Results and discussion

Logical view: at the beginning ARTSS notation was applied to create a business model of the future digital twin of ECPS using the brainstorming method discussing with fruit-growers: business goals and ecosystem factors, and risks (see Fig. 1). Speaking about the business model, it is possible to estimate the yield by taking into account the orchard potential productivity, orchard area and the age of trees. It is necessary to know the yield amount before planning the storage capacity, workforce, and equipment needed for harvesting. However, the productivity (yield per area) of an orchard depends on various factors - cultivar dependent and human-determined. Yields depend on cultivar biological traits and their tendency to grow that include rootstock influence on the tree size, too. Fruit growers determine other factors of productivity that combine orchard systems like the tree density, type of canopy, and the tree height as well. The next level of influence on productivity is abiotic and biotic conditions determined like the meteorological situation, pests and diseases. The abiotic stress situation is mostly related to winterhardiness including flower buds, spring frosts during flowering, pollination, and fruit-set, as well as the fruit development and harvest time. Pest (insects and diseases) activity, partly depending on the meteorological situation, reduces the orchard productivity or at least the fruit quality. Precise data about an orchard yield can be obtained using UAV, meanwhile, the artificial intelligence can provide yield forecasting. Yield forecasting gives the possibility for fruit growers to evaluate external influences (weather and pests) and plan the time of harvest, as well as determine the proportion of predefined categories according to the fruit quality to selling directions (dessert, processing or determined as waste).

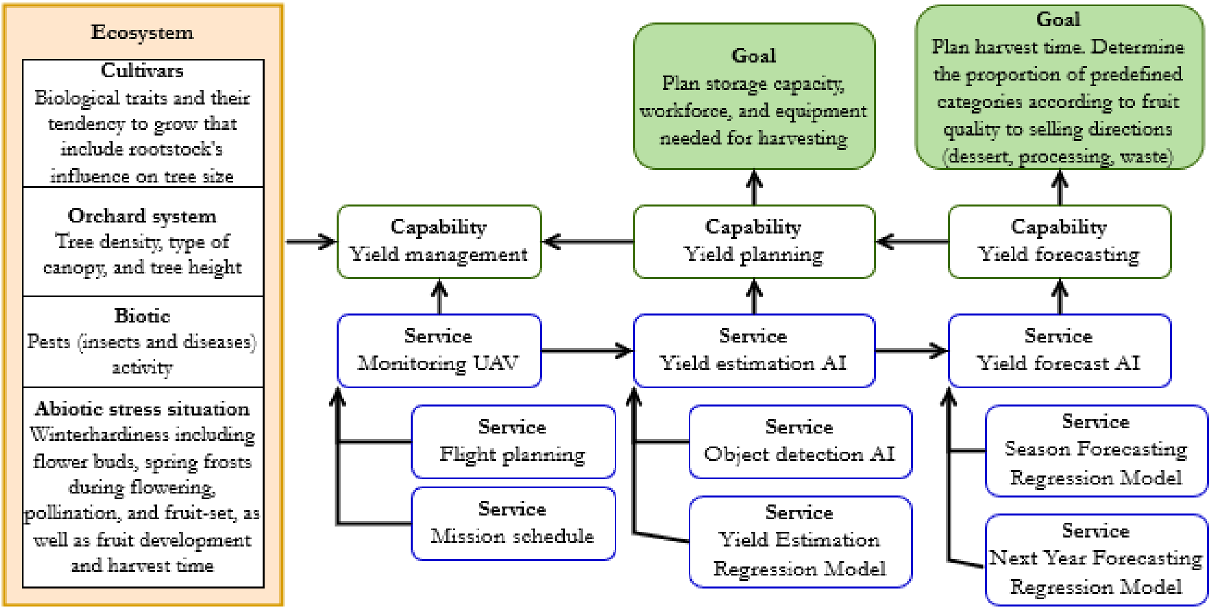

Fig. 1. **Capability model of the smart orchard digital twin**

Process view: based on the capability model (Fig. 1), OPD was developed to explain the required components and processes of the cyber-physical system to provide estimated services for fruit-growers. The developed OPD shows how smart orchard supports decision-making of fruit-growers by providing the yield and forecast data, as well as, it depicts required components including artificial intelligence, base station of UAV, meteo-data brokers, methods and data (see Fig. 2).

