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BIOSYSTEMS ENGINEERING XXX (XXXX) XXX

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/issn/15375110

Special Issue: Intelligent systems for environmental applications

Research Paper

Smart farming IoT platform based on edge and cloud computing

Miguel A. Zamora-Izquierdo [a], *José Santa* [a,*], *Juan A. Martínez* [b], *Vicente Martínez* [c], *Antonio F. Skarmeta* [a]

[a] *Department of Information and Communication Engineering, Computer Science Faculty, University of Murcia, 30100, Murcia, Spain*

[b] *Odin Solutions S.L, C/ Perú, 5, 30820, Alcantarilla, Spain*

[c] *Centro de Edafología y Biología Aplicada del Segura (CEBAS), Consejo Superior de Investigaciones Científicas (CSIC), 30100, Murcia, Spain*

ARTICLE INFO

Article history:
Received 31 January 2018
Received in revised form
27 September 2018
Accepted 26 October 2018
Published online xxx

Keywords:
Precision Agriculture
IoT
Hydroponics
NGSI
Edge Computing
Smart Farming

Precision Agriculture (PA), as the integration of information, communication and control technologies in agriculture, is growing day by day. The Internet of Things (IoT) and cloud computing paradigms offer advances to enhance PA connectivity. Nevertheless, their usage in this field is usually limited to specific scenarios of high cost, and they are not adapted to semi-arid conditions, or do not cover all PA management in an efficient way. For this reason, we propose a flexible platform able to cope with soilless culture needs in full recirculation greenhouses using moderately saline water. It is based on exchangeable low-cost hardware and supported by a three-tier open source software platform at local, edge and cloud planes. At the local plane, Cyber-Physical Systems (CPS) interact with crop devices to gather data and perform real-time atomic control actions. The edge plane of the platform is in charge of monitoring and managing main PA tasks near the access network to increase system reliability against network access failures. Finally, the cloud platform collects current and past records and hosts data analytics modules in a FIWARE deployment. IoT protocols like Message Queue Telemetry Transport (MQTT) or Constrained Application Protocol (CoAP) are used to communicate with CPS, while Next Generation Service Interface (NGSI) is employed for southbound and northbound access to the cloud. The system has been completely instantiated in a real prototype in frames of the EU DrainUse project, allowing the control of a real hydroponic closed system through managing software for final farmers connected to the platform.

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* *Corresponding author*. Fax: +34 868 884151.

E-mail addresses: mzamora@um.es (M.A. Zamora-Izquierdo), josesanta@um.es (J. Santa), jamartinez@odins.es (J.A. Martínez), vicente@cebas.csic.es (V. Martínez), skarmeta@um.es (A.F. Skarmeta).

https://doi.org/10.1016/j.biosystemseng.2018.10.014

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Please cite this article as: Zamora-Izquierdo, M. A et al., Smart farming IoT platform based on edge and cloud computing, *Biosystems Engineering*, https://doi.org/10.1016/j.biosystemseng.2018.10.014

Abbreviations

3G	Third-generation Networks
6LoWPAN	IPv6 over Low power Wireless Personal Area Networks
CoAP	Constrained Application Protocol
CPS	Cyber-Physical Systems
GMS	Global System for Mobile communications
HDFS	Hadoop Distributed File System
IDAS	IoT Device Management Generic Enabler
IoT	Internet of Things
IPv6	Internet Protocol Version 6
JSON	JavaScript Object Notation
LoRa	Long Range
MQTT	Message Queuing Telemetry Transport
NFV	Network Function Virtualisation
NGSI	Next Generation Service Interface
PA	Precision Agriculture
Paas	Platform as a Service
REST	Representational State Transfer
SMS	Short Message Service
VIM	Virtualised Infrastructure Manager
WSN	Wireless Sensor Networks

1. Introduction

New trends in agriculture seek to manage crops in controlled environments such as greenhouses, which enable the recreation of the quasi–optimal parameters that plants need to improve the production or duplicate the environmental conditions of specific geographical areas to locally obtain products that are usually imported. Moreover, severe weather variations that impact on crop production can be avoided with a tight management of temperature, humidity and lighting. Modern agriculture aims at increasing crop yield in terms of production and quality. One of the advances in modern agriculture is the spread of soilless culture Resh (2012), also known as hydroponics, which further increases productivity. However, in comparison to open field vegetable crops, the fertiliser requirements are eight to ten times higher. For this reason, these agricultural systems also require an intense use of water and fertilisers that have to be managed in a efficient way. In open hydroponic systems where drainage is released into the environment, up to 31% of nitrates and a 48% of potassium applied are discharged, implying pollution and eutrophication of land and water. European Union policies try to reduce the environmental costs of intense agriculture through different instruments and directives (Common Agricultural Policy - CAP, Nitrates Directive - 91/676/EEC, Water framework Directive - 2000/60/IEC).

As an alternative to open hydroponic systems, full recirculation systems (also known as closed systems) were initially developed in The Netherlands, but the percentage of producers that use them in their greenhouses in the rest of Europe is very low, mainly because these systems need to be designed and adjusted to the specific conditions where production is taking place. The adoption of re-circulation using moderately saline water, as is the case of Mediterranean areas, requires detailed information of crop response to salinity, in order to optimise management of drainage recirculation. However, one of the main problems of closed recirculating systems is the build-up of salts in the nutrient solution. It is well known that salinity severely limits the productivity of crops and, as a difference from Northern European countries, the electrical conductivity of the water used for irrigation in Mediterranean areas is usually high. In order to avoid discharge of drainage and maintain the electrical conductivity of the nutrient solution at optimal levels for plant growth in these areas, it is necessary to add low conductivity water, which can be obtained from a purification unit based on a reverse osmosis system. However, these sophisticated systems requires high degrees of automation.

In recent years high monitoring and control capacities are obtained in agronomic systems thanks to the use of new information and communication technologies. These combine with industrial automation to enable Precision Agriculture (PA) (Gebbers & Adamchuk, 2010). Current sensors offer highly accurate values of the status of crops, and actuators are able to manage irrigation, change climate factors or enrich the soil with the needed nutrients (Mulla, 2013). When appropriate, computer intelligence techniques are also put into play to further improve production in PA by reducing diseases and the need for human intervention in regular activities. This is a must in extreme PA cases such as the previously discussed hydroponics one, where natural resources of common agriculture are left aside and even more precise control actions must be carried out. Hence, automation is, without doubt, the future of agriculture, but new frameworks improving the modularity of hardware and software units, and assuring the precise management of crops in an efficient way are needed.

Recently the Internet of Things (IoT) has implied the integration of communication capabilities to sensors and actuators (Atzori, Iera, & Morabito, 2010), which is highly relevant in the PA domain (Ray, 2017). Now it is possible to obtain hardware solutions powered with firmware that interconnects these final devices with gateways through wireless channels and using open and/or regulated protocols that avoid proprietary solutions. Wireless sensor networks (WSN) further evolve this with communication topologies that reduce infrastructure costs and reduce power consumption, hence reducing costs in PA exploitation (Riquelme et al., 2009).

