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Smart Environments Design on Industrial Automated Greenhouses †

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† Presented at the 13th International Conference on Ubiquitous Computing and Ambient Intelligence UCAmI 2019, Toledo, Spain, 2–5 December 2019.

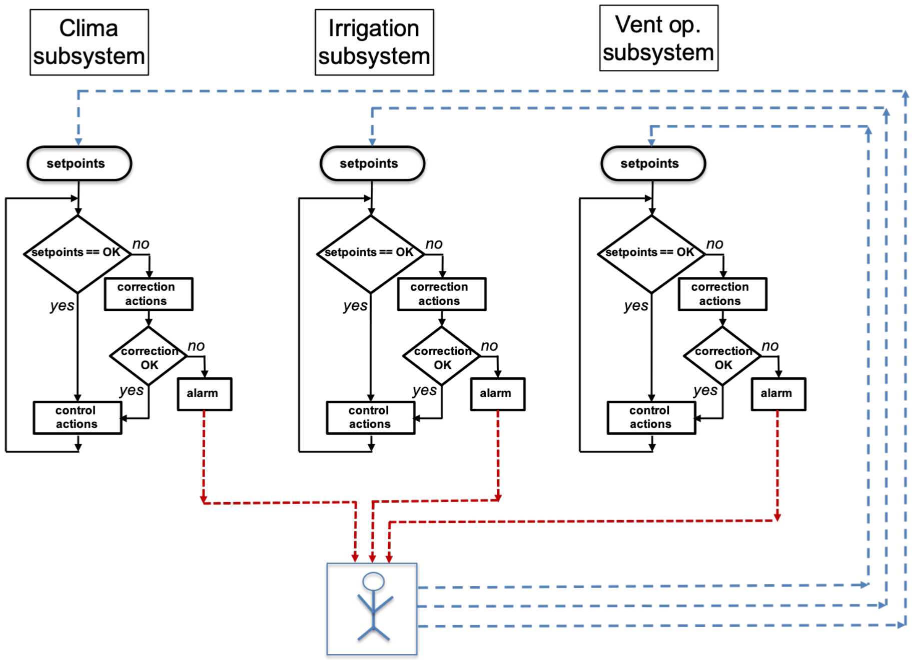
Published: 20 November 2019

Abstract: Greenhouse automation carried out with monitoring and control technologies optimizes the cultivation processes in industrial scenarios. In recent years, new trends and technologies have emerged in the agricultural sector. The application of Information and Communication Technologies has clear benefits. Embedded hardware systems development, new communication protocols over the Internet and applied Artificial Intelligence paradigms have increased the services' capabilities. These technologies can be installed both in new facilities and in facilities that are already functioning. This paper analyses the integration of these paradigms into automated greenhouses. An integration model is proposed and developed in the plant experimental unit installed at the University of Alicante. This unit already has an automated system that controls air conditioning, soil conditions, and irrigation, but these control subsystems are not integrated. In this work, new processing nodes with integrated data are designed to develop new detection, prediction and optimization services. These services increase the performance of the installation and create smart environments in agricultural production.

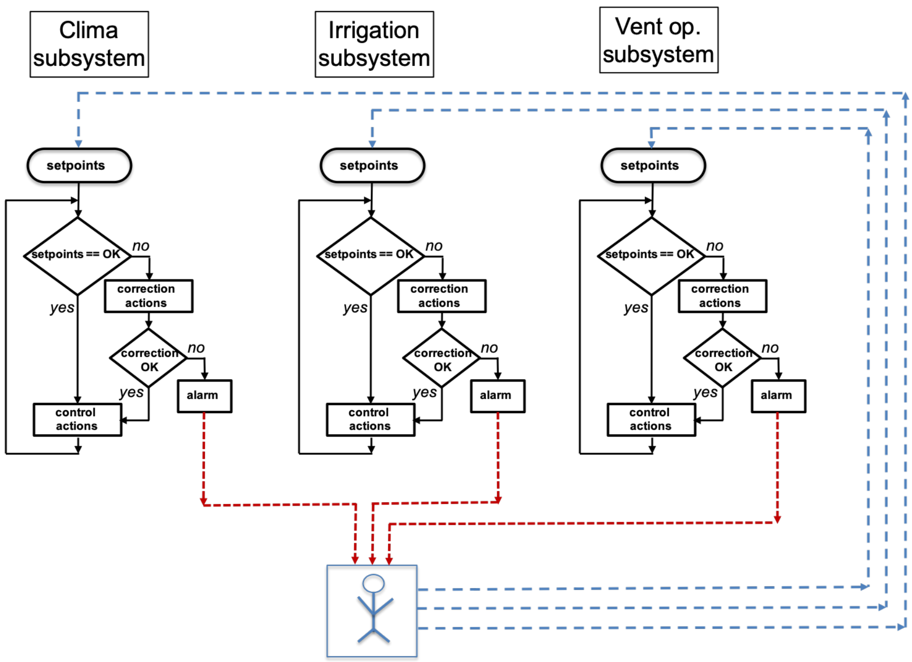
Keywords: precision agriculture; ubiquitous sensor network; internet of things; artificial intelligence; embedded devices

