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A MATHEMATICAL MODEL TO ENABLE THE VIRTUAL COMMISSIONING SIMULATION OF WICK SOILLESS CULTIVATIONS

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Abstract

Soilless culture is seen as a promising tool in the vision of food security due to its ability to provide intensive food production in limited areas with more efficient utilization of the resources. In this context, flexible test-benches can be developed to investigate optimal fertigation strategies to maximize returns on inputs while preserving resources. However, flexible test-benches are more complex than traditional soilless systems since the control software must concurrently manage different fertigation strategies, and a larger number of sensors and actuators is utilized. In this work, the use of the Virtual Commissioning (VC) simulation is embraced for supporting the design of the control software of flexible test-benches and its functional verification. A mathematical model that reproduces the discrete-event behaviour of the physical system is proposed and applied to a case study for demonstrating that the introduced modelling approach enables the VC simulation of flexible test-benches for wick soilless cultivations. Given the importance of the food security challenge in the 'worldwide landscape', it is expected that this work may enhance the investigation in the research topic of farming strategies for soilless culture.

Keywords: Control software, Modelling, Soilless culture, Virtual commissioning, Wick cultivation.

1. Introduction

Food security is the most urgent challenge for the agricultural sector since the global population is exceeding 7.2 billion and is continuously increasing. In 2050, population has been estimated to reach 9.6 billion with more than 60% living in urban areas [1]. However, different factors complicate this context such as the progressive drop of fertile soil surface [2], the development and diffusion of many pathogens due to the monoculture approach [3], and the high resource consumption due to the volumes of water and fertilizer lost in the ground due to leaching [4].

Soilless culture is seen as a promising tool in the vision of food security due to its ability to provide intensive food production in limited areas with more efficient utilization of the resources, including non-arable areas such as deserts and cities [5]. Soilless culture is a method of growing plants in an inert medium using a solution of mineral nutrients dissolved in water [6]. Among the different practices, this work deals with wick soilless cultivation. In this practice, plants are fed with a nutrient solution via ‘wicks’ such as Pro-Mix, Vermiculite, Perlite or Coconut Fiber wicks amongst others. Like all the soilless culture practices, wick soilless cultivation depends on different agronomic and environmental variables that must be controlled to optimize returns on inputs while preserving resources [7].

Food production with soilless culture is going to reduce the most relevant differences between agricultural and industrial processes [8]. Few evidence can be found considering that production processes are: (i) carried out in contained and more controllable spaces (e.g., greenhouses, tunnels, etc.); (ii) are more repeatable due to the control of several variables, such as lighting, climatic parameters and nutrient supply amongst others; (iii) can be more easily automated. Therefore, technologies of the industrial automation domain are being applied in soilless culture.

In a recent survey concerning the adoption of automation technology in soilless culture [9], it is remarked that research should be performed to identify optimal ‘set-points’ for the controlled variables. However, this optimization problem is complex since the set-points depend on several factors such as the cultivated crop and its stage of growth. Mathematical models and experimental approaches are being utilized to solve this problem. According to Barbieri [10], a flexible test-bench is proposed for wick soilless cultivations to investigate optimal fertigation strategies through experimentation. The proposed test-bench is potentially able to individually manage different samples of crops in terms of irrigation dose and frequency, and concentration of the delivered nutrient solution. Therefore, different fertigation strategies can concurrently be implemented and compared. However, the complexity of the test-bench is higher than traditional soilless systems since the control software must concurrently manage different fertigation strategies, and a larger number of sensors and actuators is utilized.

In the industrial automation domain, Virtual Commissioning (VC) is generally utilized for the design and verification of the control software of complex systems. VC enables the evaluation of the system’s functionality, performance and safety before its physical assembly and commissioning [11]. VC is performed by interfacing a simulation model that reproduces the discrete-event behaviour of the physical plant to the hardware or emulated controller which contains the software to be validated. Nowadays, VC is implemented in many automation applications [12], due to its ability to speed-up the commissioning process. For instance, an industrial study showed that real commissioning time is reduced approximately by 75% when VC is implemented beforehand [13].

As shown by Lee and Park [11], there can be two possible configurations in VC: Hardware-in-the-Loop (HiL) commissioning involving a virtual plant and a real controller; Software-in-the-Loop (SiL) commissioning involving a virtual plant and an emulated controller. HiL commissioning is generally utilized for validating non-functional requirements, while SiL commissioning for functional ones. In this context, *f*unctional requirements define how the system must operate, while non-functional requirements specify additional system properties, such as its performance [14]. Being a first research on the topic, only the verification of functional requirements through SiL commissioning is considered within this work.

In the context of wick soilless culture, the novelty of this work is the introduction of a mathematical model to enable the use of the VC simulation for the design of the control software of flexible test-benches and for the verification of the system functional behaviour. The article is structured as follows: Section 2 describes the state of the art, and the proposed mathematical model is introduced in Section 3. Section 4 applies the model to the flexible test-bench presented by Barbieri [10]. Obtained results are discussed in Section 5 and finally, Section 6 presents the conclusions and sets the directions for future work.

2. State of the Art

The literature concerning the adoption of automation technology in soilless culture is continuously increasing as shown in Fig. 1. This figure was obtained by searching the following list of keywords within the Scopus database: (soilless culture or wick or hydroponics or aeroponics) and (automation or automatic or automated). Papers containing the chosen keywords in their title, abstract or keywords were plotted. The list of selected keywords was defined considering that soilless culture refers to all the practices of growing crops in an inert medium such as wick culture, hydroponics and aeroponics [5].