These novel sensors and actuators also need evolved automation nodes potentially acting as IoT gateways. Hence, traditional control units installed at the crop side are now considered Cyber-Physical Systems (CPS), involving hardware nodes with computing, storing and communications capabilities to control and interact with industrial processes (An et al., 2016). CPS is now the scientific-agreed term used for networked (distributed) embedded systems to gather data from sensors, communicate with actuators and cooperate among them to cover automation needs.

At the same level of importance as IoT or CPS, cloud computing (Voorsluys, Broberg, & Buyya, 2011) has been the last hit in PA (Choudhary, Jadoun, & Mandoriya, 2016). Here an extra level of flexibility is offered by a remote software platform providing monitoring and control management. These software platforms can be easily extended on demand and avoid the installation of complex systems at the local level. In cloud computing, crop data are gathered through a communication channel offered by local controllers (e.g., CPS nodes) that, additionally, can also allow certain control actions. All data are saved by a software entity usually virtualised in a data centre that offers Platform as a Service (PaaS) resources. The access to crop monitoring and control features is finally offered by web services accessible from a number of platforms, including desktop computers and smart phones.

Lately, a trendy paradigm not exploited in agriculture is fog and edge computing. Traditionally, these paradigms are focused on improving system reaction by reducing network delay, since computing nodes are close to end devices. However, in the PA area, network performance requirements are more relaxed, though a critical issue is the reliability of the channel connecting the crops with the control modules. The solution proposed here is to move part of the data analytics and control features from the cloud to nodes close to end-devices in the network path. This implies a reliable management of CPS actions requiring high accuracy and, additionally, intermediate data filtering capabilities.

In this frame, the solution presented in this paper covers the needs for fully automated PA scenarios including the mentioned special case of Mediterranean areas, through a three-tier open source software platform that distributes computing at CPS, edge and cloud planes, according to the needs of each action. IoT communication technologies are used to connect sensors and actuators with CPS nodes. Here, atomic control actions are executed at CPS level, while greenhouse main control actions are orchestrated by an edge layer composed of four control modules for irrigation, climate, nutrition and auxiliary tasks. They are powered by Network Function Virtualisation (NFV), so they can be instantiated at different nodes along the network path, from the crop to the cloud. IoT communication protocols such as Message Queue Telemetry Transport (MQTT) or Constrained Application Protocol (CoAP) are used to communicate CPS nodes with these subsystems. Finally, the cloud layer is given by a FIWARE middleware that stores, processes and enables management web services for remote monitoring and control. The cloud module of the platform communicates with the rest of system nodes using the Next Generation Service Interface (NGSI), in the form of a southbound NGSI to link with edge subsystems, and a northbound NGSI to allow access to final applications. According to the state of the art presented later, the next novelties are presented in this work:

- Highly-flexible three-tier architecture for PA that fosters software and hardware modularity across the different abstraction levels of the solution.
- An NFV-based solution is proposed in an edge layer to perform local operation decisions in a PA-based environment, which can be deployed opportunistically at different levels of the network.
- Efficient and reliable PA operations are assured through distributing responsibilities between edge and CPS planes, avoiding problems originated from network failures when using a remote cloud control.
- Full instantiation of the proposal with a real field deployment validating the operation of the system in the challenging area of hydroponics.

The structure of the paper is as follows. Section 2 presents the works in the literature that aim at solving the PA problem using new information and communication technologies. The overall proposed platform is described in Section 3, while Section 4 gives details about the FIWARE-based cloud and edge solution. Then, a real prototype of the system is described in Section 5. Section 6 focuses on the real operation of the platform, describing main procedures and including validation results extracted from the prototype. Finally, conclusions and future works are presented in Section 7.

2. State of the art

The first steps in PA were focused on the automatic control of actuators on the basis of sensor data gathered from crops. Usually, in these systems sensors and actuators were wired with an automation node. The control area has evolved gradually, as can be seen in the rule-based scheme presented by Canadas, Sanchez-Molina, Rodriguez, and del Aguila (2017), or the event-driven solution described by Pawlowski, Sanchez-Molina, Guzman, Rodriguez, and Dormido (2017). However, the real advance in the last years in PA has been in the line of integrating new information and communication technologies to support farmers in management and decision making.

The first solutions using communication networks in controlled agriculture were based on common Internet technologies used in common PC applications. Marhaenanto, Soni, and Salokhe (2013), for instance, presented a crop management system that uses remote desktop and regular client/server applications. Another set of proposals in this line are based on using Web connections to directly access crop sensors and control actuation nodes, such as by Bajer and Krejcar (2015). Here, a set of Arduino nodes that are wired with sensors and actuators are managed through the Internet, accessing a Web application available in the firmware.

IoT integration in PA has implied an evolution in the way actuators and sensors communicate with gateway nodes and even the Internet. Regarding communication technologies, new IoT-capable nodes integrate new transceivers able to save energy and create network topologies adapted to field conditions, where cellular or WiFi-like base stations are rare. As the proposal of Akka and Sokullu (2017) shows, multi-hop topologies using wireless sensor networks can allow the routing of data messages through the communication nodes to reach a gateway with Internet connectivity. Here, the ZigBee technology is used, as by Lamprinos and Charalambides (2015), where gathered data is finally accessible through a Web server available in the gateway.

More recent advances in the IoT area include network protocols to connect with remote devices through Internet by using application-level messaging optimised for reducing data rates. S. Muthupavithran, Akash, and Ranjithkumar (2016) used the MQTT protocol to collect data from sensor nodes at greenhouses for monitoring purposes, for instance. These protocols allow the collection and analysis of data at intermediate cloud middleware, as discussed by Shukla, Panchal, and Patel (2015). Kaloxylos et al. (2014) presented a more developed system in this line. Here, data from a real deployment of sensors is gathered by a gateway using ZigBee, and then sent to a data cloud powered by FIWARE through Web-based protocols. The work exploits the idea of open interfaces to create multiple client applications accessing the cloud module. However, IoT protocols are not used and a quite preliminary version of FIWARE is employed. Martinez, Pastor, Alvarez, and Iborra (2016) presented research on the cloud plane to manage crops in PA environments. Here the FIWARE core, together with a set of additional enablers, are used to connect with IoT gateways through several protocols, such as MQTT or CoAP, and current and historical data are maintained in the cloud for analytics purposes. The FIWARE performance is evaluated for PA in terms of a set of synthetic tests, but a real development of the proposal is not given. The same research group have presented (Lopez-Riquelme, Pavon-Pulido, Navarro-Hellin, Soto-Valles, and Torres-Sanchez (2017)) a real system, but it is limited by the technologies and functionalities offered. Data is collected from the crops through a Web-based protocol over GPRS and only monitoring features are included in the system.

An evolution of exclusively cloud-based platforms is the inclusion of intermediary processing stages in the data path. Liu (2016) performed local preprocessing at data collection gateways, before sending monitoring information to the cloud. This idea is further exploited by Ferrandez-Pastor, Garca-Chamizo, Nieto-Hidalgo, Mora-Pascual, and Mora-Martnez (2016), where a set of IoT protocols and technologies are also evaluated in a real hydroponic deployment. However, in these works a lack of flexibility is noticeable in the way edge computing is implemented, and this layer is exclusively oriented to data fusion.

