Int J Interact Des Manuf (2016) 10:355–367
DOI 10.1007/s12008-014-0243-2

ORIGINAL PAPER

# A systems-engineering approach for virtual/real analysis and validation of an automated greenhouse irrigation system

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Received: 5 September 2014 / Accepted: 13 September 2014 / Published online: 24 September 2014


**Abstract** In the context of multidisciplinary complex systems design, modelling and simulation are key components in decision making. It allow engineers to validate design alternatives at early development stages. Consequently, it is possible to reduce uncertainty on requirements compliance and secure better decisions for downstream stages of product development. This article describes the analysis of a virtual prototype of an automated greenhouse irrigation system. It is modelled and compared with the real system implementation, finding some differences and similarities between both system testing approaches. The intrinsic dependence of experimentation and modelling is also discussed as both, experimental and random data, are important to be used as inputs to validate virtual models.

**Keywords** Systems modelling · Virtual prototyping · Mechatronics · Systems engineering · System validation

## 1 Introduction

Climate changes are affecting agriculture worldwide, exposing plantations and crops to extreme weather conditions (e.g., floods, droughts, among others) [1]. Therefore, greenhouse environments became an important food source for the humankind, while they serve as ideal cultivation environments [2]. Nevertheless, to have an idea about the general state of a greenhouse system, it is important to have detailed information, at least, from the most relevant variables affecting the environment.

In greenhouses applications, the main and the most commonly monitored variables are: (1) temperature, (2) relative humidity, (3) light intensity and (4) soil moisture. By monitoring these environmental variables, a global idea about the state of the greenhouse can be achieved. Specifically for the plant, the soil moisture is the most critical parameter to monitor because depending on its value, diverse fungi might attack the plant.

The need of constantly monitor and control environmental variables, has turn greenhouses into complex multivariable environments, representing a challenge in terms of systems development and manufacturing [3]. Additionally, greenhouse control and monitoring systems are based on different disciplines like Information and Communication Technologies (ICT), mechanical engineering and electronics, among others. Hence, their development process must be done collaboratively by multidisciplinary teams. Nevertheless, each discipline develops its project section individually, using its own software and tools, which means that they can test the complete system once a first physical model or prototype is built.

This article, presents the development process of an automated greenhouse irrigation system, based on enriched virtual models and simulations. This simulations reduce the uncertainty that exists when a design concept, developed with computer aided tools, is taken to the real world [4]. Thus, a virtual prototype of the greenhouse irrigation system was designed, modelled and simulated using the RFLP (Requirements Functional Logical Physical) approach. Then, a physical prototype was built and implemented into a real greenhouse environment in order to compare both models.

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The physical prototype was also used to validate and calibrate the virtual prototype after having real environmental data. Therefore, the virtual model could be used for further optimization processes.

This article is structured as follows: A brief introduction about the background and context of the problem is presented in Sect. 1. Section 2 presents the literature review focused on existing greenhouse monitoring and control systems, as well as an analysis of different systems modelling and simulation techniques that might be applied in automated greenhouse environment development processes. Section 3 presents the development process and tests of a virtual prototype from an automated greenhouse irrigation system. Section 4 presents the physical implementation of the previously developed system to validate and calibrate the virtual prototype. Section 5 presents project results. Finally, Sect. 6 presents conclusions and further work.

## 2 State of the art

### 2.1 Greenhouse monitoring and control systems

Agricultural development has been an important fact throughout human history, as it is a key source in terms of ensuring food production over the time. In the last decades, the planet has been experiencing abrupt weather changes and the phenomena has expanded to areas that were not affected before. The way agriculture is answering this challenge, is by implementing greenhouse systems [2], which are glass or plastic buildings intended to monitor and control environmental variables in order to optimize agricultural production processes and ensure food production despite weather changes.

Greenhouses are becoming more interesting systems in terms of complexity. This complexity is caused, among others, because the number of variables that directly affect plants and the production model, which has changed from small farms to intense production and the so-called Precision Agriculture (PA) paradigm. PA can be defined as the management of spatial and temporal variability at a sub-field level to improve economic returns and reduce environmental impact [5]. In addition to this, fields regarding automation and optimization processes of the greenhouses have been rising in terms of basic and applied research. Nevertheless, the inclusion of technology in greenhouse systems is not enough by itself. The complex agricultural environment, combined with intensive production requires the development of robust systems with short development time at low cost [3].

In order to develop reliable and robust greenhouse environments, control and monitoring systems have been highly developed during last decades based on current technology advances. For instance, the implementation of Wireless Sensor Networks (WSN) to monitor environmental variables (e.g., temperature, soil moisture, etc.), reduced maintenance and installation costs, related to wiring and harness. This alternative provides installation and operation flexibility, enhancing also the potential to install and expand such systems in remote locations [6–8]. Additionally, as greenhouses are multi-variable, nonlinear and uncertain systems [9], WSN can be used to find the relationship between environmental conditions and crop diseases or growth problems, which can be later used to implement precise greenhouse control systems [10].

The implementation of this kind of WSN in greenhouses has allowed farmers to automate and control specific processes. For instance, precision irrigation systems represents up to 80 % of fresh water resources worldwide [11]. This can be achieved, by implementing WSN to monitor environmental variables, providing an effective way to assess water needs and optimize water usage [12,13]. Therefore, tree death caused by excessive or poor irrigation can be avoided [14]. Additionally, monitoring and control tasks can be carried by automated systems for long periods of time, which would be impossible for human workers [15].

### 2.2 Systems modelling and simulation

Greenhouse environments usually rely on ICT and mechatronic systems in order to improve their performance. Besides, the development process of such complex systems must be based on interdisciplinary and collaborative work, because of the multiple disciplines involved.

On the other hand, methods and tools for interdisciplinary work have been evolving, mainly driven by constant changing customer's needs. Nowadays, consumers are demanding products richer in technologies [16], which means that complex systems development processes need multidisciplinary teams. Additionally, product developers must reduce costs, time-to-market and increase the overall quality of products. This has to be achieved without rising products price and taking care of other aspects like sustainability and transport, among others [17].