1. Introduction

The increasing importance of new applied technologies in the agricultural sector to optimize not only the production efficiency and the quality of agricultural products but also the energetic efficiency of greenhouses and the reduction of pollution has required new climate control systems. Therefore, the design of greenhouses has progressed from simple plastic covered greenhouses to automated greenhouses, thus advancing in this respect. Automation in agriculture, called Precision Agriculture (PA) [1,2], is one of the main paradigms in this process. In the last few years, the development of Internet technology has resulted in smart greenhouses where the automation of climatic environment allows processing information and executing tasks through algorithms that include prediction and classification process based on models of Artificial Intelligence (AI). Despite climate environment being controlled in a smart greenhouse; there is still the problem of maintaining the most favorable climate for the adequate development of plants because it highly depends on the external climate. Moreover, there are large variations in air temperature and humidity inside the greenhouse throughout the day [3]. These authors found that air temperature inside a greenhouse follows patterns of heterogeneity as a function of the incidence of sunlight and time of day, with the highest air temperature heterogeneity present in the central hours of the day, and it is higher in the horizontal dimension rather than vertically. In addition, they observed that the vast majority of homogeneous days correlate with cloudy days. Developments in the field of monitoring and control offer new resources that improve the agricultural facilities. New advances from embedded electronics, communications and applied artificial intelligence introduce new possibilities not yet developed.



(a) Automated



(b) Smart

Figure 1. The sub-image automated represents a current automated system, where the agronomist manages the setpoints (control variables). The sub-image smart shows the proposal of this work, where an artificial intelligence platform detects and acts automatically, introducing prediction and optimization services that are supervised by the agronomist.

Information and Communication Technologies (ICT) are available, but they have not been widely introduced in agriculture: expensive systems and difficulties in installing and maintaining are the main barriers. Different works propose the integration of these technologies adapted to agricultural processes. In general, designs based on layers are applied [4–6]: sensorization, control management, communication and Internet services are the main levels or layers that are proposed. The differences between them are the hardware, the algorithms used, the communication protocols and the proposed services. In general AI algorithms are implemented at high levels of this design in levels or layers. The goal is to propose integration models of ICT technologies to convert automated systems into systems with services based on environmental intelligence (shown in Figure 1). This paper presents research to design and develop smart services in industrial greenhouses.

2. Related Works

Nowadays, the technologies that support the agricultural practices in a smart greenhouse are based on Wireless Sensor Networks (WSN) for monitoring soil o substrate, plant and the environment variables. Several research works concluded that environmental magnitudes of the climate inside a greenhouse are affected by materials and structural design of the greenhouse. Venlo greenhouse [7] is the most popular design of greenhouses in central- and north-European countries. It is constituted by zenithal windows with a very fine mesh screen to prevent the entry of pests like whiteflies and thrips, which are very small. However, these screens impede ventilation and, in some cases, reduce light transmission [8–10]. The air exchange is necessary for an adequate development of plants that is mainly achieved by natural ventilation in a Venlo greenhouse, with the roof ventilation as the dominant method of ventilation. However, the natural ventilation is not enough in regions where the temperatures are very high, where forced ventilation by the use of fans or extractors is required [11] in order to replace the warm inside air with cold outside air. Even in these areas, the demonstrated efficiency of combining forced ventilation and fogging systems [12] or evaporative cooling systems is necessary to decrease air temperature [13–15]. Nevertheless, there is a problem controlling condensation for the use of fogging systems. Therefore, air conditioning systems are needed. Other condition that should also be taken into account is light. Light condition is one of the most important variables for proper plant growth, and it is closely linked to air temperature. Presently, LEDS are commonly used because of their cost efficiency, durability and low thermal energy generation. Moreover, several studies showed the improvement in plant growth by using LEDS due to the range of colors they provides [16,17]. Historically, the irrigation in a greenhouse depended on the climate, but optimization of irrigation comes through knowing the plant and soil water state. Currently, the implementation of WSN to apply cost effective irrigation scheduling was demonstrated by several authors [18,19]. As previously seen, different authors demonstrated that the application of new technologies to manage the most important climate and irrigation system is efficient for the adequate growth of plants in a greenhouse. However, there is a lack of integration of diverse automated parameters in order to create the perfect combination of control systems.