In general, these works in the literature partially cover IoT interconnection, data collection and access through clouds, and only some initial edge computing approaches are found. Realistic systems offering (1) flexibility in the hardware used at crop site, (2) edge computing nodes at which to filter data powered by NFV, and (3) efficient and reliable execution of both sensing and control tasks, are not common in current works. In this line the current paper presents an integral crop management system supporting up-to-date IoT technologies and protocols and supported by FIWARE, which divides essential PA tasks in control modules instantiated in virtualised nodes that orchestrate atomic tasks to be executed at local CPS.

3. System architecture

The overall control architecture of the solution presented to cover PA management needs is depicted in Fig. 1. It is essentially distributed into three main planes: crop (local) CPS tier, edge computing tier, and data analytics and smart management at the cloud. The CPS and cloud planes are designed to be respectively deployed at the local crop premises and remote data servers, respectively. The intermediate layer for edge computing comprises a set of virtualised control modules in the form of NFV nodes that can be instantiated along the network path, from the field facilities to the cloud plane on the Internet. This increases

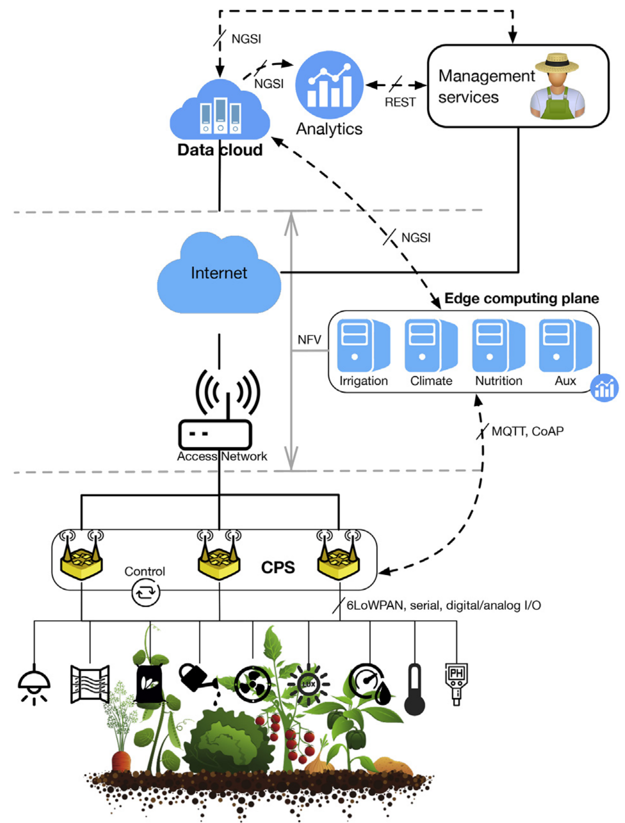

Fig. 1 – Overall architecture of the PA platform. The cloud, edge and CPS planes are separated by dotted lines. The edge computing modules are instantiated as NFV elements, allowing their placement at the most convenient network level.

versatility in the deployment of the solution, at the same time connectivity performances with the CPS layer are met.

At the crop premises, sensors and actuators for PA automation are deployed and connected with CPS nodes. Examples of sensors are solar radiation, humidity, temperature, CO_2, pH meter, electrical conductivity, liquid consumption (flow meters) or pressure sensors, while some of the actuators considered are soil and water nutrition pumps, valves and activation of devices (watering and ventilation devices, lighting, or automated windows). These are connected with CPS units through wired channels using industrial serial (usually RS485) or direct digital/analogue I/O connections. For wireless communications, 6LowPAN is used to connect with dataloggers, which include several sensors.

All the CPS units are interconnected with the Internet through an access network using multiple technologies, such as microwave radio links, fibre optic or DSL. In this architecture, low level operations that require minimum latency and high reliability in the communication with sensors or actuators are executed at CPS nodes. These are considered as atomic actions, such as closing a window, execute an irrigation mandate for a period of time or ventilating until a CO2 level is reached. Additionally, there are emergency reactive actions locally implemented in the CPS nodes that require real-time operation and can be launched without the human or edge plane supervision. An example of these are the opening of windows and turning on ventilation if the greenhouse inner temperature reaches a predefined threshold.

The second processing and managing level of the layered architecture is the edge computing plane, which includes a set of NFV-powered control modules in charge of orchestrating the CPS layer. The subsystems of the edge layer make up the main operative control of the greenhouse and they are in charge of irrigation, climate, nutrition and auxiliary tasks, including alarms and energy management. At this layer, data fusion and aggregation is carried out to offload analytics functions usually performed in the cloud, given that the cloud part of the platform could serve a multitude of crops and users. The edge control modules are virtualised through NFV techniques that allow their instantiation at different levels in the network path, and they communicate with CPS nodes using IoT communication protocols such as MQTT or CoAP. MQTT is especially considered, given that it is more addressed to the management of industrial processes, however, CoAP is also supported for particular non-critical monitoring tasks not involving control.

As depicted in Fig. 1, the data cloud serves as the interface between users and the core platform. Here is where the current status of the crop and configuration parameters are maintained. The NGSI interface is used to send data updates and receive notifications upon data changes. A change in configuration parameters triggers control actions that are managed by edge subsystems. Moreover, as can be seen in the diagram, special analytics coupled with concrete service needs are performed using the cloud as data source. For the communication between final applications and the analytics module, a REST interface transporting JSON data is used.

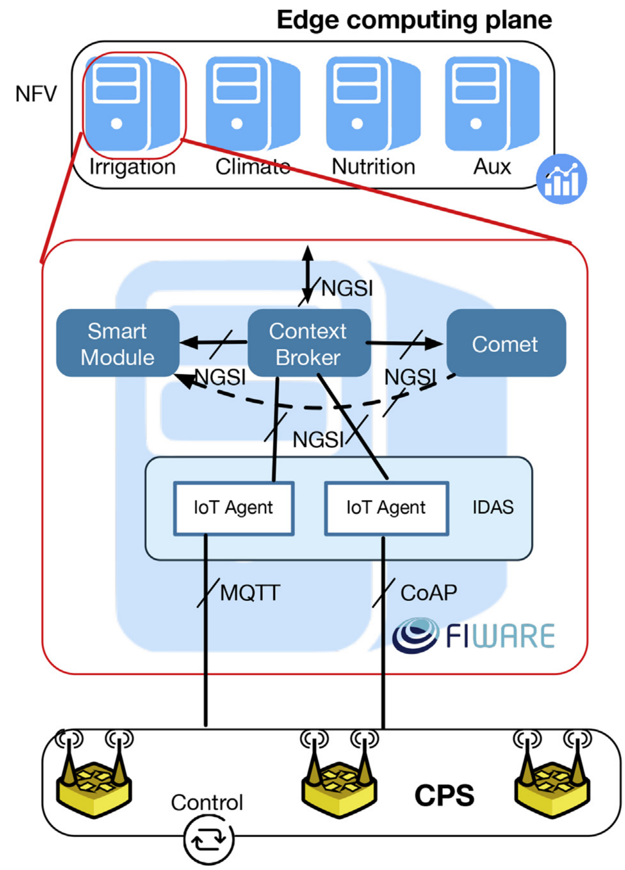

Fig. 2 – Edge computing plane. Each NFV-based control module is instantiated as a compact FIWARE domain that interconnects the cloud and CPS planes, and performs smart control actions offloading the cloud and providing extra reliability.