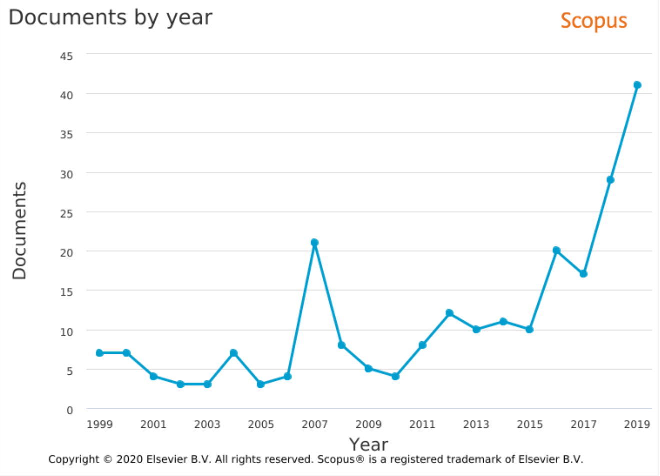


Fig. 1. Papers concerning the adoption of automation in soilless culture published in the last twenty years

Modu et al. [9] show extensive literature review concerning the adoption of automation technology in soilless culture. Automation has been utilized especially for the fertigation management since the pH and electrical conductivity (EC) values of the solution influence the nutrient uptake by plants, and consequently the plant productivity [15]. Automated systems able to deliver a nutrient solution with established values of pH and EC have been investigated since the 90s [16]. On the one hand, systems able to control the pH and EC values but not the individual ions have been developed [17-21]. On the other hand, systems able to individually control pH, macro- and micro-nutrients have been proposed [22, 23]. Automation has also been utilized to improve the energy efficiency of the process [24, 25], to control additional agronomic and environmental variables such as led light, temperature, and water level [26, 27], and to remotely monitor and control the physical system [28, 29]. However, the literature lacks studies on the adoption of the automation for the development of flexible test-benches.

Flexible test-benches are more complicated than traditional soilless systems since the control software must concurrently manage different fertigation strategies, and a larger number of sensors and actuators is utilized. Virtual Commissioning can be used for the design and verification of the control software before the physical assembly and commissioning of the system. VC requires the development of a simulation plant model fully described at the level of sensors and actuators. However, only biological models able to simulate the crop growth and the plant nutrient uptake have been proposed for soilless cultures [30-32]. To develop the control software through VC, discrete-event simulation models must be implemented. Given this, the novelty presented in this work is the introduction of a mathematical model to enable the VC simulation of wick soilless cultivations for the design and verification of the system functional behaviour.

3. Mathematical Model for Wick Soilless Cultivations

This section describes the proposed mathematical model and is structured as follow: the requirements identified for modelling wick soilless cultivations are illustrated in Section 3.1. Section 3.2 presents the defined mathematical model, and Section 3.3 shows its implementation in the Simulink simulation environment.

3.1. Model requirements

A model is any description of a system that is not the ‘thing-in-itself’ (*das ding an sich* in Kantian philosophy). Every model is designed to study some property of a system and must implement the correct abstraction to properly reproduce the investigated property [33]. For this reason, it is fundamental to establish which aspects should be simulated before starting the modelling process. The following requirements are identified to enable the VC simulation of wick soilless cultivations:

- Modelling actors: The model must implement the behaviour of the processes and elements typical of wick soilless cultivations:
    - Processes: In wick soilless cultivation the following processes are commonly implemented: Water filtering to remove water chloride and total suspended solids (TSS); EC and pH correction to generate a nutrient solution with an established value of pH and EC; fertigation to irrigate the crops with the generated nutrient solution

  - Components: Pipes, filters, drip emitters, substrate, plants, and tanks containing water; concentrated nutrient solutions for the EC correction; acid for the pH correction.
  - Actuators: Solenoid valves and pumps for generating the nutrient solution and performing the fertigation operation, thermal resistances for regulating the nutrient solution temperature, and air compressors for agitating the concentrated nutrients to avoid their precipitation; mixing the nutrients with the water during the preparation of the solution; improving the efficiency of the heating operation.
  - Sensors: pH and EC meters for the generation of the nutrient solution, thermocouples for the temperature control, and specific sensors for detecting physical boundaries and alarm conditions; e.g., level sensors, etc.
- Functional behaviour: Since the objective of the model is to support the design and verification of the functionality of wick soilless cultivations, the model does not need to perfectly mimic the continuous-time behaviour of the physical system. For instance, it is not necessary to model the chemical reactions that occur during the preparation of the nutrient solution or the plant nutrient uptake. To enable the development of the control software, the model only needs to replicate the sequence of events that occur in the physical system; viz. its discrete-event behaviour.
- Interface: VC is valuable only if the verified control software can be deployed into the physical controller without the need of changes, which may constitute a source of error. Therefore, the developed model must implement the same interface in between the controller, and the physical sensors and actuators to enable the seamless deployment of the verified code.
- Graphical display: A graphical display able to represent the system state must be available to facilitate the code debug operation.