Therefore, new methodologies and product development strategies have arisen in order to analyse and optimize such complex products (e.g., greenhouses). These methodologies and strategies, can be applied in agricultural systems development, as well as they have been applied in other industries. For instance, the VDI 2206 guideline integrates mechanical engineering, electrical engineering and information technology concepts [18], providing an useful guideline for mechatronic systems design [19,20], integrating ICTs, mechanics and electronics engineering. Such systems are rising its use among industry and academy. Consequently, modelling and simulation tools will need to include the main disciplines involved in these type of systems design.

The RFLP modelling approach, enables close interaction and collaboration among different engineering disciplines involved in the creation of these type of systems [21]. Additionally, it enhances requirement comprehension and traceability, accelerates product development, simulation process and complex system analysis [22]. It also allows user to link the 3D-Model with logical and dynamical behaviours, creating enriched virtual prototypes that can be used to validate design alternatives within a virtual environment at early design phases [23,24]. This is a critical aspect in decision making as early design phases usually define a considerable amount of the lifecycle costs [25]. Consequently, modelling approaches, as the RFLP approach, are useful as physical prototypes are being replaced by virtual prototypes in order to validate products at early design stages [24,26]. Virtual prototyping may also reduce risk in equipment damage or operators injuries due to design errors or bad usage [27]. However, an accurate virtual prototype means longer simulations and higher development time [28]. Moreover, when modelling complex systems, such as mechatronic systems, design engineers must have a good understanding of the real system, in order to model it using mathematical models [29] to represent multi-domain behaviours.

Regarding interactive approaches in engineering design, "Interactive Design" is defined as a technique to support decision making during early product design stages. It must be able to encourage collaboration among different disciplines, provide high fidelity simulations (including the context in which the product will be immersed) and allow human interaction [26,30]. Nevertheless, some authors propose three (3) main problematics related to Interactive Design: (1) collective engineering, where the quality of the final product depends on the collaboration among people and companies involved in the development process, (2) functional and marketing integration, while market tendencies must be taken into account in order to correctly meet consumer needs and (3) adaptive extended simulations, while virtual prototyping development instruments are not enough suitable to support early stages of the design process. These problematics, can be fulfilled by different kinds of interactions that must be modelled: (a) cognitive, (b) sensorial and (c) pure physical interaction [26].

Therefore, early design validation, based on the RFLP approach, can operate as an Interactive Design technique, where marketing and engineering concepts, among others, are taken into account during the complete development process. Additionally, products can be analyzed by using high fidelity simulations, based on physical interactions either from internal product components as well as product interaction with the context in which it will be used. Besides, final user is able to interact with the virtual prototype in order to evaluate and test it through a virtual environment. Therefore, it allows design engineers to determine which solution fulfils customer requirements from two different perspectives: (1) an engineering perspective, where product is analyzed based on simulation results [31] and (2) a marketing perspective where end-user satisfaction level can be determined by performing interactive simulations in order to evaluate if the product fulfils user expectations.

Finally, when modelling mechatronic systems, there is always some sort of uncertainty, while the verification and validation steps are performed comparing the virtual prototype behaviour with real data obtained from the physical prototype [4]. Therefore, this article presents the development process and set up of a complex greenhouse system, evaluating differences and similarities found during the process of virtual analysis by using RFLP modelling and the physical analysis by implementing a monitoring system in a real greenhouse experimental environment.

## 3 Virtual implementation of an automated greenhouse irrigation model

The RFLP approach was followed in order to model, simulate and validate the virtual prototype of a greenhouse monitoring and irrigation system. Initially, system's requirements had to be defined. to do so, the design team defined and discussed, together with end user, the main requirements and activities that the system must perform in order to have a clear idea about what will be implemented.

Next, a functional structure was created by using 2D-Blocks that represent functions. Additionally, interaction among blocks (functions) is represented by arrows. Each function or group of functions is intended to comply with one or more requirements. Therefore, design team can guarantee that costumer requirements will be addressed with further design solutions.

After completing the functional structure, a logical architecture had to be defined. The logical architecture is also represented by 2D-Blocks, this time representing the components that will perform the previously defined functions. Those components will be the same to be integrated in the physical implementation, and they are analysed by mathematical, physical and logical models. Those models are added to logical blocks, in order to analyse and simulate the virtual model behaviour, aiming to get close to the physical behaviour. In this step, all links between the different entities of the system were defined, including the control rules and strategy to be implemented.

Finally, a 3D-Model of the monitoring and control unit was created. With this virtual approach, the design team is able to visualize the physical aspect of the system, as well as to verify components' assembly and ensure the correct fitting of product components.

The details of the virtual implementation through RFLP steps are presented in the following subsections.

## 3.1 Requirements

The requirements for greenhouse monitoring system design were defined and are listed in Table 1. From requirements, some measurable parameters can be identified, giving insights on what variables can be monitored and controlled, taking into account the environment in which the system is going to be implemented.

The target environment, used as case study in this research project, is located in a experimental greenhouse environment in the university campus, where biological experiments take place. The main variables to monitor were defined according to the activities developed by the responsible staff of the crops, as well as some extra variables intended to provide more information relevant to the greenhouse staff.

There was one critical variable to control the irrigation system, being its activation/deactivation. It was selected as main output variable, mainly for two reasons: (1) irrigation is the most important input to obtain high quality plants and (2) the implementation of its control did not imply major modifications to the current greenhouse structure, being able to use it while regular biological experiments were carried out.