4. FIWARE-based cloud and edge solution

Here we present the details of the cloud and edge planes of the instantiated architecture. We have used the FIWARE platform to provide the main software modules. In our particular case, the ORION Context Broker[1] is chosen to provide access to the greenhouse status information stored in it, providing different methods to register/update, request and subscribe for certain data records; Comet[2] is included to provide persistence to the data; and the IoT Device Management Generic Enabler (IDAS) is chosen to connect with IoT devices.

This section discussed how FIWARE is used at edge and cloud layers of the architecture illustrated in Fig. 1.

4.1. *Edge computing plane*

The edge computing plane can be deployed according to the features and requirements of the target PA scenario. This way, it is possible to move the edge computing plane next to the cloud or, by contrast, to instantiate this logic next to the local deployment. This can be done thanks to virtualisation.

Control modules in the edge plane are developed as NFV nodes, which allows us to easily move the components according to the aforementioned requirements. For this reason, each control module provided by our solution is instantiated in a specific virtualised image that is launched opportunistically depending on the scenario requirement. Images are hosted by a Virtualized Infrastructure Manager (VIM) that allows remote management through a proper API.

As depicted in Fig. 2, each control module comprises a Context Broker, two IoT Agents of the IDAS GE for CoAP and MQTT communications, and the Comet GE provides persistence to the data. Hence, each IoT Agent acts as intermediary between the information provided by the CPS layer and the Context Broker. Additionally, a specific software entity (Smart Module in the figure) is responsible for managing the tasks related to the specific control module.

For the case of the MQTT support, the MQTT IoT Agent acts as broker to provide the meeting point of the publish/subscribe scheme to allow communications with CPSs. We have defined the next MQTT topics (the notation is simplified for the sake of clarity, but details can be found in the IoT Agent Step by Step guide[3]):

[1] https://fiware-orion.readthedocs.io.
[2] https://fiware-sth-comet.readthedocs.io/.
[3] https://github.com/telefonicaid/iotagent-json/blob/master/docs/stepbystep.md.

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- *CPS1*, *CPS2*, … *CPSn*: a specific topic is created for each of the CPSs instantiated in our platform, where the corresponding CPS is configured as publisher and the control modules at the edge plane are set as subscribers.
- *Irrigation*, *Nutrition*, *Climate* and *Aux*: one topic is created for each control module virtualised in our architecture. This way, they can manage the CPSs involved in their activities by sending concrete instructions. Hence, each control module is configured as publisher for its corresponding topic, and the CPSs are configured as subscriber for each of them.

By using a Context Broker per control module, we can perform edge computing tasks without accessing the cloud plane. In the concrete case illustrated in Fig. 2, for instance, the software unit in charge of irrigation intelligence is subscribed to the information of interest in the local Context Broker, being notified this way with changes received from the related CPS, including soil moisture and temperature, among others. In the same way, each of the decisions made by the smart module provokes changes in data records within the Context Broker, which in turn generates the publication of MQTT requests through the IoT Agent that finally reaches the related CPS.

4.2. *Cloud plane*

Computer intensive tasks or those requiring a global view are undertaken at the elements deployed into the Cloud plane, which have been also virtualised in high-end servers.

Figure 3 describe all the functionality provided by the cloud plane. Again, an instance of the Context Broker is used to maintain data records and handle NGSI interfaces. As a difference from the Context Broker instances included at the edge plane, the one included here maintains high-level data records about the status of the crop, including also filtered or preprocessed values coming from the edge level. An NGSI subscription is maintained by a Comet instance to save historical data, and another one is used to feed Big Data routines. Final management services interact with these two components in order to obtain all needed information to perform final decisions that are supervised by human operators.

Data analytics are enabled by a distributed file-system that saves information among several machines. We have employed the Hadoop Distributed File System (HDFS) for this purpose. Another FIWARE enabler called Cygnus is in charge of taking data records from the Context Broker and saving them in Hadoop. Finally, our data analytics component will compute all the reasoning processes to assist decisions to be carried out by management services.

5. Prototype

The target greenhouse of the system is the Experimental Greenhouse of CEBAS-CSIC illustrated in Fig. 4, a governmental research facility in Murcia, south-east of Spain, with geographical coordinates 38.1079837° N, −1.0355991° E and 120 m of elevation. It has a surface of 462.5 m^2 (25 m × 18.5 m) and is between 5 and 7.5 m in height. Beside the greenhouse,

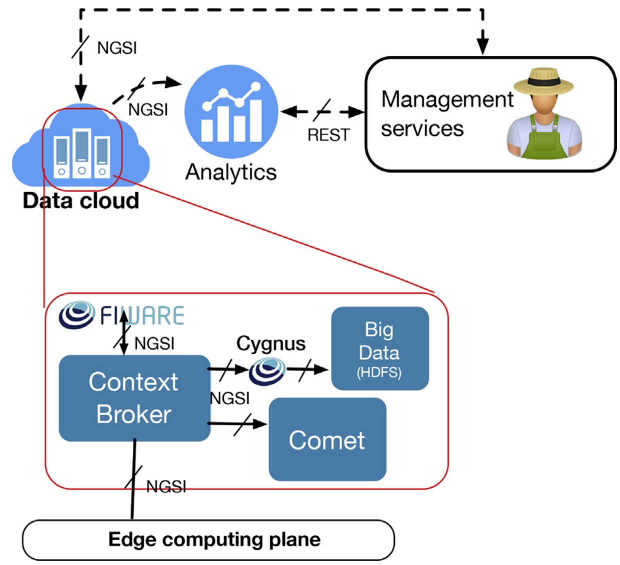

Fig. 3 – Cloud computing plane. A virtual representation of the greenhouse state is maintained in a high-end FIWARE deployment, which is complemented with Big Data analytics to better support the human intervention.

we have built a room of 60 m^2 for the machinery and control systems.

Plants of tomato (Solanum lycopersicum) are selected for the pilot system, one of the most economically important and extended crops in south Europe. Tomato is produced in 38% of the European greenhouse surface, so this prototype is potentially extensible to many other greenhouses. However, thanks to the flexibility of the solution proposed, it can be easily deployed for other crop species. Additionally, the software in charge of formulating the nutrient solutions, can be easily adapted to the nutritional needs of other crops.

The tomatoes were transplanted in a soilless system in a first cycle on 17th October 2016 and were harvested on 26th may 2017 (7 months). Plants were grown in 19 rows, 54 plants

Fig. 4 – View of the interior of the greenhouse. The growing rows and the raffia thread to maintain the tomato plants are visible in the main view, while the humidifier module and climate sensors are shown in the small photo.

per row, and they were guided with raffia thread to conduce the plant growth. A second cycle was carried out between 7th June 2017 and 30th November 2017, but this time reducing the number of plants to 486. The plants were grown in the greenhouse under controlled conditions of temperature, humidity and irrigation. The maximum temperature was established to 27°C and the reference humidity was 60%. The plants were daily irrigated with a nutrient solution containing $Ca(NO_3)_2$, KNO_3, $MgSO_4$, KH_2PO_4, Fe and micro-nutrients. Drainage volume, pH and electrical conductivity in the greenhouse is daily controlled too. The mineral composition (anions and cations) and microbiological control of the irrigation nutrient solution and drainage are analysed weekly, to ensure that the calibration of the software is correct.