3. Smart Greenhouse Design

3.1. Requirement Analysis

The requirements are specified by the agronomist and information and communication technicians. The agronomic approach introduces crop, soil, climate, water, nutrients, energy and irrigation requirements. The ICT approach proposes the use of digital technologies to automatize and optimize. In this work, agronomist and ICT technicians establish the requirements to introduce new services and capabilities in automated systems. The main subsystems in an agricultural production process and their relationship with ICT technologies are the following:

- ***Crop***: Temperature, light, water, oxygen, mineral nutrients and other support are the control parameters. Sensors with this data are used as inputs to the automation and optimization processes. RGB sensors capture images daily that can be processed to analyze the evolution of production. Expert users can design different kinds of processes using the images captured.
- ***Soil***: The roots of the plants are surrounded by soil that supports the growing plant. Soil moisture, conductivity or disease control should be treated using sensors and actuators.
- ***Climate***: Plants grow within a limited temperature range. Humidity and temperatures that are too high or too low will reduce production. Vegetable plants and many flowers require large amounts of sunlight. Special plant-growth lamps can be used to grow these plants. In the same way as in the previous cases, sensors and actuators are necessary.
- ***Water and nutrients***: Water Temperature, pH and Electro-Conductivity (EC) are variables that need to be controlled. Soilless growing requires complete and effective hydroponic nutrient solutions. Liquid nutrients (nitrogen, phosphorus, potassium) are prepared by the agronomist.
- ***Energy***: Monitoring energy consumption and renewable generation are important requirements to design sustainable facilities.
- ***Irrigation***: Irrigation time control is important. The plant receives moisture and nutrients using the irrigation process. Irrigation strategies for optimization are important in improving processes.
- ***User interfaces, data storage, control and communication services*** must be designed. Tables and graphs with statistical data show data in real time. IoT resources store principal data. Subsequent analysis generates information about the growing process.
- ***Events detection, classification, and data prediction*** are new requirements for the proposed value-added services. These services can be designed and developed in any greenhouse subsystem. New operation and integration resources must be introduced.

3.2. Smart Greenhouse Model. Hardware and Software Ecosystem

Automated systems in greenhouses automatically control the climate, the crop irrigation and the actions of closing vent openers. These systems are configured manually by the technician, introducing the setpoint values. The agronomist selects the climate setpoint, irrigation time schedule and nutrients parameters irrigation water. Most of these systems have a model based on subsystems (climate, irrigation, automatic vent openers). These subsystems are installed without designing interactions between them. Irrigation programming is not integrated with climate conditions. The closing and opening of automatic vent openers is not related to other subsystems either. Another important factor is that the three subsystems, when the setpoints are set, do not have the capacity to predict events that can automatically modify the value of these variables. This fact is important in the optimization and improvement of this type of facilities. The model proposed in this work, after analyzing different types of automations in greenhouses, aims to convert these scenarios into intelligent systems, with the ability to predict automatic actions and to integrate all subsystems and make them interoperable. The design of this platform provides a solution that can be used in automated greenhouses already built. The design proposes:

- Hardware platform using embedded devices to integrate greenhouses automated subsystems.
- Software platform with artificial intelligence paradigms that perform prediction and classification tasks to automate new actions.

With these two platforms, automated greenhouses become spaces where services based on new intelligent services are implemented. In this work, the model proposed is designed on the greenhouse of Research Technical Services at the University of Alicante.

First, an architecture hardware that integrates the different subsystems (climate, crop irrigation, vent openers and renewable generation) must be interoperable to design and implement smart services. The proposed architecture is based on two levels. A level formed by programmable control devices (control nodes 1,2,3,4 in Figure 2) connected to each subsystem already installed. The controllers connect to each other and to the local network, managed by a gateway. The controlling nodes communicate with the second level, the network management servers (device 5,6 in Figure 2) using IoT protocols. The two requirements of each controlling node are: IoT communication capacity and minimum processing capacity.

- **IoT communication:** If the node implements prediction or classification models, it needs a multiprocess operating system (Linux). If the node only implements a control thread, a microcontroller with a single programming thread is needed.
- **Processing capacity:** One of the most used IoT protocols is Message Queuing Telemetry Transport (MQTT). The control node must have the necessary communication interfaces to transmit data using this type of communication protocol.