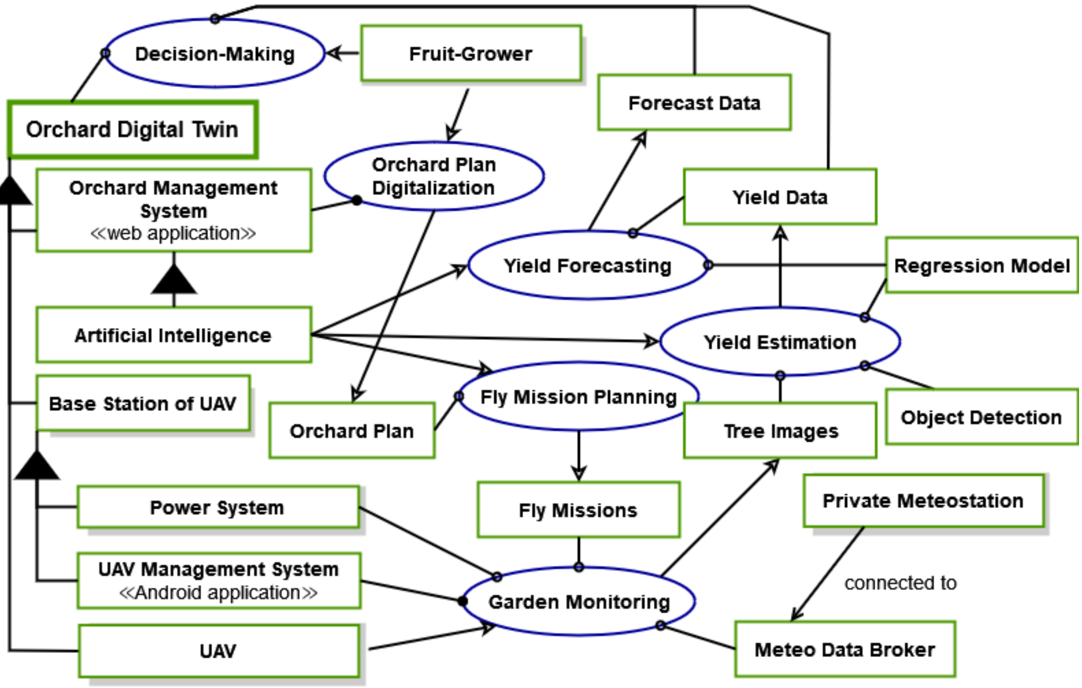

Fig. 2. **Digital twin OPD of smart orchard**

Project view: when the requirements of end-users (Fig. 1) and components and processes of solution are defined (Fig. 2), it is possible to specify the project tasks and work packages, which are required to achieve a business goal (see Fig. 3). In our case, it was additionally required to arrange an orchard for LivingLab to test smart solutions like "Autonomous orchard for yield monitoring".

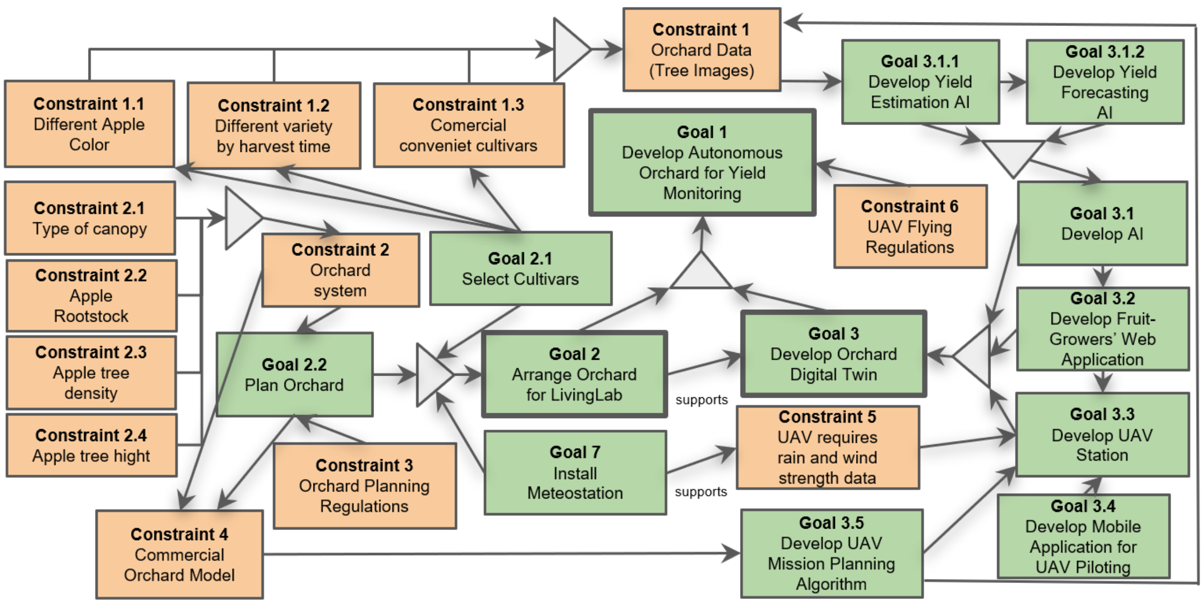

Fig. 3. **4EM diagram of project (autonomous orchard for yield monitoring using UAV)**