3.2. Mathematical model

The mathematical model is described using the nomenclature of the state-space representation, where ‘*u*’ indicates a controller output signal, and ‘*y*’ a controller input signal. The model applies for a double stock system [34], where two stocks of concentrated nutrients (i.e., stock A and B) are utilized for controlling the EC value, and one stock of acid for the pH correction. However, similar equations can be developed for a system able to control the individual ions of the nutrient solution. Next, the mathematical model of the elements identified in Section 3.1 is illustrated:

- Tank: Defining as Q the volumetric flow rate and D_t the tank diameter, the liquid volume V_t and height h_t within the tank are calculated as:

$$V_{\mathrm{t}} = V_0 + \int (Q_{out} - Q_{in})dt \tag{1}$$

$$h_{\mathrm{t}} = \frac{4 \cdot V_{\mathrm{t}}}{\pi \cdot D_t^2} \tag{2}$$

- Digital level sensor: The sensor is physically positioned at a certain height within the tank $h_{threshold}$:

$$y_{out} = \begin{cases} 1, & if\ h_t \geq h_{threshold} \\ 0, & if\ h_t < h_{threshold} \end{cases} \tag{3}$$

- Analogue level sensor continuously senses the liquid height within the tank:

$$y_{out} = h_t \tag{4}$$

- Pump: Delivers liquid only if the controller has turned the pump on ($u_p = 1$) and if the upstream tank has liquid ($V_{up} \geq 0$):

$$Q_{out} = \begin{cases} Q_{pump}, & if\ (u_p = 1\ \&\ V_{up} \geq 0) \\ 0, & otherwise \end{cases} \tag{5}$$

- Solenoid valve: Delivers liquid only if the controller has turned the solenoid valve on ($u_{el} = 1$))::

$$Q_{out} = \begin{cases} Q_{in}, & if\ u_{el} = 1 \\ 0, & if\ u_{el} = 0 \end{cases} \tag{6}$$

- Reverse osmosis filter: Used to filter water chloride. This component is characterized by a waste to water ration that we model with the constant k_f. For instance, a 1:1 waste to water ration indicates a $k_f = 0.5$:

$$Q_{out} = k_f \cdot Q_{in} \tag{7}$$

- Mesh filter: Used to filter solid particles and does not modify the flow rate:

$$Q_{out} = Q_{in} \tag{8}$$

- EC control: A weighted average is utilized to model the change in EC. The suffix '*A*' indicates the concentrated solution coming from stock A, '*B*' the one coming from stock B, and '*W*' the tap water:

$$EC_s = \frac{EC_A \cdot V_A + EC_B \cdot V_B + EC_W \cdot V_W}{V_A + V_B + V_W} \tag{9}$$

- EC meter: Analogue sensor that continuously senses the EC of the solution:

$$y_{out} = EC_s \tag{10}$$

- pH control: A weighted average is utilized to model the change in pH. The suffix '*a*' indicates the solution coming from the acid stock, and '*m*' the liquid within the mixing tank:

$$pH_s = \frac{pH_a \cdot V_a + pH_m \cdot V_m}{V_a + V_m} \tag{11}$$

- pH meter: Analogue sensor that continuously senses the pH of the solution:

$$y_{out} = pH_s \tag{12}$$

- Temperature control: An ideal thermal resistance is utilized for heating the nutrient solution, where for ideal is considered that the electrical power is converted into heat without losses. The actual temperature T_s can be computed from the initial temperature T_i the resistance power P and the solution specific heat capacity c_s and mass m_s:

$$T_s = T_i + \int \frac{P}{m_s \cdot c_s} dt \tag{13}$$

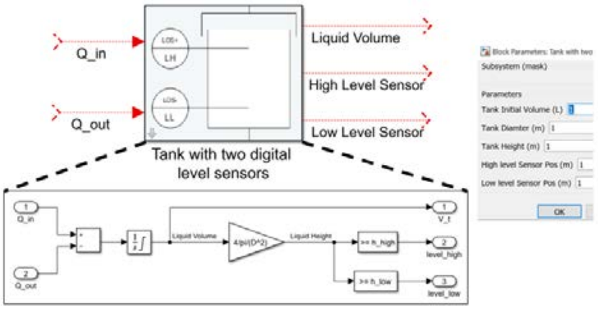
- Thermocouple: Analogue device that continuously senses the temperature of the solution:

$$y_{out} = T_s \tag{14}$$

In the mathematical model, pipes are not implemented since the focus of the model is not their dimensioning. Drip emitters are simulated by setting the flowrate of the upstream pump as the sum of the flow rate of the drip emitters. Air compressors are represented as LEDs since do not produce any effect on the modelled elements. Substrate and plants are modelled as tanks. The pH and EC are dealt as two independent variables since the change in the EC value induced from the pH correction has been demonstrated to be negligible [35]. Finally, it can be noticed that the model only contains the discrete-event behaviour of the physical components and does not include any controller element. In fact, the control functionality will be integrated through the connection of the physical model with the emulated controller for the realization of the SiL commissioning simulation.

3.3. Model implementation

The implementation of the mathematical model in Simulink is shown in Fig. 2 for a tank with two digital level sensors. The algebraic and dynamics equations of the components are first modelled. In this case, equations (1-3) are implemented for simulating the intended behaviour. Then, a ‘mask’ is generated for creating an ‘input-output’ representation of the element, and an image is associated to the mask for improving the model readability. Finally, a ‘parameter dialog box’ is created for configuring the actor with the parameters of the corresponding physical component. In the case of the considered tank, the user can define the liquid initial volume, the tank height and diameter, and the physical position of the two digital level sensors.