## 3.2 Functional

A functional structure was created based on the system's requirements. In a Blocks Diagram, the main container, represented by the outer block, corresponds to the main function of the greenhouse irrigation system. This main block, has inner blocks that represent sub-functions. From a system's physical structure point of view, each block should represent every functionality of the system, as well as external (environmental) components, such as water flow, being a physical component that interacts with the system, and considered as support functions in the RFLP approach. Support functions may represent external factors that affect the technical system that is being analysed. Additionally, interaction among functions and sub-functions is represented by arrows. Each function or group of functions is intended to comply with a requirement (for the case under study, from Table 1). In this case, the functional structure was composed of five sub-functions:

i. Supply water: Water must be supplied, for the irrigation system to work.
ii. Simulate plant conditions: Support sub-function designed to manipulate weather flow in order to test system reaction and accuracy.
iii. Monitor weather and plant conditions: In order to control certain environmental variables, the system must know their values.
iv. Control water flow: As the main goal is to design an irrigation system, the water flow must be controlled.
v. Supply electric energy: The system should work using electric energy, therefore, it must have an energy source.
vi. Process data: All data obtained from the monitoring system must be processed and converted into useful information needed to control the system.

Finally, after creating and fully integrating the functional structure, the design team has a clear vision of what the system should do to satisfy engineering requirements. The functional structure is shown in Fig. 1.

## 3.3 Logical

Once the functional structure is clear, the logical architecture can be defined. It is composed of logical elements which are the system components and sub-components, which are intended to fulfil system's functions. They are represented by 2D-Blocks and each logical block has an specific function assigned to it. Those functions have associated mathematical, physical or logical models, in order to enrich the simulation and represent at a high level the component that is going to be used on the physical system. Mathematical and physical models can be created using the Dynamic Behavior Modeling (DBM) workbench, while logical models are defined using the State Logic Modeling (SLM) workbench. In this case, the logical architecture was composed of (i) water source, (ii) plant, (iii) sensors, (iv) solenoid valve, (v) 12v energy adaptor, (vi) Arduino platform and (vii) a control panel (as shown in Fig. 2):

i. Water source: This block represents the water pressure over the system.
ii. Plant: This logical block is an array containing temperature, relative humidity, light and soil moisture values over the time.
iii. Sensors: Four different sensors (temperature, relative humidity, light and soil moisture.) and their specific equations were modeled and connected to the Arduino platform and environment behavior blocks.
iv. Solenoid valve: A 12v solenoid valve was modeled using the DBM workbench. It was controlled by a digital signal sent the Arduino platform.
v. 12v energy adaptor: A 12v energy adaptor was modeled using the DBM workbench. This adaptor was intended to supply electric energy to the entire WSN and the solenoid valve.

**Table 1** Greenhouse irrigation system—requirements

| ID | Requirement |
|---|---|
| 1 | Greenhouse monitoring system and irrigation control for ensuring quality |
| 1.1 | The system must have an electrical power source |
| 1.2 | The system must be able to convert weather data into useful information |
| 1.2.1 | The system must process data |
| 1.3 | The system must monitor ambient temperature |
| 1.4 | The system must monitor ambient RH |
| 1.5 | The system must monitor light |
| 1.6 | The system must monitor soil moisture |
| 1.7 | The system must be able to activate/deactivate the irrigation system |
| 1.8 | The system must be able to keep track of the times that the irrigation system is activated |
| 1.9 | The system must be able to send a maintenance alert for the irrigation system, according to pre-defined values |
| 1.10 | The irrigation system activation/deactivation must be dependable of more than one variable measure |
| 1.10.1 | The implicated variables must be compared in order to decide the activation/deactivation of the irrigation system |

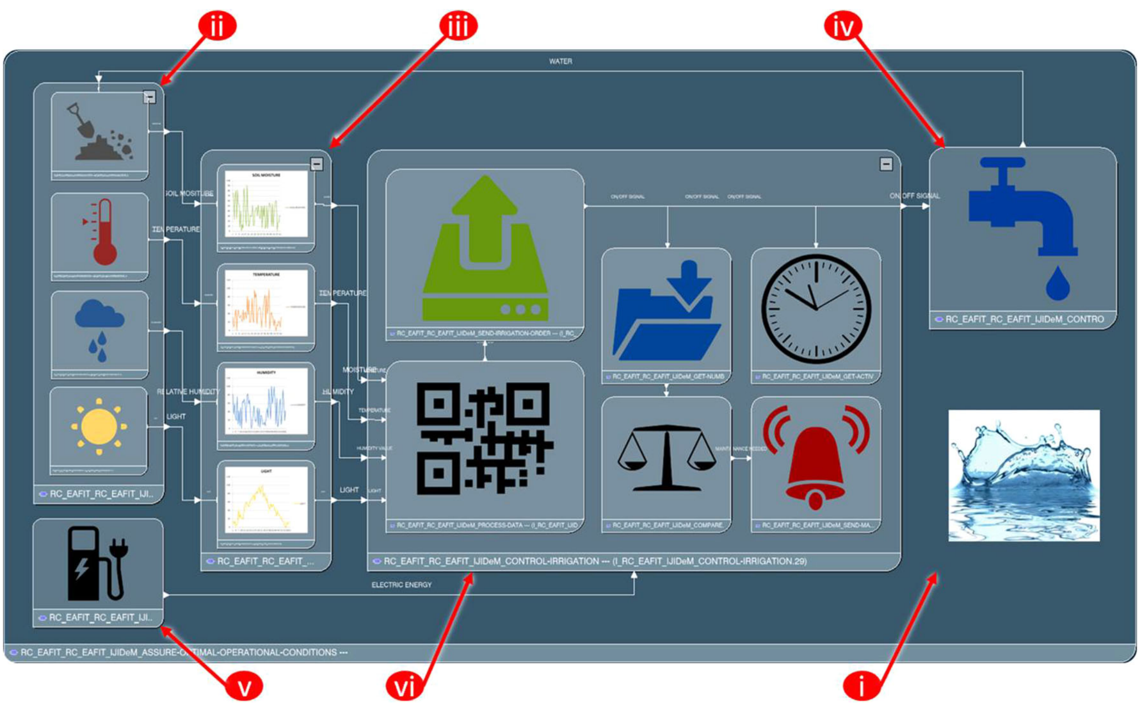


**Fig. 1** Greenhouse irrigation system—functional structure

vi. Arduino platform: This logical block was created with the same inputs and outputs that a real Arduino platform has. Additionally, it contained a logical program to control the valves and the alarm signal depending on the current state of the monitored variables (see a detailed view in Fig. 3).

vii. Control panel: A user interface was designed and modeled using the SLM workbench. Different buttons and digital displays were integrated into the same control panel, which allowed the user to control and monitor the system. Additionally, it had failure and maintenance alert indicators.

