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An Open Loop Distribution Module for Precise and Uniform Drip Fertigation in Soilless Culture

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Abstract—In soilless culture, the definition of efficient fertigation strategies is fundamental for the growth of crops. Flexible test-benches able to independently manage groups of crops are key for investigating efficient fertigation practices through experimentation. These test-benches must be able to provide nutrient solution (NS) in a precise, uniform and repeatable way in order to effectively implement and compare different fertigation strategies. This article describes a distribution module for investigating fertigation practices able to control the fertigation dose and frequency. The proposed solution is characterized in terms of precision, uniformity and repeatability since these parameters are fundamental in the implementation of effective experiments for the investigation of fertigation practices. After a calibration process, the implemented system reaches a precision of 1mL, a uniformity of 98.5% at a total cost of 735USD.

Keywords—Precision horticulture, test-bench, fertigation strategy, automation, flexibility.

I. Introduction

SOILLESS *culture systems* (SCS) are increasingly adopted as a major technological component in the modern greenhouse industry due to the independence of the crop from the soil [1]. Fertigation is the injection of fertilizers into an irrigation system and is the most critical activity in soilless culture since the crop does not receive nutrients from the substrate [2]. Fertigation requirements vary based on numerous factors such as plant species, cultivar, growth stage, utilized substrate, season, and climate conditions [3]-[5]. Due to the lack of standard and optimal practices, and due to the complexity of the problem, test-benches are fundamental for investigating fertigation practices [6]. Test-benches must be able to provide NS in a precise, uniform and repeatable way in order to effectively implement and compare different fertigation strategies. In this article, an open-loop distribution module able to control the fertigation dose and frequency is proposed and characterized.

In SCS, overhead, surface and subsurface irrigation can be applied to deliver the NS to the plants [7]. Overhead systems apply NS to the aerial part of the plants via sprinklers. However, these systems result in excessive waste of water while they favor fungal diseases due to frequent wetting of the foliage [8]. Subirrigation relies on capillary action to deliver water and nutrients from below growing containers [9]. Subirrigation has been tested experimentally and compared with drip irrigation [10] [11]. However, it is rarely applied in commercial cultivations because it favors salt accumulation in the upper portion of the root zone due to the lack of salt leaching [12], [7]. For these reasons, fertigation in SCS is dominated by *drip irrigation* systems [1] and this method is selected for the proposed distribution module.

Drip irrigation systems can be installed either on the surface or below the soil tillage zone. With respect to the traditional drip irrigation, subsurface drip irrigation offers the advantages of lower maintenance costs, less evaporation loss and less interference with cultural operations [13]. However, it is difficult to monitor system operation since most components are located below the soil. For example, reduced performance caused by emitter plugging cannot be easily detected. Therefore, surface drip irrigation was selected for the proposed distribution module.

In trickle drip irrigation, water is introduced into the soil through small-size orifices placed directly on the soil surface [14]. The size of the orifice and its operating pressure determine the trickle discharge rate. In order to make the discharge rate independent from the fluctuations of the operating pressure, pressure-compensated (PC) drip emitters were introduced [15]. Pressure-compensated drip emitters were adopted due to their capability to make the discharge rate independent from the operating pressure.

Coconut coir was utilized as substrate since: (i) its air/water ratio allows plant roots to grow evenly throughout the substrate; (ii) its high cation exchange capacity traps cations from the solution and releases them through root absorption; (iii) slabs are sold as ready to use with drain slits and precut plant holes [16]. Eventually, either feedback or open loop systems can be implemented for controlling the precision of the fertigation. For example, load cells or flow rate sensors can be used for calculating the amount of discharged NS. However, since soilless culture is based on frequent and accurate irrigation [12], sensors with high resolution should be selected and placed on each irrigation station. Since the use of sensors would considerably increase the cost and complexity of the system, an *open-loop system* was used for this study.

Similar approaches to the one proposed here were presented in [17]-[19]. These researchers used automated fertigation systems designed to maintain an objective media moisture content in potted plants. PC drip emitters were used and the activation/deactivation of the irrigation was regulated through solenoid valves. However, fertigation precision, uniformity and repeatability were not explicited in these works.