Tank Initial Volume (L) 1
Tank Diamter (m) 1
Tank Height (m) 1
High level Sensor Pos (m) 1
Low level Sensor Pos (m) 1

Fig. 2. Simulink model of a tank with two digital level sensors.

4. Case Study

In this section, the mathematical model presented in Section 3 is applied to the flexible test-bench for wick soilless cultivations illustrated by Barbieri [10]. Section 4.1 resumes the previously proposed test-bench, while Section 4.2 applies the model to the test-bench.

4.1. Flexible test-bench for wick soilless cultivations

The flexible test-bench for wick soilless cultivations is a double stock open system, meaning that only pH and EC are controlled, and fresh nutrient solution is supplied with each irrigation. The test-bench consists of two modules respectively shown in Figs. 3 and 4 with the PID representation (piping and instrumentation diagram). Each element is named with a character followed by 3 digits. The character indicates the role of the component, while the first and second digits respectively the assembly unit and the tank in which is placed. The last digit is utilized for digital level sensors to differentiate between high-level and low-level sensors. The last digit is set to 0 for high-level sensors, and to 1 for low-level sensors. For instance, L121 defines a digital low-level sensor placed in the tank 2 of unit 1. Next, the two modules are illustrated.

The Nutrient Solution Module (NSM) is responsible for preparing nutrient solutions with an established value of pH and EC (Fig. 3). The NSM consists of:

- Filtration Unit: Tap water is collected into the T110 tank through the activation of the V110 solenoid valve. Then, the P110 pump supplies the water into the F110 inverse osmosis filter for reducing its chloride and TSS content. Finally, the filtered water is accumulated into the T120 tank connected to the recipe preparation unit through the P120 pump. Two digital level sensors are placed into the two tanks for triggering the filling and emptying operations.
- Recipe Preparation Unit: C200 air compressor agitates the fertilizer tanks T220 and T230 to prevent the concentrated nutrients from settling down. Whereas the T210 acid tank does not require agitation. Air is also delivered to the T240 mixing tank for mixing the nutrients during the preparation of the solution. A low-level sensor is *placed* on tanks T210 (acid stock), T220 and T230 (A and B stocks) to inform the operator when the acid and the concentrated nutrients must be refilled. Peristatic pumps P210, P220 and P230 delivers acid and nutrients for the control of the pH and EC of the solution. The actual value of the pH and EC is respectively sensed with the Q240 and I240 meters. The A240 analogue level sensor continuously senses the liquid height within the tank.

The fertigation module (FM) is responsible for the implementation of the fertigation strategy and can independently manage two samples of plants. The FM is illustrated in Fig. 4 and consists of:

- Warm-up Unit: Once the P300 pump is active, V310 solenoid valve delivers the solution prepared in the NSM to the T310 tank. The solution is heated using the H310 electrical resistance. The actual value of the temperature is sensed with the T310 thermocouple and the C300 air compressor is turned-on to improve the efficiency of the heating operation. The L311 low-level sensor is placed on the tank for indicating when the nutrient solution must be refilled. Apart from the pump P300, two instances of each component are implemented since two samples of plants are independently managed.

Distribution Unit: V410 solenoid valve and P410 pump are activated to enable the fertigation of the T410 crop sample. The nutrient solution goes across the F410 mesh filter to remove solid particles that may damage the pump. M410 hygrometer continuously senses the moisture of the crop sample and fertigation is triggered when a ‘low threshold limit value’ is reached. Again, two instances of each component are implemented since two samples of plants are independently managed.

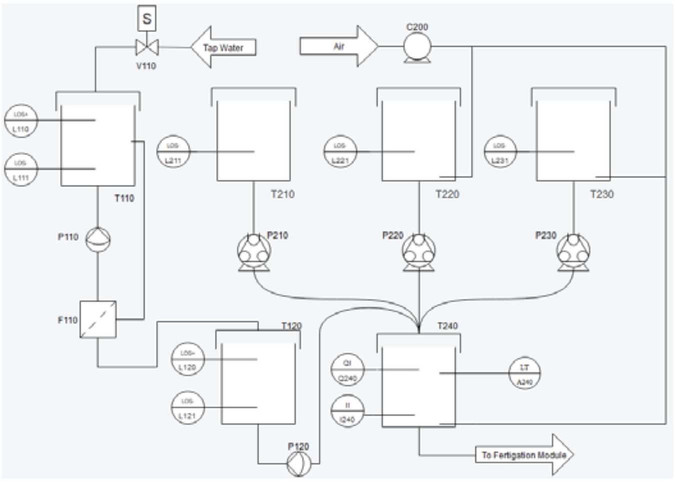


Fig. 3. PID diagram of the Nutrient Solution Module [10].