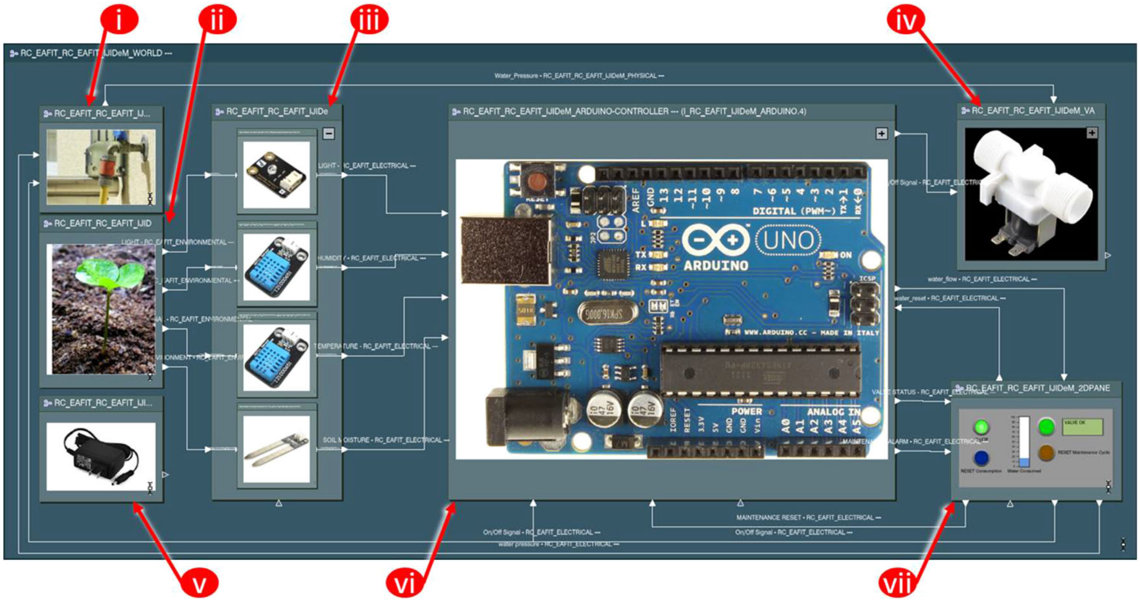


Fig. 2 Greenhouse irrigation system—logical architecture

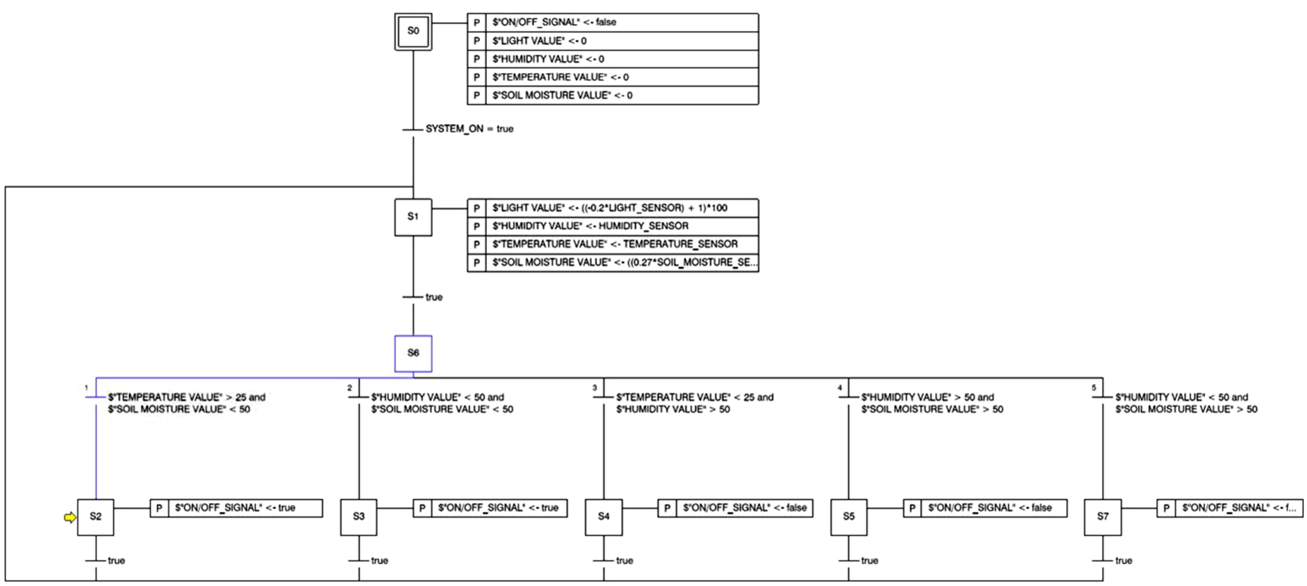


Fig. 3 Logical control detail

### 3.4 Physical

Finally, the 3D-Model was created, based on the final components that integrate the entire system. Thus, it served as a tool to verify assembly, tolerances and fittings. Additionally, it let the design team to define materials, manufacturing processes and assembly sequences, among others. Furthermore, the 3D-Model represents the physical properties of the virtual component and it has to be linked with the behaviors previously defined in the logical architecture (Sect. 3.3). Therefore, physical properties of the system, like inertia and weight, are taken into account during the simulation. Figure 4 shows the 3D–Model, where each logical component has a 3D representation. The list of system components, equivalent to those listed in the logical architecture, is:

i. Water source
ii. Plant
iii. Sensors
iv. Solenoid valve
v. 12v energy adaptor
vi. Arduino platform
vii. Control panel