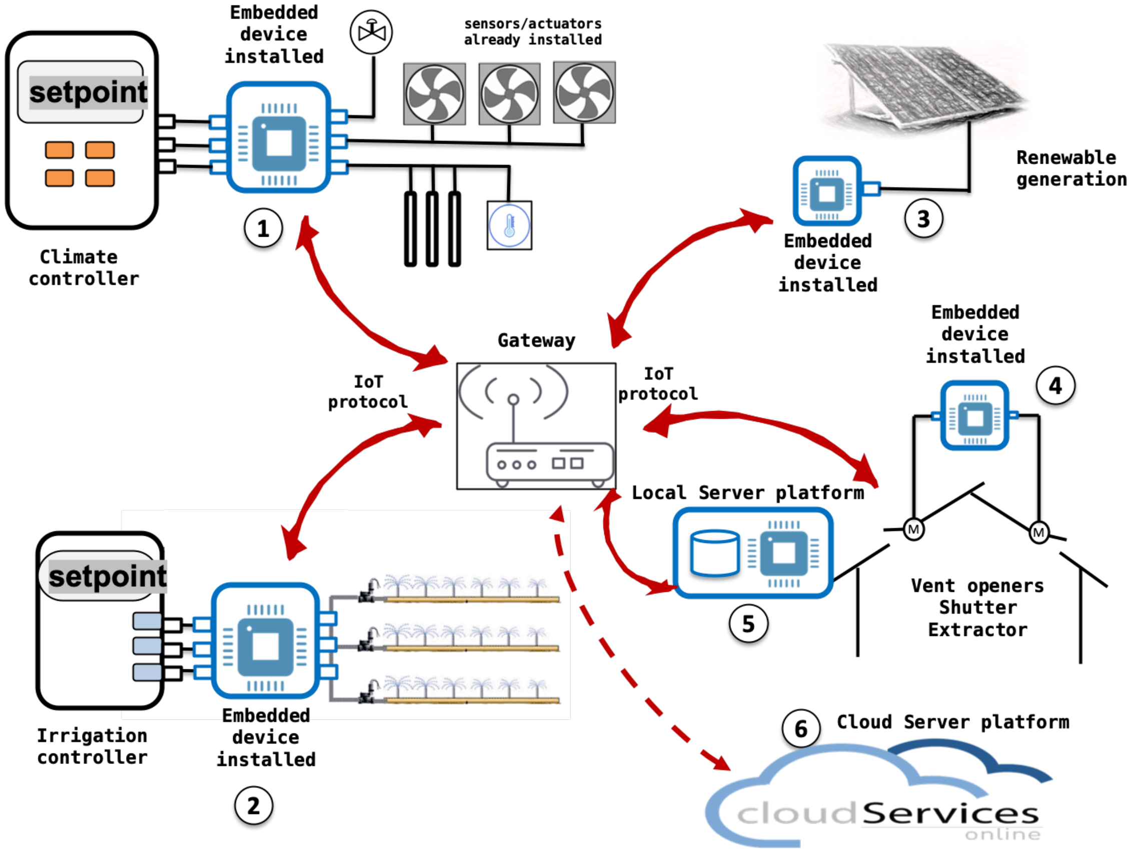


Figure 2. Architecture based on embedded controllers (control nodes). These nodes provide integration capacity through communication with IoT protocols and development of AI applications implemented in each node. The server layer is used to develop services with higher processing requirements, for storage and cloud services, among others.

Two types of embedded devices are proposed (microcontroller with only 1 computing process and controller with multi-thread operating system). The first can be used as a controller without AI algorithms, the second is used in AI processes and server node services (Figure 2). In the proposed architecture, both types of controller are used. The controller with less processing capacity is used in two types of nodes (units 3 and 4 in Figure 2). The devices with greater capacity (units 1 and 2 in Figure 2) implement AI algorithms for prediction and classification. The outputs of these algorithms are communicated to the server modules (units 5 and 6 in Figure 2) that automate modifications in the set points.

3.3. Facility Model. Automated Greenhouse

The research was carried out in a Venlo greenhouse belonging to the Unit of Plant Experimentation, which is located in the extension area of the Campus of the University of Alicante (38°22′48″ N, 0°31′37″ W and 95 m above the sea level). The experimental greenhouse is constituted by a steel frame structure and glass as greenhouse covering both the walls and the roof. It has a rectangular area of 5 m ×10 m (width × length) and its height is 4.4 m. The main physical features are:

- Two air conditioning units with hot/cold system. An extractor. A system of horizontal and vertical screens.
- 18 high-pressure sodium lamps.
- An irrigation system consisting in drip and sprinkler irrigation.
- Six growing tables.
- Two zenithal windows with insect-proof screen (0.40 mm × 0.45 mm of mesh opening).
- A measurement station constituted by an anemometer and weather vane for velocity (Km/h) and direction measurement of the wind, solarimeter for the measure of the global radiation (W/m^2), and a rain gauge sensor (L/m^2).
- Temperature (°C) and relative humidity (%), sensors inside the greenhouse.
- Temperature (°C) and relative humidity (%), sensors outside the greenhouse.
- A fog generator system by means of nebulizer nozzles. Two lateral shading screens that do not allow light through.
- A thermal screen in the roof with a high-quality metallized knitting that moderates day/night temperatures.