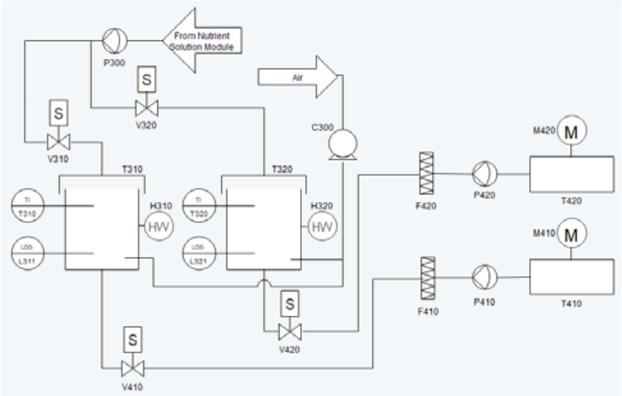


Fig. 4. PID diagram of the Fertigation module [10].

4.2. Mathematical model of the flexible test-bench

Next, only the mathematical model of the NSM module is illustrated (Fig. 5). The equations described in Section 3.2 were modelled in Simulink following the method indicated in Section 3.3. Then, the obtained actors were connected for implementing the behaviour of the NSM. Finally, the 'parameter dialog box' of each actor was configured for instantiating the different elements. 'From' and 'Go to' blocks were utilized to pass a signal from one block to another without visually connecting them. In this way, the model is 'cleaner' and visually replicates the PID diagram shown in Fig. 3.

The graphical display representing the status of the module is illustrated in Fig. 6. Since the control software will be deployed into the CoDeSys PLC (programmable logic controller), the graphical display was modelled in the CoDeSys programming environment. Tanks, sensors, and pipes were drawn using the shapes provided from the CoDeSys visualization library, while pumps, air compressors and solenoid valves were represented by importing the image of their

PID symbol. Different colours were utilized for indicating the status of digital sensors and actuators. For instance, the V110 solenoid valve is active in Fig. 6, along with the low-level sensors L111, L211, L221 and L231. Whereas the value sensed from analogue devices is directly shown in the graphical display. Finally, the liquid height within the tank was scaled to effectively mimic the actual height that the liquid would have in the physical system.

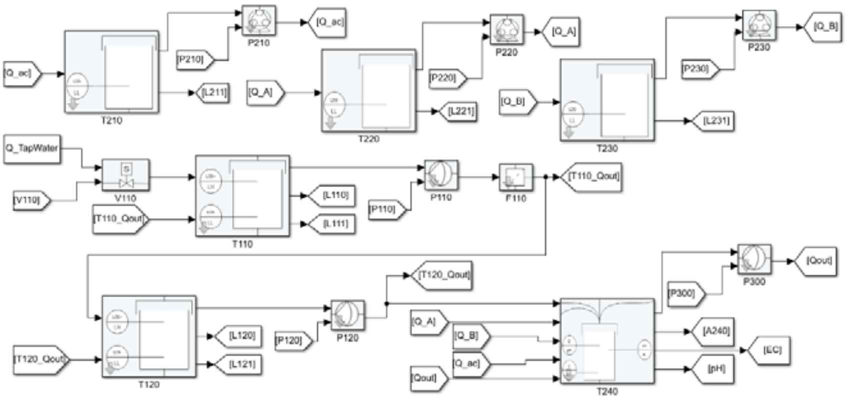


Fig. 5. Simulink model of the Nutrient Solution Module.

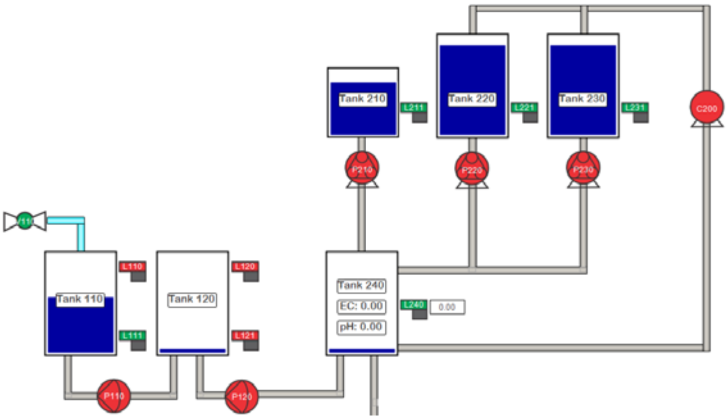


Fig. 6. CoDeSys graphical display of the Nutrient Solution Module for visualizing the status of the physical plant.

5. Results and Discussion

In this section, the methodology presented in Fig. 7 is applied to validate the role of the proposed mathematical model for supporting – through VC simulation – the design of the control software of the flexible test-bench and its verification of functional requirements. The control software is first conceptualized using the state machine diagram formalism. Then, the diagram is converted into PLC code through the application of a design pattern. After that, a VC simulation is implemented for verifying the obtained PLC code. Finally, test cases are generated from the functional requirements to formally verify their fulfilment. In this section, only the design and verification of the control software for the NSM is presented.

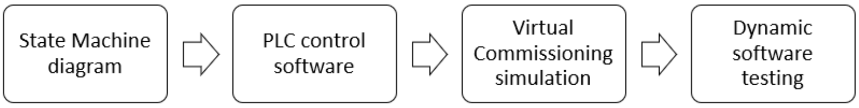


Fig. 7. Methodology utilized for validating the role of the proposed mathematical model in the development of the control software of the flexible test-bench.