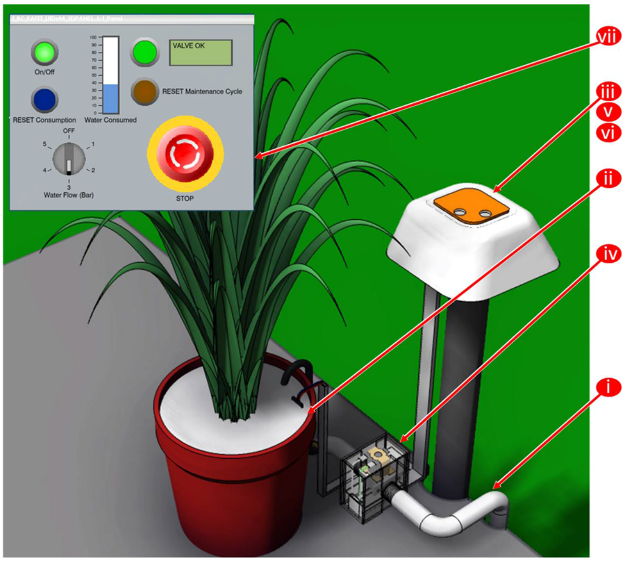


**Fig. 4** Greenhouse irrigation system—physical view (3D-Model)

**Fig. 5** Physical greenhouse environment

## 4 Physical implementation of the automated greenhouse irrigation system

### 4.1 Experimental greenhouse description

A local greenhouse environment was used as the experimental scenario for testing purposes of the physical prototype. As described before (see Sect. 3.1), the Greenhouse used for the case study belongs to the Industrial Processes Engineering department who has greenhouses for research purposes available at the campus. However most of them does not have any type of instrumentation or monitoring system in order to keep track of the system state. The case study was developed in the Greenhouse shown in Fig. 5.

The target greenhouse is located in the south area of the campus, near a three-floors building and it was created for research and academic works, mainly in the biological area. It has two entrances and is not totally isolated from the outside, as it has a space between the walls and the roof. The total area of the greenhouse is 50 m$^2$ and does not have industrial crops production. Inside the greenhouse there are tables of 8 m long in which the plants are located. Plants grow on individual plastic bags. It is not desirable to have a common soil for all the greenhouse, because of the type of treatments that can be performed, which includes: (1) promote plant growth, (2) induce plant diseases or (3) leave the plant untreated.

The irrigation of the selected greenhouse was initially programed at an specific time during the day without taking into account the real state of the plants. Data about the greenhouse state in terms of temperature, relative humidity, soil moisture and light intensity were not collected and no continuous automated monitoring was implemented.

The physical structure of the greenhouse was composed by stainless steel (structural) and plastic film (covers), as shown before. There is an open space between the walls and the roof, so the greenhouse is not totally isolated from the outside. For testing purposes, the modification of the walls and roof to have more control over the variables was dismissed as the main structure can not be modified while the biological experiments were in process.

### 4.2 Variables analysis

As mentioned before, and issued from the system requirements, the variables that mainly affect the greenhouse behaviour are:

- Temperature
- Relative humidity (RH)
- Light intensity
- Soil moisture

For monitoring those variables, low-cost Arduino compatible sensors where used. The data gathering and processing was carried using an Arduino UNO board (see details in Table 2).

It is important to remark, as mentioned in Sect. 1, that soil moisture is one of the most critical variables to control because, depending on its value, diverse fungi might attack

**Table 2** Implemented sensors and processor

| Component | Reference |
|---|---|
| Temperature and RH sensor | DHT11 |
| Light sensor | DFR0026 |
| Soil moisture sensor | SEN0114 |
| Processor | Arduino UNO board |

the plant. It is important to notice that the soil is not common for all the plants in the greenhouse, each of them grow in separate plastic bags. This is in order to keep the biological experiments safe.

In the implemented system, control actions to modify the soil moisture are carried by an electro-valve coupled to the irrigation system. For testing purposes, the soil moisture is part of a complete controlled loop in which the system is able to modify the environment, as for the modification of other variables, big changes must be introduced to the greenhouse itself which cannot be made during the biological experiments that were taking place. Nevertheless the other three variables (temperature, relative humidity and light intensity) must be monitoring because the intended output to the irrigation system is logically dependable of combinations among the four inputs. Also, those other variables represent important information for staff in charge of the greenhouse and people conducting the biological experiments.

### 4.3 Physical system set-up

The starting point for the implementation is the system tune-up through sensors calibration. Sensors were calibrated according to the greenhouse environment and the desired behaviour of the system. Relative humidity, light intensity and soil moisture are given in percentage, while Temperature is presented in Celsius degrees. The Soil Moisture sensor was calibrated experimentally by running tests with the real soil that the plants has in the greenhouse, letting the soil completely dry after one day of sun which correspond to 0 % of soil moisture and placing the sensor in pure water which represents 100 % of soil moisture. Also different points of moisture were taken between those two extreme points to guarantee an accurate equation for the signal adaptation of the sensor. This behavior was set according to Eq. 1, where SM is the value of the soil moisture and SR is the raw signal sent by the sensor.

$$SM = \frac{0.0675 \times SR - 2.3}{100} \tag{1}$$

For the physical implementation, the complete system was packed in a specially designed water-proof case (see Fig. 6), containing the sensors, processor and wireless communication devices.

The main system actuator, for controlling in closed loop the soil moisture, was a 3/4″ solenoid valve attached to the main entrance of the irrigation system. The rules for valve activation/deactivation signals, were sent directly by the Arduino board. The system could be connected by wire (USB Cable) or by wireless (ZigBee module) to a laptop computer to record data. As the valve was the only component available in the system for a direct reaction regarding the soil moisture, the system was capable of sending alerts to the user after a certain (configurable) number of activation cycles in order to be aware of preventive maintenance and avoid system failures.