The automatic control of the greenhouse (shown in Figure 3) is carried out by a computer, which allows the agronomist to program the diverse control inputs to create the environment for the adequate development of the plants and the best energetic efficiency of the greenhouse. Control variables are:

- Vent openers by percentage of opening, extractor by on-off control.
- Air conditioning regarding temperature setpoint.
- Thermal screen by percentage of opening with reference to the radiation setpoint.
- Fog system by on-off control with a cyclic temporization.
- Extractor by on-off control in relation to temperature and relative humidity setpoint.
- Light lamps and shading screens by on-off.

The acquisition of the measures has been achieved with 1 minute as sample step and the data can be graphed.

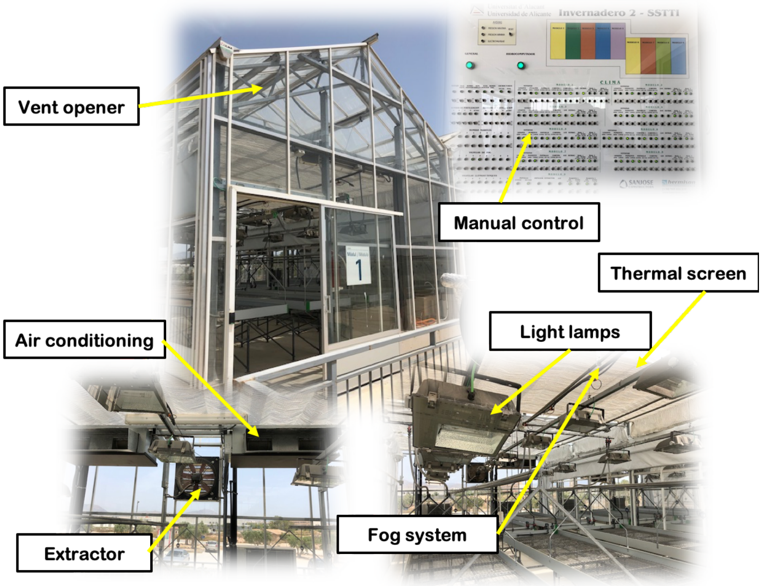


Figure 3. Greenhouse on which the integration model is designed and installed. The current automatic control is integrated with a new intelligent control system that increases functionality and adds new services.

4. Experimental Work

4.1. Design Requirements

To design, develop and implement the set of value-added services to the automated installation, techniques based on the user-centered design (UCD) are used. In this sense, both the ICT technician and the agronomist jointly define the new services to optimize and improve the processes. UCD is an approach that puts the users at the center of its design and development. The approach in both lines (ICT technicians and agronomists) allows to design innovative services that can be developed, implemented and tested in a cycle (defined in the standard ISO 13407):

- Requirements gathering—Understanding and specifying the context of automated facilities.
- Requirements specification—Specifying the agronomist and organizational requirements.
- Design—Producing designs and prototypes.
- Evaluation—Test and capture feedback data.

Algorithms that implement AI models are installed in embedded devices with multi-threaded operating system.

Another important decision is the choice of the programming platform used: language and installed libraries. The language used is Python. Python programs can be close to pseudo-code and have an easy implementation for artificial intelligence processes. It is a general language that does a little of everything at a good enough complexity-performance tradeoff with a full suite of tools for productionizing machine learning. The AI services that can be designed and implemented depend, on the one hand, on the experience and knowledge of the agricultural technician in the processes and, on the other, on the knowledge of the software-hardware installation of the ICT technician. The experimental plant unit of the University of Alicante has designed the services shown in Figure 4. The agronomist defines the setpoints in hourly sections depending on the crop and the expected climatic conditions. A new prediction algorithm has been developed. The architecture and defined design allows to develop different services (shown in Table 1) that extend the capacity of the automated installation, converting it into a smart installation.