Since the idea is to design a system suitable for Mediterranean crops, the substrate used in the demonstration is coco peat, which is a challenging material regarding turbidity of the drainage and the microbial content.

In the following subsections, we describe the main parts of the greenhouse facilities and the deployment of computing nodes to deal with edge and cloud planes of the architecture.

5.1. *Greenhouse facilities*

The greenhouse has a set of equipment mainly deployed inside a machinery room beside the crop. These facilities are composed of several hardware units described in the following subsections, and all of them are managed by our three-tier control system, whose particular implementation is also detailed.

5.1.1. *Nutrient solution unit*

The nutrient solution unit is where all nutrients needed for optimal plant growth are mixed, and it is controlled by a CPS and finally orchestrated by the edge computing nutrition control module. This unit consists of five fertilisers tanks and one acid tank used to adjust pH. All of them with a volume of 500 l. The unit provides the crops rhizosphere with the 12 essential elements to complete their life cycle: nitrogen, sulphur, phosphorus, calcium, potassium, iron, copper, manganese, boron, zinc, molybdenum.

As detailed in Fig. 5, the content of these six tanks are mixed with the disinfected drainages, tap water and high quality water from the osmosis system, to prepare a nutrient solution in the nutritive solution tank of 3000 l. For this, we have installed magnetic pumps for each fertiliser, level sensors for the tanks, electrical valves, flow meters, and an electromechanical stirrer in the main tank. The nutrition control module (edge computing layer) controls the nutrient solution based on the electrical conductivity, pH and temperature measured on the impulsion pipe of the pump, which finally irrigates the crop, taking the nutrient solution from the tank.

5.1.2. *Irrigation unit*

Three intermediate tanks are used to work with different nutrient solutions to make easier the experiments, as can be seen in Fig. 5. The solution to be used is pumped to irrigate the crop during 5 min and several times, with an estimated flow of 3000 $l\,h^{-1}$. Irrigation and drainage flows are measured by flow meters that provide digital inputs to the CPS calibrated to 1 $pulse = 0.1l$. The whole process is controlled by the irrigation control module in the edge computing layer. Untreated drainage water is collected in a tank with a capacity of 1000 l, which is later pumped and pre-filtered to remove impurities of every nature and consistency.

5.1.3. *Disinfection unit*

The filtered water is conducted through the disinfection unit (lower part of Fig. 5), which was initially based on ultraviolet treatment to reduce or eliminate microbial content, and thus reduce the appearance of diseases. Lately the system has been replaced by another unit based on a reactor of electrolysis, which has shown to be more effective, as the results presented in Section 6.2 indicate.

A precise dimensioning of the process using our system allows the totally effective treatment of illnesses that are transmitted by water pathogens. This unit is able to treat a maximum of 200 $l\,h^{-1}$ of drainage.

The disinfected water is stored in a 5000 l tank with control level, where it is analysed. The electrical conductivity, pH and temperature are measured on the impulsion pipe of the pump, which sends back the water to the main nutritive solution tank. The whole process is controlled by a CPS, following the parameters indicated by the nutrition control module in the edge layer.

5.1.4. *Purification unit*

The system has a purification unit with a reverse osmosis equipment that transforms tap water into low electrical conductivity water that can be mixed with drainages and tap water to prepare final nutrient solutions. The pilot has a purification unit able to generate 100 $l\,h^{-1}$ of low electric conductivity in a 5000 l tank, together with a flow meter, valves and pump needed to inject the water, which are connected with a CPS and controlled by the nutrition control module in the edge layer.

5.1.5. *Climate unit*

The greenhouse has an IPv6 over Low power Wireless Personal Area Network (6LoWPAN) deployment, where sensors are directly interconnected using Internet protocols, to measure the temperature, humidity, solar radiation and CO2. A CPS device is provided with peripherals dedicated to manage the different climatic devices.

Although the platform is capable of managing up to thirteen climatic systems, the physical facilities of the prototype greenhouse has currently the following hardware:

- Ventilation system with four overhead motorised windows.
- Thermal-shade screen system on the roof, with an electro-mechanical traction system for opening and closing. It gets 48% of shadow and 55% of energy saving.
- Air cooling system, which consists of a humidifier module and three helical extractors. The extractors have a flow of 38,000 $m^3\ h^{-1}$.
- Air fog system, used to humidify and cool the greenhouse through water evaporation. It has a pressure pump of 1 HP and 25 l, and an air compressor of 4 HP and 50 l.

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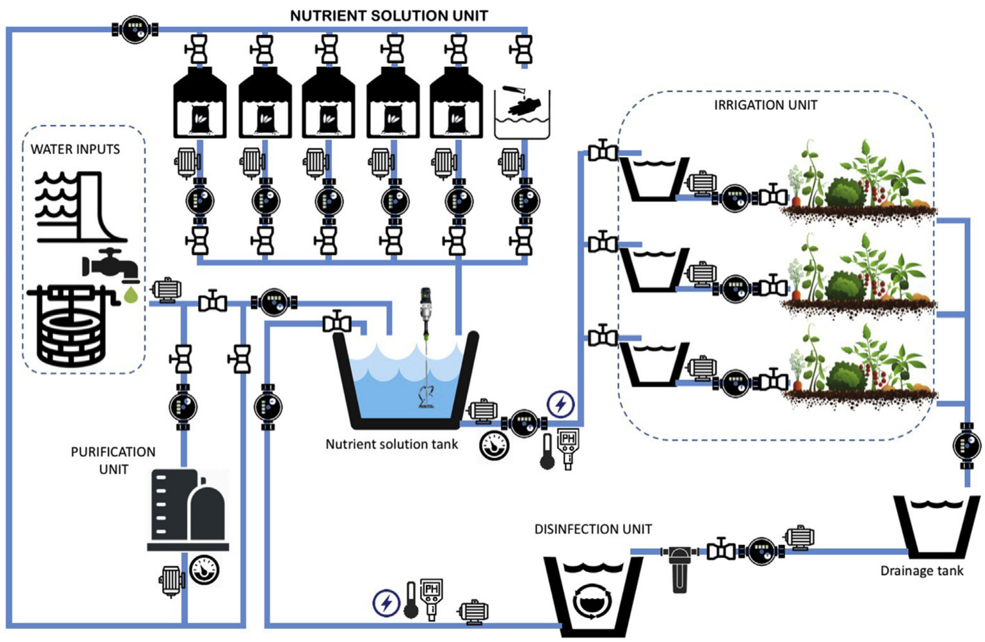

Fig. 5 – Water cycle for nutrition and irrigation in the greenhouse. Low quantities of water and nutrients are needed thanks to a complete automated system that adapts nutrition according to a formula tuned at the cloud plane and executed by edge control modules.

Table 1 – Sensors used in the prototype greenhouse, including relevant data (details available in data sheets).