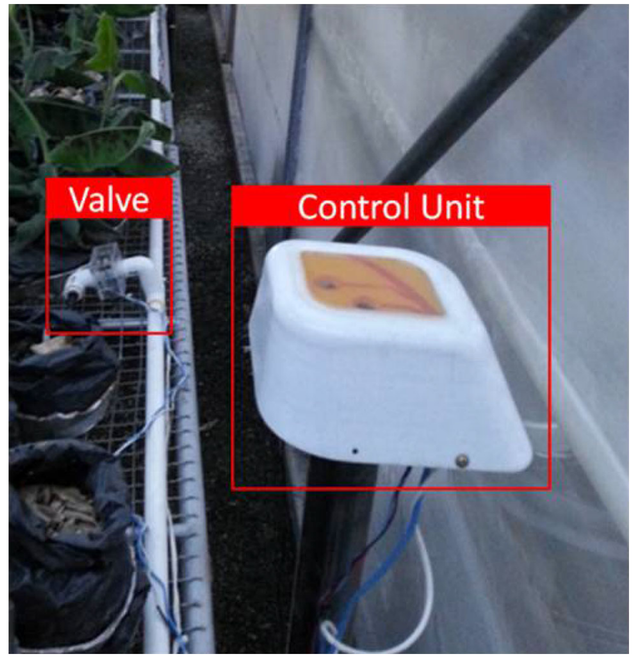


**Fig. 6** Real implementation

For all monitored variables, a desired level was selected and the rules for the activation/deactivation of the valve were defined heuristically according to these levels. Higher than the desired level or lower than the desired level. For the rules definition, Soil Moisture and Relative Humidity had priority as the most influential variables to define the irrigation action to take. Rain possibility can be predicted, when there is low temperature and high relative humidity, so the irrigation system is not activated. The complete set of rules can be seen in Table 3.

## 5 Results and discussion

As mentioned in Sect. 2.2, the modelling of complex systems enable timely decisions in systems design or operation. It is important for predicting system behaviour according to specific conditions. To do so, a reliable model is needed. That is the case of the current article where a virtual model (morphological and behavioural) of a greenhouse irrigation system was built, together with the real implementation of the system in a experimental greenhouse.

To verify the reliability of the virtual model, two validation scenarios were performed. Test 1: Virtual and physical implementations were tested by introducing specific input

**Table 3** Heuristic rules for irrigation system activation

| Temp. | Relative humidity | Light | Soil moisture | Irrigation |
|---|---|---|---|---|
| High | High | High | High | Off |
| High | High | High | Low | On |
| High | High | Low | High | Off |
| High | High | Low | Low | On |
| High | Low | High | High | Off |
| High | Low | High | Low | On |
| High | Low | Low | High | Off |
| High | Low | Low | Low | On |
| Low | High | High | High | Off |
| Low | High | High | Low | Off |
| Low | High | Low | High | Off |
| Low | High | Low | Low | Off |
| Low | Low | High | High | Off |
| Low | Low | High | Low | On |
| Low | Low | Low | High | Off |
| Low | Low | Low | Low | On |

**Table 4** System response using simulated weather input values

| Variable | Virtual model | Real implementation | Dif. | Error (%) |
|---|---|---|---|---|
| Total opening time (s) | 390.5 | 390 | 0.5 | 0.128 |
| Water consumption (L) | 19.525 | 19.5 | 0.025 | 0.128 |

values to the different variables that are monitored (temperature, soil moisture, relative humidity and light intensity), in order to simulate different weather conditions that may affect the system. Therefore, system's response to different weather changes was tested and compared between the virtual model and the physical implementation. Test 2: After validating the behavior of the virtual model, another test was performed in order to validate system's response to real-weather input values, as it would be in real operational conditions. For this scenario, real measurements of monitored variables where the input for both, virtual and physical implementations of the greenhouse irrigation system. The total time that the valve remains open, the number of activations and the consumed water were the outputs used in both experiments to compare the physical and virtual implementation. The error percentage shows how accurate is the virtual model in comparison to the physical implementation and could be used for future predictions. Results from both tests are described and analyzed below.

### 5.1 Test 1: simulated weather input values

The virtual model was tested under a simulated weather environment, were specific input values were defined for the monitored variables, in order to determine system's behaviour under specific weather conditions. Variable's values were forced to predetermined levels. Output variables were the total time that the valve remained opened and water consumption. Additionally, the total opening time was used to calculate the water flow rate, which depends on the amount of water volume by time and can be calculated by using $Q = V/\delta t$. Where $Q$ is the water flow rate, $V$ is the volume and $t$ is the time.

Next, the simulated environmental changes (by giving specific values to input variables) were replicated for the real implementation in order to find the similarities/differences of both behaviours. For testing and comparative purposes, a 30 s sampling time was defined for the virtual simulation and real implementation. As both models ran under the same system settings and environmental conditions, the total amount of consumed water was used to compare their behavior.

Results obtained from the test, demonstrated that the virtual model shows to be reliable in terms of simulating the expected behaviour of the implemented physical system. System's response differences between the virtual model and the physical implementation are shown in Table 4, which presents the valve's total opening time and consumed water. Besides, the percentage error was calculated for each output

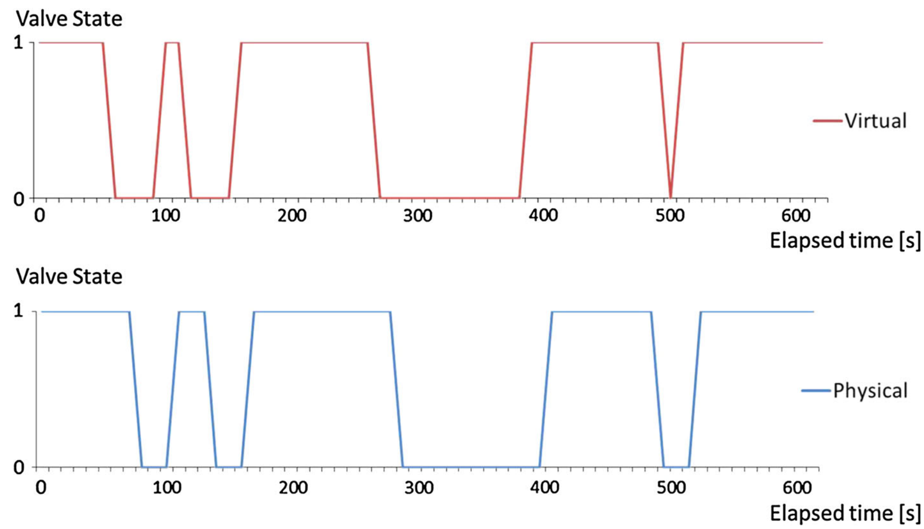


**Fig. 7** Valve activation behaviour during simulated weather tests

variable in order to compare the accuracy of the virtual model against the physical one (Eq. 2).

$$E = \left| \frac{VM - PM}{PM} \right| \quad (2)$$

where $E$ is the percentage error, $VM$ is the value obtained from the virtual model and $PM$ is the value obtained from the physical model.