Three basic criteria were chosen for the creation of the LivingLab orchard: different apple colour, different variety by harvest time, and commercially convenient cultivars. Initially, 25 varieties of apple trees were selected according to the mentioned criteria, and then the 8 most suitable ones were selected using the elimination method. Meanwhile, planning the orchard, fruit-growers have to make decisions related to the production type and cultivars – oriented to dessert production and/or processing, consumption time of fruits, following decisions related to the tree size (height) that are influenced by rootstocks, soil properties. Subordinate to the tree size are planting distances between rows and trees (orchard density), the type of tree canopy (tree training system) [12]. All together it is an orchard system. If the tree size reducing rootstocks are used, the tree support system should be implemented. It traditionally consists of anchors, poles (like concrete), wires, tensioners and/or stakes (bamboo). Several risk reducing technologies could be combined - covering systems: hail, rain, insects protecting; irrigation systems. In the near future the multifunctionality (multi production) of orchards should be taken into account. It is related to the possibility to combine tree support systems and/or risk reducing technology with solar energy capturing, establishing solar panels above the trees etc. Meanwhile, the use of UAVs in commercial orchards means that new risks appear in the management process, which need to be taken into account. The most important thing is the work organization process, which needs to be separated in the desired time, which means that people or equipment are not in the orchard at the time when the UAV flight is carried out there to collect the necessary information. By transferring coordinated organization of the process, it is possible to avoid risks without causing danger to human life, equipment damage or damage to UAV.

4EM diagram is sufficiently suitable to depict the required components of ECPS as well as regulations and non-technical tasks as constraint elements providing a full picture of the requirements to project managers and system analysts (see Fig. 3).

Physical view: if components and constraints (technical/non-technical requirements) are identified, the market analysis must be completed to find the appropriate devices and services, which can satisfy requirements and their compatibility. Additionally, the important elements are licences, device design, its availability on market and delivery possibilities. Maybe it is the most complex part, because it requires wide knowledge and multi-factor consideration at once. However, if it is well completed, it can strongly decrease development and maintenance costs and complexity. The result diagram of the autonomous orchard based on the digital twin paradigm is depicted in Fig. 4.

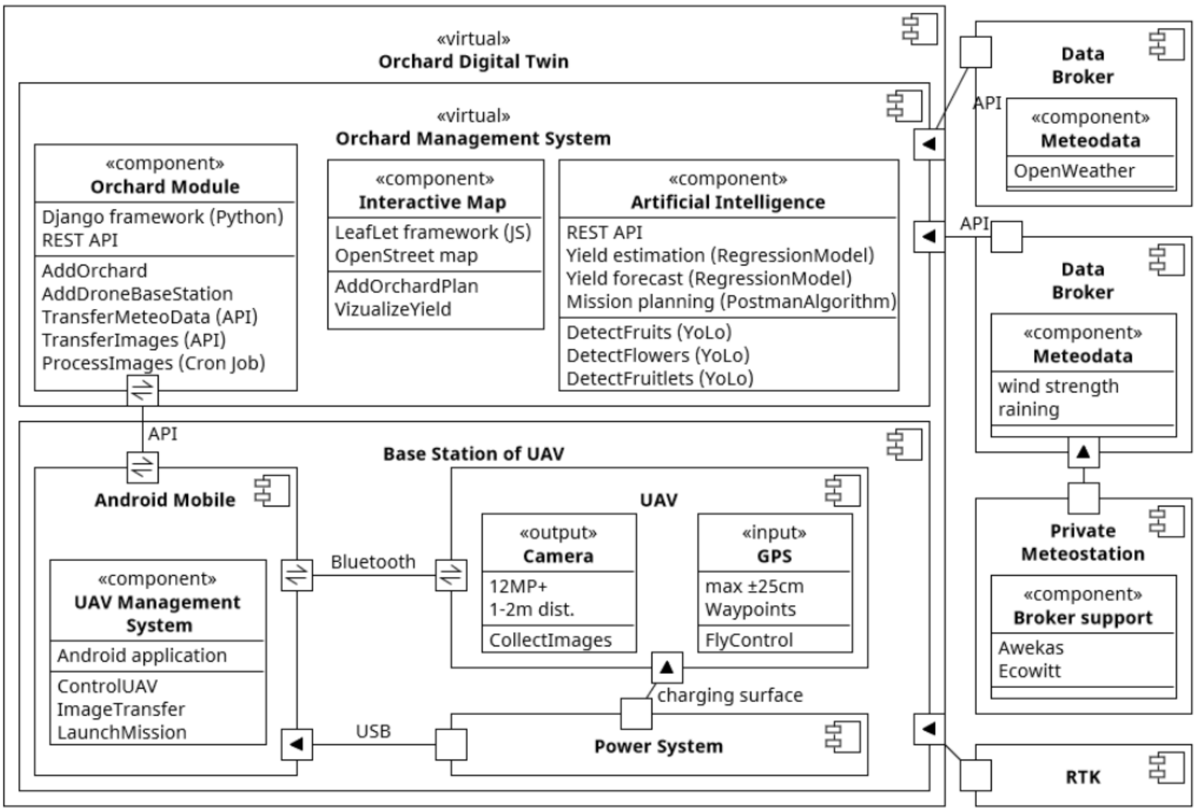

Fig. 4. **IoT component diagram describing technical/non-technical parameters and connections among components of cyber-physical system**