Sensor	Model	Main features
Temperature/Humidity	E + E Elektronik EE160	Hum. sensor HCT01-00D Accuracy ±2.5% Temp. sensor PT1000 Accuracy ±3°
Electrical conductivity	B&C Electronics 2731312-31/3-017T	Range 0–5000 $\mu S \ \ cm^{-1}$ Max. temp. 80° Max. press. 10 bar at 20°
pH	B&C Electronics SZ 1093	Range 0–13 pH Max. temp. 80° Max. press. 7 bar
Level controller	Omron K8AK-LS1	Control output: relay 5A/240V_{AC} Max. temp. 50°
Liquid counter	ARAD SF 15	Resolution 1 pulse per l Max. press. 5 bar Max. temp. 60°
Flow meter	Gems FT110 G3/8	Resolution 1 pulse per ml Max. press. 14 bar Accuracy ±3%
Solar radiation	Apogee Instruments Inc. SP110	Sensitivity 0.2 mV per W m^{-2} Accuracy ±5%

- Heating system with a 100,000 kcal boiler, a stainless steel heat exchanger and 1 HP pumps for three distribution units.

A broad range of sensors from the market were considered to fulfil the operation and environmental requirements of the platform. They were studied within the DrainUse project[4] attending to the functionality provided and cost, and the finally selected ones are included in Table 1, indicating the model and main operation features. The operation of these sensors have been validated through the two cycles of tomato crop, presenting correct reads after the initial calibration procedure carried out in the CPS and 6LoWPAN logger.

5.2. *Control of the greenhouse*

Main operation tasks are programmed and supervised by humans using the management services when required, with the intelligent support provided by data analytics. New high-level configuration parameters in the cloud Context Broker trigger notifications and changes in the Context Broker of edge control modules, which in turn are in charge of managing the

[4] Life DrainUse project:www.drainuse.eu.

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operation of the individual greenhouse areas through mandating their corresponding CPSs.

5.2.1. *CPS deployment*

Each control module in the edge computing plane has been initially assigned with a master CPS unit, resulting in a fully distributed system. The nutrition master CPS unit is in charge of controlling the nutrient solution, disinfection and purification hardware units, that is, the complete water cycle except for the irrigation action itself, which is carried out by a separate master CPS unit (and edge computing module). Unlike many commercial fertigation systems, we have decided to separate irrigation from nutrition control in order to have more flexibility to implement intelligent irrigation programs, apart from simply considering time and volume. Finally, the climate hardware unit is managed by the corresponding master CPS unit and control module. The three master CPS nodes (and edge control modules) are complemented by an auxiliary CPS and control module in charge of energy monitoring, alarms management and other auxiliary tasks as access control.

Concrete implementations of emergency procedures in the auxiliary CPS include the described high temperature case, but also the lack of enough water flow from input pipes and additional support for energy cuts. In the first case, the human operator is warned of the water flow problem by the application described in Section 5.2.3, using the regular communication channel through the edge and cloud planes. However, to cover power cuts, the auxiliary CPS is equipped with a GSM modem and a backup battery to warn a human technician with an SMS message. The contact number can be configured in the user application described later.

The master CPS consists of an IPex16 controller from Odin Solutions (OdinS), which is shown in Fig. 6, with a 32-bit CPU, 4 MB of memory expandable with microSD, Ethernet, USB, CAN, 3xRS232, 1xRS485 and 16 I/O ports, which can be configured by software as digital or analogue input/outputs. It supports 3G, 6LowPAN, Sigfox and LoRA. Each master CPS is able to manage eight additional slave I/O boards using CAN. The configuration of the controllers is done easily through its web server, and it permits us to configure atomic reactive (high priority) tasks independently from the MQTT commands received from the edge computing layer. In our case the

Fig. 6 – CPS hardware considered in the deployment. The IPex16 controller has been used due to their capabilities and flexible configuration.

Fig. 7 – Electrical panels installed at the crops, where CPS units are installed with a proper power source inside a machinery room built next to the greenhouse.

communication of the CPSs with the network is through LAN. The communication among master and slave CPS nodes is done through CAN bus, allowing distances up to 1 km. This permits to distribute CPSs along the facilities.

Both master and slave CPS nodes are installed in the separated electrical panels showed in Fig. 7. A fifth electrical panel contains the power meters of the installation. Figure 8 presents a diagram with the connection of different sensors with an IPex16-based CPS unit, indicating as well the MQTT protocol they use to communicate with the edge layer. As it depicts, both sensors and actuators use direct I/O lines for connection. Thus, by configuring analogue inputs, e.g., measurements such as temperature, humidity or pH can be transmitted from the sensor to the corresponding edge control module. Digital inputs are used for counters and, digital outputs are used to actuate over the elements of the greenhouse. Remote sensors that cannot be easily wired with the CPS are interconnected with 6LoWPAN.

The prototype system has 134 I/O wired signals distributed among all IPex16-based CPSs, and also some wireless signals using 6LowPAN. Most of the data collected come from wired digital outputs to solenoid valves, pumps, other motors (p.e. windows, screens systems) and analogue inputs from sensors (temperature, humidity, radiation, CO2, etc.). We also have a set of digital inputs from the different flow meters (liquids consumption). Sensors interconnected through 6LoWPAN are wired with Mex06 data loggers from OdinS, which are low-power devices especially prepared for remote control and monitoring. They include a 16-bit CPU, 4 MB of memory expandable with microSD, 1xRS232, 1xSDI-12 and, what is of relevance, 1xRF 802.15.4 g over which 6LowPAN operates. Mex06 loggers are especially designed for outdoor settings such as the agricultural scenarios, since it is provided with a water and dust-proof enclosure. It is prepared to be provided with a battery and a solar panel. The operation of these units have been validated connecting sensors deployed along the crop: temperature, humidity and solar radiation.

Both IPex16 (CPS) and Mex06 (wireless data logger), have been adapted by OdinS within the DrainUse project. Hence, the firmware of theses units have been improved as a result of this research to serve as generic-purpose MQTT units for high-precision automation environments.

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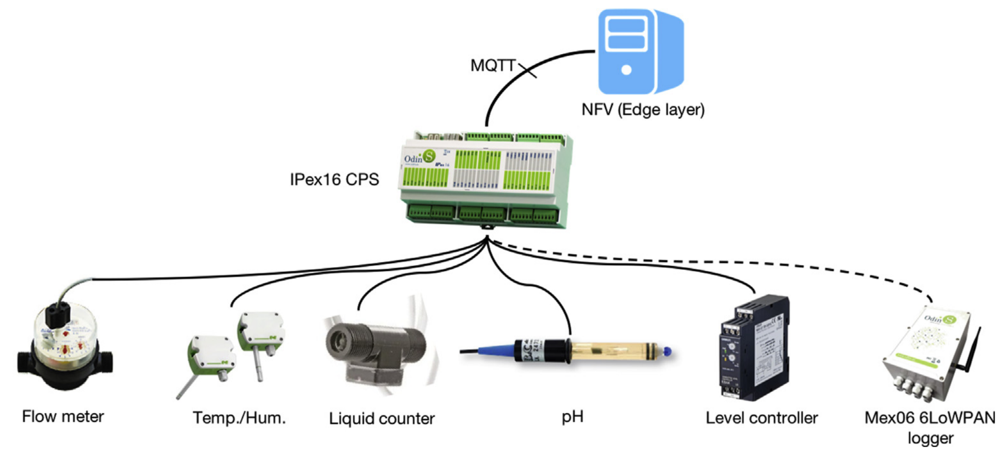

Fig. 8 – Interconnection of the edge layer with sensors through the IPex16 CPS unit.