On the other hand, regarding the opening time difference, it is due to a delay that takes place between reading the variable value and sending the order to the valve. This delay, can be clearly seen in Fig. 7, which compares the valve activation signals for both models.

It is important to remark that, as it was shown in Fig. 7, the deviation between the virtual and real response is due to sample time differences. In the virtual model, it is possible to determine more accurately when the valve change its state (open/close). However, in real implementation, the valve status detection depends on sample time, as it is only possible to know that between two samples, a change of state occurred. This can be minimized by reducing sampling time. However for the purpose of the present project it was admissible for predicting consumption accurately.

### 5.2 Test 2: real-weather input values

Having proved the reliability of the virtual model under a simulated weather environment, a second test was performed using real-weather input values. The physical device was installed in the real greenhouse environment. However, as real conditions usually do not change as fast as they did in the simulated weather environment test, the field test had to be conducted during almost an entire day (21.3 h). Therefore, a sampling time of ten minutes had to be defined in order to reduce the amount of data gathered from the WSN, obtaining 129 sample points for each variable.

As well as in the simulated weather environment tests, output variables were the total time that the valve remained open and water consumption. Figure 8 presents the results obtained from both models, the virtual and the physical one, showing the behavior of the four monitored variables during the test. Values obtained from the light and relative humidity sensors clearly show the difference between day and night, where light and temperature values decrease during the night while relative humidity increases due to dew.

On the other hand, Fig. 8 illustrates the behavior of the controlled variable (soil moisture) vs. set point. It shows how the system is able to take the soil moisture value up to the desired set point. Nevertheless, as the control strategy used was not the optimal, a higher quantity of on/off cycles were needed in order to guarantee the correct soil moisture value. Consequently, the valve life span will be reduced due to the frequency of the activation/deactivation signals.

Finally, Table 5 compares the results obtained from the virtual simulation and the physical implementation. In this case, the difference between both models was higher than the ones presented in Table 4 for the simulated weather inputs. It is mainly due to the fact that the soil moisture sensor signal was affected by electromagnetic noise, which was not taken into account in the virtual model. Therefore, values obtained from the physical soil moisture sensor differ from the virtual one. Thus, activation/deactivation signals sent by the controller where different in both cases, even if the same values were evaluated under the same rules for both models. This can be clearly seen in Fig. 9, which compares the valve activation signals for both models.

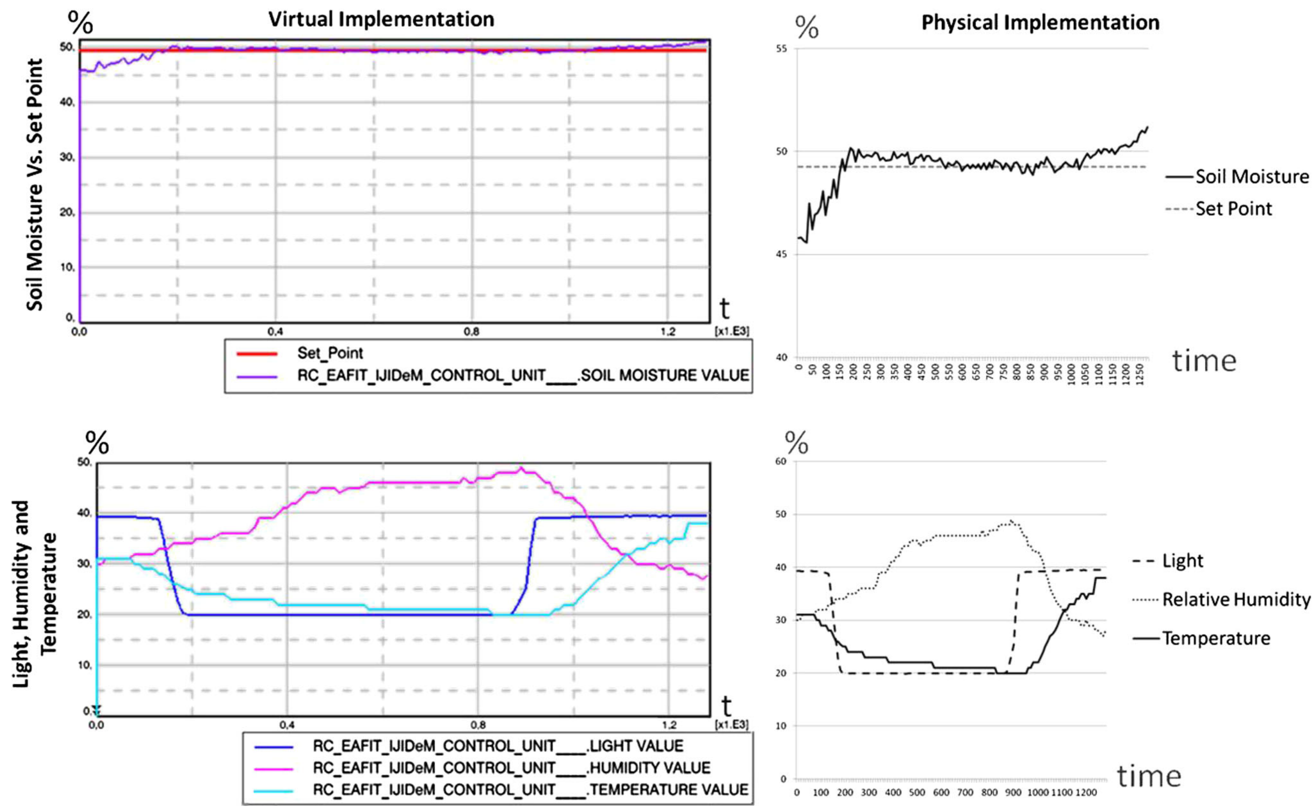


**Fig. 8** Virtual vs. physical implementation

**Table 5** System response using real-weather input values

| Variable | Virtual model | Real implementation | Dif. | Error (%) |
|---|---|---|---|---|
| Total opening time (s) | 669,0 | 682,3 | 133 | 1.949 |
| Water consumption (L) | 334,5 | 341,15 | 6.65 | 1.949 |