Deployment view: the sketch map of the UAV station and meteostation locations in LivingLab was drawn up (see Fig. 5). In this study it was not required to make a complex geospatial analysis, because the smart orchard and the meteostation were predefined [13]. However, it would be an optimization problem for large commercial orchards with the need for multiple UAV- and meteo-stations.

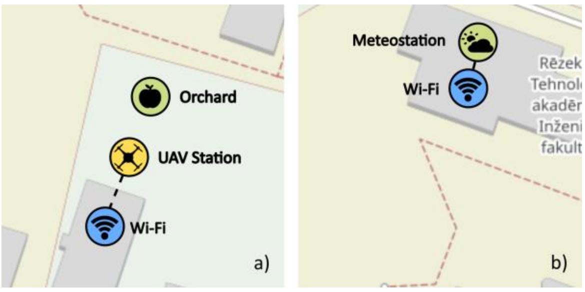

Fig. 5. **Location of physical components:** a – UAV station in orchard; b – meteostation

The developed model of an autonomous orchard will help fruit-growers make decisions according to estimated yield - planning necessary tools, materials, machines and number of fruit pickers (seasonal workers), storage capacity and fruit selling strategy. Usually, the harvest time is very tense due to the cultivar specific harvest window, structure of cultivars depending on their ripening time in the orchard. Next step - grower or fruit-grower organisations will have possibilities of planning selling, organise preselling agreements with wholesalers, planning their financial flow, current assets.

The proposed methodology offers a more specialised approach to the system modelling task focusing on modelling the digital twin of ECPS. The methodology fills the gap of system requirements definition on a high level and its less complicated knowledge specification makes it easier to communicate the system design with the domain experts than some of the more widely used systems modelling notations such as Business Process Modeling Notation (BPMN). Classical system modelling languages and notations like BPMN and Unified Modeling Language (UML) are still relevant in further refining the requirements and production of the system architecture specification.

Speaking about 4EM, ARTSS CDD and OPD, they can be simply drawn and elegantly depict the functional and non-functional requirements of the ECPS. Meanwhile, the IoT component diagram completes required tasks (description of technical/non-technical parameters of components and connections among them), however, the IoT component diagram is sufficiently complex to draw it and make some changes. Additional complexity of the IoT component diagram is a predefined structure of elements, which is suitable for electronic devices. Meantime, the eco-cyber-physical considers more different components. Therefore, the visual notation must provide more freedom for description of their technical/non-technical parameters. Considering the deployment view, the location map of devices is not really suitable for the autonomous orchard system, because the project is targeted to provide a platform for fruit-growers, but the prepared map is the authors' use-case of LivingLab. The selection of the map was based on the previous experience with IoT device deployment for a smart orchard [13], which showed successful results, because orchard arrangement required to solve plenty of constraints: soil quality, land area, sunlight, Wi-Fi availability, camera allocation etc. In the case of the autonomous orchard, the CORAS risk analysis diagram [14] will be more suitable, because it is important to understand the orchard system, fruit-growing field works, fly trajectory, possible threats, vulnerabilities, and risks.

Conclusions

The digital twin "4 + 1" model was presented based on the example of the autonomous orchard monitoring system. We applied the modern visual notations like 4EM, ARTSS, IoT component diagram and OPM as well as the location map for device position planning. The novelty of the study was to evaluate the effectiveness of selected models to describe the digital twin as ECPS. The proposed methodology fills the gap of system requirements definition on a high level and its less complicated knowledge specification makes it easier to communicate the system design with the domain experts. In this specific study, the location map was not strongly useful. Therefore, it is recommended to replace it with CORAS risk analysis visual notation. Meanwhile, the IoT component diagram completed its tasks, but it is complex for drawing and can be reconsidered in the future.

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Author contributions

Conceptualization, S.K., G.M. and I.Z.; methodology, S.K.; validation, G.M. and I.Z.; formal analysis, S.K., I.Z., G.M., E.R., L.L.; writing – original draft preparation, S.K., I.Z., G.M., E.R., L.L.; writing – review and editing, S.K., G.M. and I.Z.; visualization, S.K.; project administration, I.Z.; funding acquisition, I.Z. All authors have read and agreed to the published version of the manuscript.

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