II. Materials and Methods

A. Proposed Distribution Module

The objective of the overall test-bench was the development of fertigation practices for soilless culture. Therefore, the

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same fertigation strategy must be applied to groups of crops in order to allow the implementation of statistical analysis. The proposed distribution module was designed to manage eight plants as shown in Fig. 1. However, the system can be scaled-up. Two coconut coir slabs were placed on an inverted gutter structure with lateral drain channels (Fig. 2). The slope of the gutter was regulated by means of adjustable suspensions that facilitates the drainage flow into a cistern placed at the end of the structure. Each slab contains four plants fed through spaghetti tubes connected to the main distribution line. PC emitters were used to provide a precise and uniform irrigation to the plants. A pump was used to deliver the NS to the PC emitters.

The implemented Distribution Module is shown in Fig. 2. A 16 mm outer diameter plastic tube is used as main distribution line, while 6 mm spaghetti tubes bring the NS to the slabs. Drops are injected into the substrate by means of vertical stakes connected to the spaghetti tubes. The gutter structure is a 0.6 mm thick S280GD steel, galvanized on both sides and covered with a Polyester coating. The SFDP1-011-070-21 pump [20] was selected as irrigation pump since can work with chemical solutions and the acceptable pH was between 5 and 10. This diaphragm pump can operate intermittent by which is ideal for implementing the frequent irrigations necessary in soilless culture. Moreover, this pump has a built-in pressure switch that automatically starts and stops the pump when pressure goes outside a defined range. This switch allows for keeping the system within the working pressure of the PC emitters. The pump was operated using an electrical relay that allowed for the control of the fertigation dose and frequency. NDJ CTNL40B PC emitters were selected [21]. These emitters are designed for a flow rate of 4L/h and have a working pressure range between 0.5 and 4 bar.

B. Validation Experiment

The distribution module was evaluated in terms of: (i) *precision*: difference with respect to a target delivered volume; (ii) *uniformity*: difference of the delivered volume in between the different emitters along the same distribution line; (iii) *repeatability*: changes in the precision and uniformity when a certain NS volume is discharged several times. Fig. 3 shows the test-bench used for the model characterization. Each spaghetti tube was connected to a plastic graduated cylinder that had a resolution of 1 mL. Next, a target delivery volume was set and the pump activation time was selected according to the target volume and the emitter flow rate:

$$t_{pump-on-th} = \frac{V_{plant}}{Q_{emitter}} \tag{1}$$

The volume delivered through each emitter is recorded and the experiment was repeated five times in order to evaluate the repeatability of the system.

The following notation was used for the calculation of the key performance indicators of the system: letter i denotes the i-th repetition of the experiment, while letter j the j-th graduated cylinder. Considering that five repetitions of the experiment were performed and that eight cylinders were evaluated, we have: i=1,,5, and j=1,,8. The following parameters were computed to characterize the precision, uniformity and repeatability of the system:

- *Precision*: root mean square error (RMSE) considering the volume provided to each cylinder and the target volume:

$$RMSE_i = \sqrt{\frac{\sum_{j=1}^{8}(V_j - V_{tgt})^2}{8}} \tag{2}$$

- *Uniformity*: uniformity coefficient (UC) [22]:

$$UC_i = 100\left(1 - \frac{\sum_{j=1}^{8}\|V_j - \bar{V}\|}{8\bar{V}}\right) \tag{3}$$

  Where $\bar{V}$ defines the average volume provided in the i-th repetition of the experiment (i.e. $\bar{V} = \sum_{j=1}^{8} V_j$)
- *Repeatability*: since each experiment was repeated five times, the RMSE and UC can be computed using the random error approach in order to identify an uncertainty range [23]. Next, the RMSE value was determined using the following equations and considering that the experiment has repeated 5 times:

$$\overline{RMSE} = \frac{\sum_{i=1}^{5} RMSE_i}{5} \tag{4}$$

$$\sigma_{RMSE} = \sqrt{\frac{\sum_{i=1}^{5}(RMSE_i - \overline{RMSE})^2}{4}} \tag{5}$$

$$RMSE = \overline{RMSE} \pm \frac{3\sigma_{RMSE}}{\sqrt{5}}(99.74\%) \tag{6}$$

A value of three standard deviations was selected for the uncertainty range calculation of (6) in order to identify a range with a probability of 99.74%. It can be noticed that the ideal solution is the one that minimizes the RMSE and maximizes the UC.