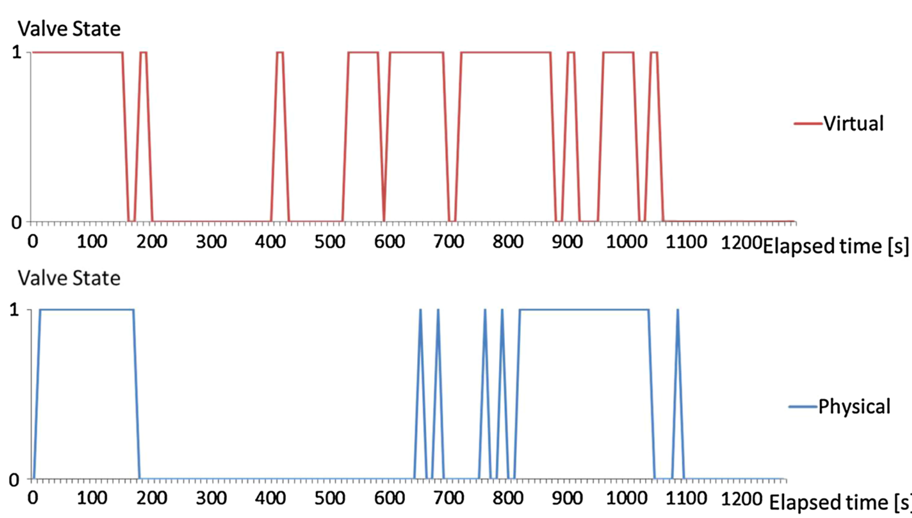


**Fig. 9** Valve activation behaviour during real-weather tests

## 6 Conclusions and further work

Complex systems simulation often requires the implementation of the physical system to validate models. Therefore, experimentation and modelling are closely related and dependable, as a reliable simulation is only completed once it is compared with the behaviour of the physical system. Nevertheless, when no historical data or information about the system is available, enriched virtual simulations help system designers to test and evaluate their concepts based on hypothetical situations, or just taking the system to critical states without risking physical resources. Consequently, after having proved the reliability of a system's virtual model, able to represent the real behaviour, such a model can be used for further system optimization and tests.

Specifically for the article's case study, greenhouse models can be used to make predictions about how will the system react under certain extreme conditions, like floods, droughts, among others. Additionally, it provides a great environment to test new control strategies, while it allows programmers to simulate the control strategy under almost-real working conditions, avoiding possible costs related to real system failure and damages, as it would be if an erroneous program is implemented into the physical system. Therefore, physical systems can keep running, while a new and optimized design or control strategy is under development by using the virtual analysis to be further implemented.

Moreover, virtual prototyping helps to get real implementations with less uncertainty about its performance. This can be evidenced by analyzing the percentage error value previously shown in Sect. 5, that can be used for future predictions about the system behaviour. The total opening time and water consumption percentage error was about 2 %, showing that the virtual model is accurate and is able to predict values for those outputs. On the other hand, as it was previously shown in Fig. 9, the number of activation signals was different on both models. Such difference can be explained by noise signals in the the physical model sensors. Besides, as the virtual model has a smaller sample time, small variations on the input signals may activate the valve, those changes might not be detectable using the real controller. However, the total time that the valve remains open and the water consumption are reliable indicators of the system behaviour as are directly related to the main output that finally is the water that goes to the crops. According to this, for future implementations the number of valve activations is not recommended as an indicator for the model reliability.

Finally, the RFLP approach can be considered as an Interactive Design technique, while it fulfils in a high rate the three (3) kinds of interactions presented before in Sect. 2.2. Regarding cognitive interaction, as the RFLP is supported by a Product Lifecycle Management (PLM) software, it allows collaboration from the different disciplines involved during the development process, such as marketing and design engineering. Furthermore, by enhancing collaboration, individual knowledge of experts can be transferred and shared within project members. In terms of sensorial interaction, human-machine interfaces can be created, therefore, user experience and interaction can be included at early design stages, without the need of physical prototypes. Thus, decision making regarding the developed product or system, can be supported either by user-interaction and technical tests performed on the virtual prototype. Finally, respecting pure physical interactions, the virtual prototype can be immersed into the environment in which it will be used, whether it is modeled directly into the software or by implementing Hardware in the Loop (HILs)/Software in the Loop (SILs) simulations to test how the product will behave in its future environment.

Consequently, further work is required in order to enrich the models and improve the three kinds of interactions previously named. For instance, for pure physical interactions, data given by sensors, directly from field, can be gathered and presented in real-time and be widely available by using ICTs and Internet connection, immersing the product into its final environment. The system can be enriched by adding more complex weather forecasting models to test system behavior and foresee possible scenarios that may affect the crops beforehand. However, by having a virtual model that represents the real system, it is possible to test new improvements to the system before change the real implementation. Additionally, important alerts can be send to the stakeholders of the greenhouse by using email, SMS, etc. Adding more functions to the system and reducing the time and frequency of visits to the greenhouse.

**Acknowledgments** Special thanks to EAFIT University for providing financial support and the experimental greenhouse, both needed to develop this project. Special thanks to the ENIM (École Nationale d'Ingénieurs de Metz) and Dassault Systèmes to invite EAFIT University to participate in the Global Factory project, from which the present case study came from.

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