This extension must occur gradually. It is necessary to establish a stage of learning and testing the appropriate models and paradigms that perform smart tasks. The strategy applied in this process is to use the installed control facilities, deploy the programmable controllers and capture the necessary datasets to develop the AI algorithms. These embedded controllers, which are integrated with current systems, implement intelligent algorithms to subsequently carry out control actions and replace the existing ones. The experimental work follows this strategy, capturing the necessary datasets to implement the first intelligent algorithms. Following the UCD method, where both the agronomist and the ICT technician participate in its development, services are designed, implemented and validated.

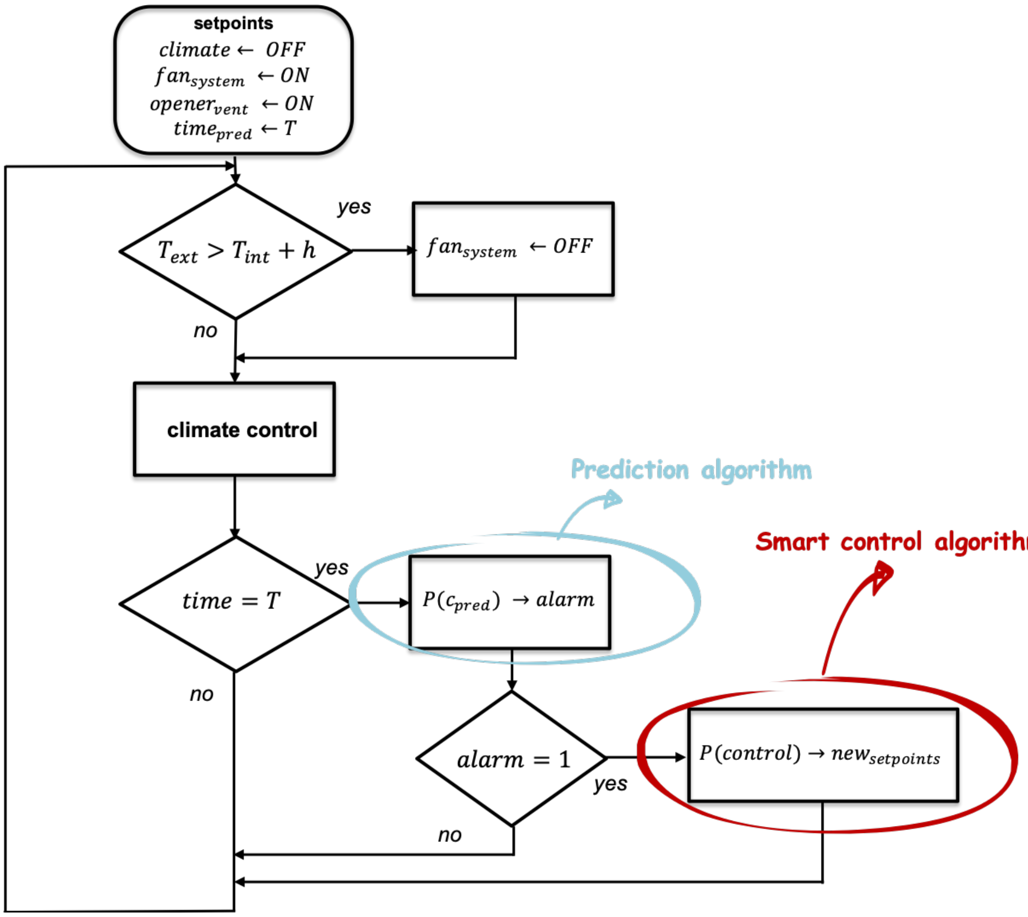


Figure 4. Prediction integration and smart control algorithms in the experimental smart greenhouse design.

Table 1. Potential services incorporated into current automated systems.

Services	Hardware	Software	Data	Process
Subsystems integration	Controller embedded and server nodes	Climate, irrigation, vent opener and extraction control algorithms communication algorithms	Sensors Climate: inside and outside data Climate: weather forecast Irrigation: soil moisture, Ph and Conductivity Renewable power: weather forecast, power generation Actuators Climate: temperature setpoint Irrigation: schedule electro valve Vent opener: open regulation Extractor: ON/OFF	Install new controllers Install new sensors/actuators algorithms implementation interfaces and communication implementation testing and validation
Climatic prediction	Climate controller Server node	Prediction algorithms on server node using: prediction tree paradigms, neural networks or any other prediction AI paradigm	Dataset with data stored: weather inside and outside and weather forecast, temperature set point, extractor and vent opener	Data collection Data analysis Statistic
Smart control	Embedded controller server node	Machine learning algorithms using: prediction tree paradigms, neural networks or any other prediction AI paradigm	Datasets: control variables actuator sensors, set points, control feedback dataset	Data collection Data analysis Statistic
Energy management	Embedded controller server node	Energy prediction algorithms using: prediction tree paradigms, neural networks or any other prediction AI paradigm	Datasets: Consumption data Renewable generation data	Data collection Data analysis Statistic
Crop growth	Webcam server node	Artificial vision algorithms using: prediction tree paradigms, neural networks or any other prediction AI paradigm	Datasets: plant growth images	Data collection Data analysis Statistic
Irrigation optimization	Embedded controller	Optimization algorithms using: prediction tree paradigms, neural networks or any other prediction AI paradigm	Datasets: soil sensors, actuators, climate prediction	Data collection Data analysis Statistic