5.2.2. *Deployment of computing nodes*

In the current deployment, edge control modules are virtualised in a local server installed at the crop premises, while the cloud plane is set-up in a high-end server at the Computer Science Faculty (University of Murcia).

Within the machinery room (beside the greenhouse) we have installed a common computer with PC architecture. It is comprised by an Intel Core i5-7400 CPU (3.00 GHz and Quad Core architecture), 16 GB of RAM and a hard disk of 1 TB. The computer runs Centos 7, and LibVirt/KVM is used to create four virtual machines, one per control module. Virtual machines are provided with 4 GB of RAM and 50 GB of hard disk capacity. This is enough to run the local Context Broker instances, which deals with only a part of the system, save data, and execute IoT agents.

The cloud server is a PowerEdge R200, with an Intel Xeon x3360 (2.83 GHz and Quad Core architecture), 32 GB of RAM and two hard disks of 500 GB each. It also runs Centos 7 and LibVirt/KVM. A single virtual machine is used here for the global Context Broker, data saving, Big Data processes and to host management with web services. The virtual machine uses 16 GB of memory and 200 GB of hard disk capacity. Good performances are obtained at the moment, but given the flexibility of our architecture, more resources could be added by modifying or moving virtual images.

The Context Broker version used has been Orion 1.7.0, which is supported by Comet release 6. Exclusively for the cloud computing plane, it is also used Cygnus 1.0 and Hadoop 2.8.

5.2.3. *User management service*

Regarding the management services identified in Fig. 3, we have developed a set of web services in HTML5 with a friendly graphical view to monitor and control the main functions of the system. Figure 9 includes a screen shot of the application area to manage climate. The view in the image includes tools to monitor the status of the climatic equipment of the greenhouse. Green-shaded parts indicate that these modules are active, such as the air-fog system, ventilation and cooling. Current values for temperature, humidity, radiation and air quality are also displayed. Usually all the greenhouse facilities are automatically managed by edge control modules

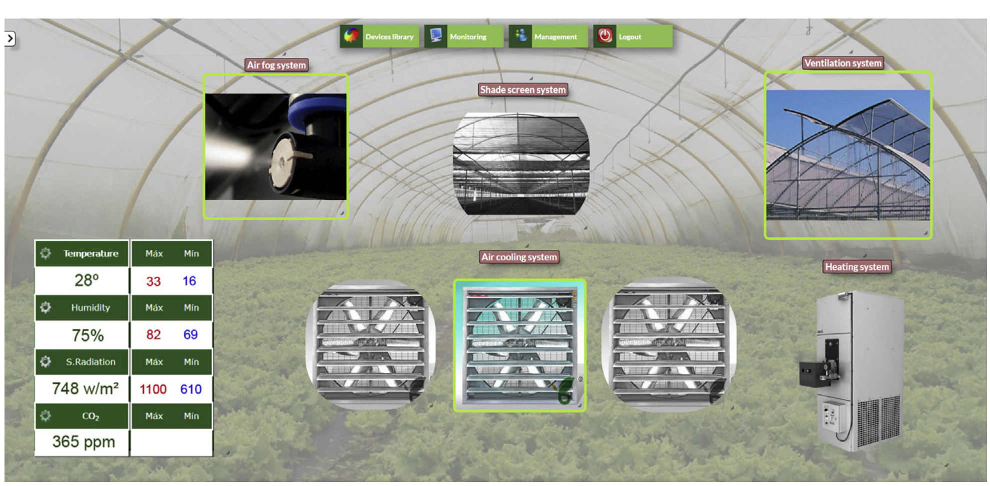

Fig. 9 – Greenhouse control service powered by HTML5, where the human operator can monitor the status of the greenhouse and set the main configuration parameters. Additionally, it allows the manual operation of individual automated modules at the greenhouse.

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according to general configuration parameters dictated at the cloud plane, by using this application. In this software it is possible to set the range of climatic parameters, or the base components of the nutrition solution, among others. Manual management of greenhouse facilities is also possible providing the required credentials.

6. System operation

This section describes the validation of the architecture and prototype from two different perspectives. First, an operation example with a real task is described attending to the three tiers of the architecture, with the aim of clarifying the function of each part of the system. Second, the platform is used in two cycles of a real crop and main results are analysed.

6.1. *Reference operation example*

Given that the nutrition management is the most interesting operation from the PA point of view, here we include a complete description of the tasks carried out to actuate on the greenhouse and assure a proper irrigation with fertilisers. The explanation is split into the cloud, edge and CPS planes, following the sequence of tasks executed.

6.1.1. *Cloud level*

In this layer, on the basis of a nutrient percentage table, the nutrition recipe (mixture) is calculated “theoretically” (there are no physical actions). To do this, a set of calculations assure that a final set of volumes of water sources and fertilisers comply with the plant needs. The steps are:

1. The first time the software presented in Section 5.2.3 is used, the following parameters must be defined:
   (a) Available fertilisers in the facilities.
   (b) Water components based on analysis carried out beforehand in laboratory of each external water source.
2. For a new nutrition mixture the next parameters are defined:
   (a) Volume of the mixture.
   (b) Nutrient percentage table with the cations–anions equilibrium concentration.
   (c) Selection of the fertiliser cubes and water sources from the list of available ones.
   (d) Target irrigation tank.
   (e) Desired pH and maximum electrical conductivity (ECmax).
3. Calculate the volume of different waters to be used so that ECmax is not exceeded, maximising the use of drainage water and reducing the cost of the mixture.
4. Compensate the excess of nutrients with a dilution recalculating the volumes of waters. The excess of nutrients are due to the already provided nutrients in the waters used.
5. Recalculate the mixture electrical conductivity considering the missing nutrients to be added. If ECmax is exceeded, a new dilution is needed in the previous step.
6 Add the missing nutrients

As a result, the volumes of different water sources and fertilisers are sent to the edge level, together with the target pH and irrigation tank.

6.1.2. *Edge level*

This layer is in charge of creating the mixture transmitted from the cloud level by orchestrating the greenhouse equipment (valves, pumps, sensor readings, etc). Hence, after receiving the different volumes it generates a complete set of operations to create the mixture. To do so, the next steps are followed:

1. Sequential discharge of waters in the nutritive solution tank.
2. Agitator activation.
3. Sequential discharge of fertilisers in the nutritive solution tank.
4. Water recirculation through a pipe with sensors, to analyse the resulting mixture.
5. pH adjustment by discharges from the acid tank.
6. Pouring into the irrigation tank selected.
7. Cleaning the nutritive solution tank using purified water.

After these steps have taken place, a set of atomic tasks are generated and transferred to the CPS level. For instance, for the first point, the sequential discharge of waters will be decomposed in atomic operations where a specific digital output is activated until the required volume is discharged. During all this process, the CPS will provide updated information by notifying its new status thanks to the MQTT protocol. Only after validating the received information, the next step will take place following the same procedure. Hence, each control module in the edge layer is responsible for orchestrating and managing the operations that are executed by the CPS level by sending atomic operations and by subscribing to the MQTT topics where the information coming from the CPS nodes will be published.