The control software was first conceptualized using the state machine diagram [36]. This formalism enables the representation of the discrete-event behaviour of a system through finite state transitions. The initial state is selected using a filled black circle. Each state has an ‘internal activities compartment’ that holds a list of actions performed while the state is active. Entry actions are executed upon entry to the state, do actions as long as the state remains active, and exit actions upon exit from the state. A Boolean condition is set on each transition to evaluate when the transition to the subsequent state can take place. Finally, a state that contains nested states (viz. ‘composite’ state) can be generated for states that have common actions and/or transitions.

The state machine diagram of the NSM control software is shown in Fig. 8. A sequential behaviour is implemented by first filling tanks T110 and T120, and then sending the filtered water to the T240 mixing tank for the preparation of the nutrient solution. Since the module must manage two different nutrient solutions, a specific target value of EC and pH is assigned based on the considered sample of plants. Composite states are utilized for states that have common actions and/or transitions. For instance, the C200 air compressor must work throughout all the steps of preparation of the nutrient solution. Therefore, a ‘nutrient solution generation’ composite state is introduced. Apart from the normal functioning behaviour, an ‘alarm’ state is implemented for automatically stopping the system in case of malfunctioning. The alarm transition is triggered either when: the operator presses the ‘alarm’ interrupter on the HMI; the liquid volume within the mixing tank is above a ‘high threshold limit value’; the acid or the concentrated nutrient tanks must be refilled.

After its representation with the state machine diagram, the control software was converted into Structured Text PLC code (ST) using the design pattern presented by Bonfe et al. [37]. A scalar ’state’ variable is utilized as a discriminator of a switch statement, i.e., CASE ... OF in ST. Transitions are evaluated by means of IF … THEN constructs and if a transition is fireable, the new state is assigned, and the exit behaviour is executed. Entry actions are implemented by using an ’entry’ flag and an IF ... THEN construct that resets the flag once the entry action has been performed. Nested states are generated with additional CASE … OF constructs placed within an IF structure that grants the execution of the nested behaviour only when the superordinate state is active. The activation of the actuators is performed in a different program organization unit (POU) written in ladder diagram (LD). ‘Coils’ are utilized to automatically make the actuators stay on as long as the state remains active. Whereas the actuator management within the ST POU would have required to set and reset the associated variable for its control.

Part of the PLC control software of the NSM is shown in Fig. 9. The NSM state machine has three hierarchical layers (i.e., composite behaviours) that are implemented with the region, state and substate scalar variables. The left-hand side of Fig. 9 illustrates the behaviour of the ‘waiting’ and ‘nutrient solution generation’ states. The initial IF construct grants their execution only when the 'working' composite state is active. The CASE construct selects the active state among the nested states of the 'working' composite state. The 'waiting' state implements an exit behaviour for selecting the tank of the 'production line' that must be refilled. Whereas the 'nutrient solution generation' composite state executes an entry behaviour to set the initial state among its nested substates.

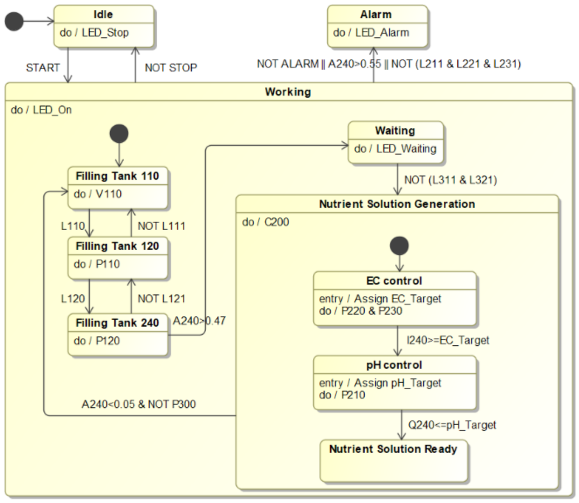
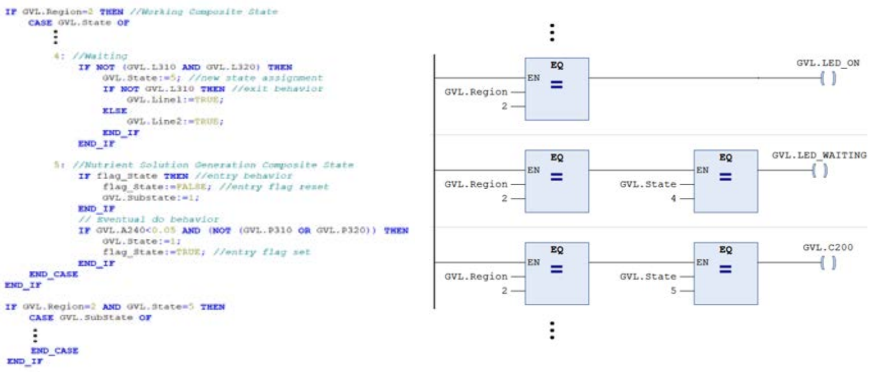


Fig. 8. State machine diagram of the NSM control software.

The activation of the actuators is shown in the right-hand side of Fig. 9. Equality operators are utilized to activate the actuator only when the proper state is active. It can be noticed that 'on' and 'waiting' LEDs are respectively on when the 'working' and 'waiting' states are active, while the C200 air compressor when the 'nutrient solution generation' state is active.