4.2. First Results

The experimental greenhouse has installed the subsystems analyzed. The agronomist schedules the conditions of each of them manually, using a web interface. The proposed design integrates different modules that make the different subsystems interoperable and that incorporate new services based on variable prediction. In the first work carried out, an algorithm for predicting the temperature of the greenhouse was developed. Every 15 min the algorithm predicts the expected temperature. With this prediction the system can act and make control decisions. The installed controller has stored a dataset of values for the last 30 days of operation. From this information, a model based on the paradigm of regression trees, programmed in python language, is obtained in a learning phase. The model is integrated into an algorithm that performs the desired prediction. Figure 5 shows this process. In Figure 6, the results of temperature prediction obtained with the model proposed in this work are shown. Other prediction and/or machine learning services can be designed and developed.

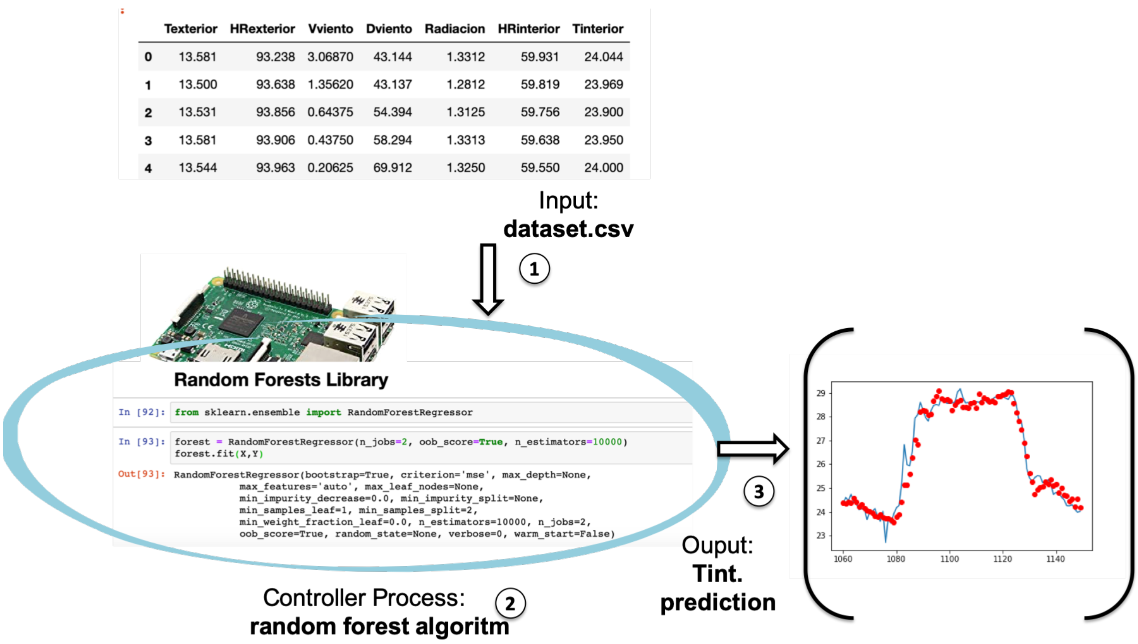
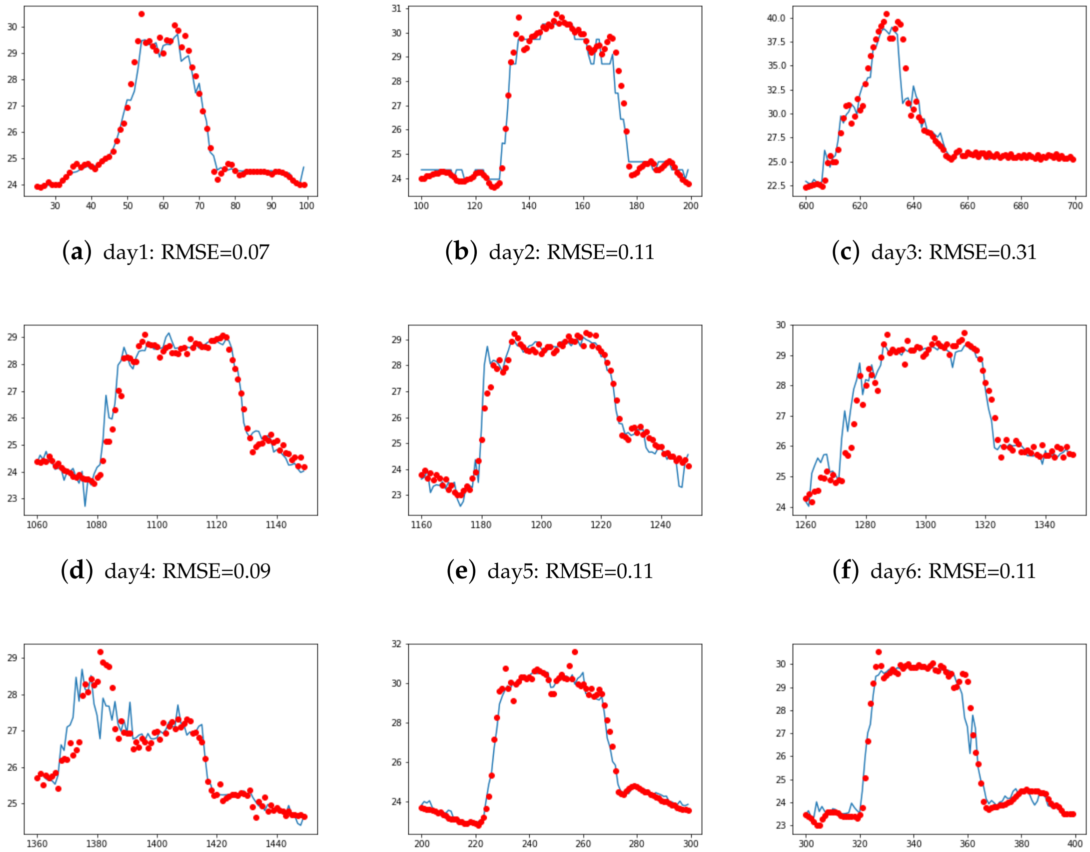