6.1.3. *CPS level*

This control layer executes the atomic tasks received from the edge layer. CPS nodes are in charge of executing sensor readings and control loops, sending these data to the edge layer by using the appropriate topics of the MQTT protocol. In this sense, no other complex logic is executed at this level, searching for the robustness in this part of the platform.

Table 2 – Main numbers of the first and second cycle of the tomato crop managed by the PA system.

	First cycle	Second cycle
Period	17/10/2016–26/05/2017	07/06/2017–30/11/2017
Number of plants	1026	486
Plants per m^2	2.2	1.2
Plants per ha	21.829	10.340
Total production (kg)	3056	3596
Fruit per plant (kg)	3.0	7.4
Fruit per ha (kg)	65.037	76.511
Revenue (€ha^{-1})	58.533	68.860

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Table 3 – Comparison between open water cycle (OC) and close water cycle (CC) in terms of water and macronutrient consumption in the two crop cycles.

Water consumption	First crop cycle			Second crop cycle		
	CC	OP	Saving	CC	OP	Saving
Total consumption (l)	118,605	195,647	39%	100,947	140,000	28%
Per plant (l $plant^{-1}$)	115	190	39%	207.7	288	28%
Per fruit (l kg^{-1})	39	64	39%	28	39	28%
Per area (l ha^{-1})	2523	4162	39%	2148	2979	28%
Nutrient consumption						
KNO_3 (kg)	31	121.73	75%	39.6	95	58%
NH_4NO_3 (kg)	3.1	15.67	80%	6.48	11	41%
$Ca(NO_3)_2$ (kg)	73	81.19	9%	41.36	61	32%
KH_2PO_4 (kg)	23.5	26.6	11%	12.59	19	34%
$MgSO_4$ (kg)	25	0	–	–	–	–
Micronutrients/Fe (kg)	2.6	4	35%	2.75	2.9	5%

Examples of task executed in CPSs are the next ones:

- *Set DO1* $=$ *ON/OFF*. Activate/deactivate a digital output, such as a valve, pump, etc.
- *Set DO2* $=$ *ON while Counter1* $=$ 1500. This is also an atomic task with a control loop, which can be used to activate a valve associated to a flow meter (irrigation by volume).
- *Get AI1*. Analogue sensor reading for a defined sample time.

As previously indicated, the auxiliary CPS also includes emergency procedures to perform reactive local tasks without supervision. Some examples are:

- Send SMS messages when a power cut is detected. The auxiliary CPS has a backup battery and a GSM modem to send these messages.
- Send SMS messages when a lack of water supply from input pipes is detected.
- Close the valves of water supply when the water consumption exceeds a threshold and send an SMS message. Probably the pipe circuit of the greenhouse is damaged.
- Take reactive actions in case of adverse climatic conditions for the plants, such as opening windows or switching on ventilation.

6.2. *System validation*

We have collected agronomic results of two cycles of the tomato crop. In the last cycle we decided to reduce the plan density to increase ventilation and lighting. The main figures of merit are included in Table 2, attending the production per m^2, ha and the total production in kg. The revenue in market price is also included at the end.

The results indicate that, although the number of plants is lower in the second cycle, the total production has been even better than in the first cycle. This fact is clearly visible in the amount of fruit per plant. This improvement has been possible thanks to the reduction of the plant density, as said above, but also because of the lack of diseases, since the new disinfection unit based on a reactor of electrolysis has been more effective.

Data obtained with the closed-loop hydroponic system (real data) have been compared with the needs of a regular open-cycle crop (estimation). The main comparative indicators for the two cycles of the crop are included in Table 3, including real and estimated values. To obtain the estimated data of water consumed in open cycle, we have assumed that the total water spent on irrigation (195,647 l and 140,000 l) would come from tap water to prepare the nutrient solution. The estimation of these volumes assume that the percentage of drainage reused in the close water cycle is added as new water in this case. The nutrients used in the open cycle are estimated following the same approach, considering that the new water needs extra nutrients as compared with the water gathered from drainages in the close cycle.

As can be seen in the results included in Table 3, the closed cycle represents a significant economic saving in the volume of water for irrigation, since the greenhouse is reusing 39% and 28% of the total water needed in the first and second crop cycles, respectively. The closed cycle has also meant a significant saving in the amount of fertilisers used in the nutrient solution. The differences in water savings between crop cycles are due to the crop periods, since the second one was carried out during summer and the plants require more water. Nutrient consumption also vary due to this fact, but also because of a variation in the water used and a better adaptation of the nutrients to the plant in the second cycle.

From the results it can be said that good production levels have been obtained, at the same time water and nutrient consumption maintain clearly below the needs of regular open crops. And this has been obtained even with the target of validating the PA operation, with no especial focus on maximising revenues.

There are important lessons learned after these two crop cycles. Attending to the hardware deployment, it has been relevant how well flow meters measure water intakes and detect circuit anomalies due to obstructions. Regarding the overall architecture of the control system, it is important to indicate that our initial conception was a static solution based on a single CPS acting as master unit, with several slave boards. This approach is similar to commercial turnkey systems available in the market, where the whole management is centralised on a controller or computer. These greenhouse control systems tend to be robust and also allow Internet

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access, but we experienced the lack of modularity, delocalisation and, above all, the lack of the flexibility provided by virtualisation. Flexibility is, in fact, particularly relevant when inserting extra services or moving the control functions to an evolved hardware. For this reason, our three-tier control system aims at a modular turnkey system, reducing engineering time in setting-up and maintenance.

7. Conclusions

The work presented in the paper describes the design, development and evaluation of a system that covers extreme PA requirements by using automation, IoT technologies, and edge and cloud computing through virtualisation. A multi-tier platform has been developed, based on: (1) a CPS local layer connected with greenhouse facilities; (2) a novel edge computing plane where to insert control modules in virtualised nodes near the access network; and (3) a cloud segment provided with higher computing and data analytics resources to support crop management decisions. Cloud and edge planes are powered by FIWARE, including the use of regulated data formats and network interfaces, and a proper connection with local and global data analytics modules has been developed. The edge plane is powered with NFV technology to increase flexibility in deploying control modules. When deployed under the access network, higher levels of system reliability are reached, since sporadic network cuts do not affect control decisions.

The whole system has been implemented in a real greenhouse in the south-east of Spain, including details about the main functional units that are controlled by our PA management platform. Moreover, two cycles of tomato crop have been used to, first, validate of the good operation of the architecture and, second, analyse the improvements of our system as compared with a regular open crop. Savings of more than 30% in water consumption have been obtained, which is highly relevant in our semi-arid area, and up to 80% in some nutrients.

As a relevant future result, we are currently porting the platform to a urban farming setting in frames of the HIDROLEAF project. In this environment we make use of intermodal containers to create portable crops. This implies extreme climatic environments that makes the most of our PA platform. Moreover, we expect to continue evaluating the system in future crop cycles to further improve operations and adapt our decision support capabilities finally offered as management services to human operators.

Acknowledgements

This work has been sponsored by the Spanish Ministry of Economy and Competitiveness, through the HIDROLEAF project (ref. RTC-2016-4827-2) and the Torres Quevedo program (grant TQ-15-08073), and the European Commission, through the DrainUse (ref. LIFE14 ENV/ES/000538) and ANASTACIA (contract 731558) projects. The authors would also like to thank the colleagues from OdinS company for their support in the prototype deployment.

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