Then, the SiL Virtual Commissioning simulation was implemented to verify the system functional behaviour. CoDeSys offers an integrated Soft-PLC, named CoDeSys Win Control V3, that emulates an industrial controller under Windows enabling the virtual execution of the control software. Therefore, the VC simulation was performed by interfacing Simulink and CoDeSys Win Control V3 using the OPC protocol (Open Platform Communications). CoDeSys Win Control V3 was run providing the control functionality to the Simulink model of the physical plant. Then, errors of the control software were identified and fixed by inspecting the status of the graphical interface. A video illustrating the result of the VC simulation is made available to the reader.

After the verification of the control software through VC simulation, the system functional requirements were converted into test cases to formally verify their fulfilment through dynamic software testing [38]. CoDeSys Test Manager was utilized for this purpose since enables the programming and execution of automated test cases. In dynamic software testing, the different actions that constitute a test case are verified by evaluating the values acquired by selected PLC software variables. Traditionally, the monitored variables change due to the forcing of variables that emulate physical sensors. In this case study, the VC simulation was utilized to enable the generation of a more realistic test environment in which the monitored variables changed because of the proposed mathematical model. Figure 10 represents some of the test cases implemented for the NSM, detailing the scenario for testing the correction of the EC for the nutrient solution of ‘line 1’. After the successful verification of all the generated test cases, the code was considered ready to be deployed into the physical plant.

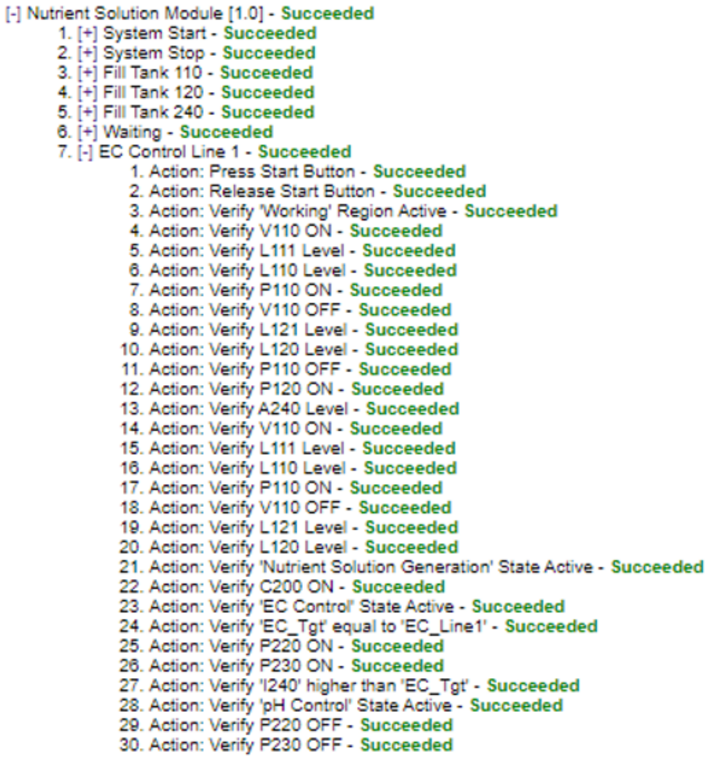


```
IF GVL.Region=2 THEN //Working Composite State
    CASE GVL.State OF
        ⋮
        4: //Waiting
            IF NOT (GVL.L310 AND GVL.L320) THEN
                GVL.State:=5; //new state assignment
                IF NOT GVL.L310 THEN //exit behavior
                    GVL.Line1:=TRUE;
                ELSE
                    GVL.Line2:=TRUE;
                END_IF
            END_IF

        5: //Nutrient Solution Generation Composite State
            IF flag_State THEN //entry behavior
                flag_State:=FALSE; //entry flag reset
                GVL.Substate:=1;
            END_IF
            // Eventual do behavior
            IF GVL.A240<0.05 AND (NOT (GVL.P310 OR GVL.P320)) THEN
                GVL.State:=1;
                flag_State:=TRUE; //entry flag set
            END_IF
    END_CASE
END_IF

IF GVL.Region=2 AND GVL.State=5 THEN
    CASE GVL.SubState OF
    ⋮
    END_CASE
END_IF
```

(a) The implementation of the state machine in ST

(b) The activation of the actuators in LD

Fig. 9. PLC control software of the NSM.



```
[-] Nutrient Solution Module [1.0] - Succeeded
        1. [+] System Start - Succeeded
        2. [+] System Stop - Succeeded
        3. [+] Fill Tank 110 - Succeeded
        4. [+] Fill Tank 120 - Succeeded
        5. [+] Fill Tank 240 - Succeeded
        6. [+] Waiting - Succeeded
        7. [-] EC Control Line 1 - Succeeded
                 1. Action: Press Start Button - Succeeded
                 2. Action: Release Start Button - Succeeded
                 3. Action: Verify 'Working' Region Active - Succeeded
                 4. Action: Verify V110 ON - Succeeded
                 5. Action: Verify L111 Level - Succeeded
                 6. Action: Verify L110 Level - Succeeded
                 7. Action: Verify P110 ON - Succeeded
                 8. Action: Verify V110 OFF - Succeeded
                 9. Action: Verify L121 Level - Succeeded
                10. Action: Verify L120 Level - Succeeded
                11. Action: Verify P110 OFF - Succeeded
                12. Action: Verify P120 ON - Succeeded
                13. Action: Verify A240 Level - Succeeded
                14. Action: Verify V110 ON - Succeeded
                15. Action: Verify L111 Level - Succeeded
                16. Action: Verify L110 Level - Succeeded
                17. Action: Verify P110 ON - Succeeded
                18. Action: Verify V110 OFF - Succeeded
                19. Action: Verify L121 Level - Succeeded
                20. Action: Verify L120 Level - Succeeded
                21. Action: Verify 'Nutrient Solution Generation' State Active - Succeeded
                22. Action: Verify C200 ON - Succeeded
                23. Action: Verify 'EC Control' State Active - Succeeded
                24. Action: Verify 'EC_Tgt' equal to 'EC_Line1' - Succeeded
                25. Action: Verify P220 ON - Succeeded
                26. Action: Verify P230 ON - Succeeded
                27. Action: Verify 'I240' higher than 'EC_Tgt' - Succeeded
                28. Action: Verify 'pH Control' State Active - Succeeded
                29. Action: Verify P220 OFF - Succeeded
                30. Action: Verify P230 OFF - Succeeded
```