Figure 5. Temperature prediction process in the greenhouse using learning dataset and Python library in embedded controller. The model used is the paradigm random forest.



(**a**) day1: RMSE=0.07 (**b**) day2: RMSE=0.11 (**c**) day3: RMSE=0.31

(**d**) day4: RMSE=0.09 (**e**) day5: RMSE=0.11 (**f**) day6: RMSE=0.11

(**g**) day7: RMSE=0.12 (**h**) day8: RMSE=0.12 (**i**) day9: RMSE=0.09

Figure 6. Predicted temperature (dots) versus measured temperature (lines) and root-mean-square error (RMSE).

5. Conclusions

In this work, the current state of the technologies in greenhouse automation is revised. Next, a model of integration between the knowledge that the agronomist has and ICT technologies is proposed as a hardware-software platform for services. Expert agronomist knows the operation rules; ICT technologies, such as embedded hardware, communication protocols (IoT), algorithm processing with high-level languages (Python) and artificial intelligence models (random forest regression) add technological resources. The services provide improvements in current operation of greenhouses. A prediction service of the inside temperature is implemented to show the model's applicability. The specific contributions of this work are related to the application of AI paradigms in automated agricultural production processes in whose development the agronomist participates. The user-centered design allows to obtain results adapted to the requirements of the installation that take advantage of AI technologies in a more optimized way. Already automated installations improve their performance by applying the process described in this work. Once the model is developed, new services can be designed and installed with the data captured by sensors and actuators. The objective is to increase the levels of automation and intelligence of the environments. The results of both the design and the results of this first experiment are positive and reinforce the basic criteria of the model and the objective that this proposal can achieve: convert greenhouses into smart environments.

Author Contributions: F.J.F.-P. and J.M.G.-C. performed the formal analysis and conceptualization. The experimental phase was implemented by F.J.F-P and M.P-H. The state-of-the-art, results and conclusions were realized by S.A.-L. and F.J.F-P. The validation was realized by S.A.-L.

Funding: This research was funded by the Industrial Computers and Computer Networks program (Informatica Industrial y redes de Computadores I2RC) (2018/2019) funded by the University of Alicante, Wak9 Holding BV company under the eo-TICC project, and the Valencian Innovation Agency under scientific innovation unit (UCIE Ars Innovatio) of the University of Alicante at https://web.ua.es/es/ars-innovatio/unidad-cientifica-de-innovacion-ars-innovatio.html.

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