III. Results and Discussions

The procedures described in the previous section were implemented. The pump was operated for 60.3s giving a theoretical delivered volume of 67mL per emitter. Obtained results are reported in Table IV. Any deviation from the theoretical value were due to:

- *Starting condition*: distribution line was empty delaying the delivery
- *Final condition*: when the pump is stopped, the residual pressure in the supply line results in some additional NS delivery

The starting condition effect is negligible since, during normal operation of the system, the distribution line will be already full of NS. However, a calibration experiment was necessary to correct the effect of the final condition effect. The following process was performed:

- $t(p \rightarrow p_{atm})$: determination of the time taken it takes the system to drop the operating pressure to atmospheric pressure after the pump is turned off
- $t_{pump-on}$: a new pump activation time was computed:

$$t_{pump-on} = t_{pump-on-th} - t(p \rightarrow p_{atm}) \tag{7}$$

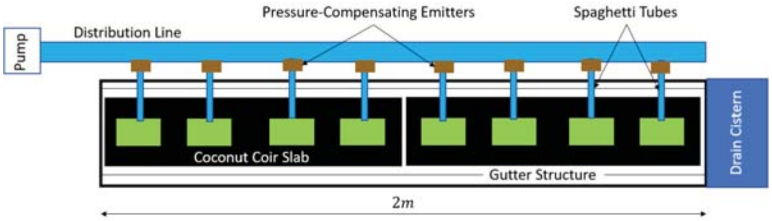

Fig. 1 Schematic of the proposed Distribution Module

Fig. 2 Implemented Distribution Module

Fig. 3 Experimental test-bench

The results of the experiment conducted to determine $t(p \rightarrow p_{atm})$ are reported in Table I. Next, the actual pump activation time computed using (7) was 53.26s. Then, a new experiment was performed to characterize the system after its calibration. The system was started with the distribution line full of NS and the new $t_{pump-on}$ was set for pump activation time. The obtained results are reported in Table V. The RMSE and UC obtained from each repetition of the experiment were computed and shown in Table II. The repeatability of the system was calculated using (4) through (6). The following results were obtained:

$$RMSE = (1.15 \pm 0.15)mL$$

$$UC = (98.76 \pm 0.20)\%$$

Therefore, the proposed system has a precision of approximately 1mL, a uniformity coefficient of approximately 98.5% and high repeatability since the uncertainty ranges are small with respect to the average values of RMSE and UC. A calibration experiment for the calculation of $t(p \rightarrow p_{atm})$ was necessary for obtaining these performances. However, $t(p \rightarrow p_{atm})$ is independent from the selected discharged volume and has to computed only once.

TABLE I
EXPERIMENT FOR THE CALCULATION OF $t(p \rightarrow p_{atm})$

Repetition	Time(s)
1	7.59
2	6.91
3	7.20
4	6.83
5	6.65
Average	**7.04**

TABLE II
RMSE AND UC OBTAINED FOR EACH REPETITION AFTER THE CALIBRATION EXPERIMENT

Repetition	RMSE	UC
1	1.27	98.96
2	1.22	98.68
3	1.17	98.64
4	1.00	98.88
5	1.06	98.65

IV. CONCLUSIONS

A distribution module able to deliver NS in a precise, uniform and repeatable way was developed. The total cost of the system was 735USD as shown in Table III. Since the gutter structure represents the highest cost, future work may concern its redesign in order to reduce the cost of the proposed system.

System behavior has not been evaluated over time. In fact, chemicals of the NS may gradually wear pump, PC emitters and stakes, and precision, uniformity and repeatability may change over time. Further analyses should be performed in order to: (i) evaluate how performance changes over time; (ii) identify replacement time for PC emitters and stakes.

TABLE III
COST BREAKDOWN ANALYSIS OF THE PROPOSED DISTRIBUTION MODULE

Element	Cost(USD)
Gutter Structure	636
Pump + Power Supply	25
Tubes	5
Arduino Uno	22
Relay	2
PC emitters and stakes	5
Slabs	40
Total	**735**

TABLE IV
RESULTS OF THE EXPERIMENT WITHOUT THE CALIBRATION PROCESS

	Volume (mL)							
Repetition / Emitter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	75	74	75	72	76	74	75	74
2	74	72	72	70	74	73	73	72
3	73	72	72	70	73	71	72	72
4	77	76	77	74	78	76	77	77
5	77	76	77	74	78	76	77	76

TABLE V
RESULTS OF THE EXPERIMENT AFTER THE CALIBRATION PROCESS

	Volume (mL)							
Repetition / Emitter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	66	66	65	66	68	66	65	67
2	66	65	66	66	69	67	66	67
3	67	66	66	67	69	68	65	67
4	67	66	66	66	69	67	66	67
5	67	66	67	66	69	68	66	68

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