Fig. 10. Report of some of the test cases implemented for the NSM.

Finally, it is demonstrated how the proposed mathematical model fulfils the requirements identified in Section 3.1. The requirement is recalled on the left-hand side, while the strategy for its fulfilment is placed on the right-hand side:

- Modelling actors: The proposed mathematical model includes the typical processes and elements contained in wick soilless cultivations. An ‘input-output’ representation was developed for the different actors and an image was associated to the representation for improving the model usability and readability.
- Functional behaviour: Algebraic and dynamics equations were identified for modelling the discrete-event behaviour of the elements contained in wick soilless cultivations. The developed mathematical model replicates the sequence of events that occur in the physical system enabling the implementation of the VC simulation and the verification of the system functional behaviour.
- Interface: The Simulink model has the same interface of the physical system. Seamless deployment of the control software seems viable and will be verified in future work.
- Graphical display: A graphical display able to mimic the system configuration was generated in CoDeSys to facilitate the code debug operation.

In summary, the proposed mathematical model enables the use of the VC simulation for supporting the design of the control software of flexible test-benches and its verification of functional requirements. By developing the PLC code of the flexible test-bench shown in Section 4, different software errors were identified and fixed using the VC simulation. Moreover, the VC simulation provided a more realistic scenario for dynamic software testing since physical variables changed because of a mathematical model and not by manually forcing their values. Since the defined Simulink model consists of a discrete-event simulation model, it must be clarified that it does not allow the verification of non-functional requirements.

6. Conclusions and Future Work

In the context of wick soilless cultivation, this work proposes a mathematical model to enable the use of the VC simulation for the development of the control software of flexible test-benches. The illustrated model simulates the discrete-event behaviour of the typical processes and elements contained in wick soilless cultivations and implements the same interface of the physical system to enable the seamless deployment of the verified control software. Moreover, a graphical display able to mimic the system status is developed to facilitate the code debug operation.

A case study was performed for demonstrating that the proposed mathematical model enables the virtual commissioning simulation of wick soilless cultivations, and the design and verification of the system functional behaviour. A flexible test-bench was modelled, and its PLC control software was connected to the model for the implementation of the VC simulation. Different errors of the PLC code were identified and fixed using the VC simulation. Moreover, the VC simulation provided a more realistic scenario for dynamic software testing since physical variables changed because of a mathematical model and not by manually forcing their values.

The approach illustrated within this work may be adopted to different wick soilless cultivations by using the proposed modelling actors, or different systems can be modelled by generating personalized actors; e.g., test-benches able to control the individual ions of the nutrient solution, etc. Therefore, it is expected that this work may enhance the investigation in the research topic of farming strategies for soilless culture since provides a useful tool for the development of flexible test-benches. Some future works are identified:

- Seamless deployment: The proposed mathematical model implements the same interface of the physical system. The developed control software will be deployed into the PLC controller of the physical test-bench to evaluate the seamless deployment of the verified code.
- Test-bench for fertigation strategies: Few mechanical adjustments must be implemented to complete the flexible test-bench proposed by Barbieri [10]. Then, an experiment will be executed to certify that the system can be utilized as a test-bench for investigating fertigation strategies in wick soilless cultivations.
- Verification of non-functional requirements: By reproducing the discrete-event behaviour of the physical system, the mathematical model proposed within this work can only be adopted to verify functional requirements. In future work, the model should be refined to also enable the verification of non-functional requirements.
- Digital Twin: In the automation domain, VC constitutes the basis for the digital twin simulation of manufacturing systems. A digital twin of the flexible test-bench should be performed to evaluate the benefits that this automation technology may generate in wick soilless cultivation.

Nomenclatures

c_s	Solution specific heat capacity
D_t	Tank diameter
EC	Electrical conductivity
FM	Fertigation Module
HiL	Hardware-in-the-Loop
HMI	Human-Machine Interface
h_t	Liquid height
k_f	Waste to water ratio
LD	Ladder Diagram
m_s	Solution mass
NSM	Nutrient Solution Module
OPC	Open Platform Communications
PID	Piping and Instrumentation Diagram
PLC	Programmable logic controller
POU	Program Organization Unit
Q	Volumetric flow rate
SiL	Software-in-the-Loop
ST	Structured Text
T	Temperature
TSS	Total suspended solids
u	Controller output signal
VC	Virtual Commissioning
V_t	Liquid volume
y	Controller output signal

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