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Design simulation of an automatic control spraying system for fruit orchards

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ABSTRACT : *The simulation of an automatic controlled spraying system for fruit orchards was carried out for different tractor speed profiles to assess preliminary design information to optimize the functioning of a final future design project. The dynamic simulation was executed for sixty seconds of system operation and one period of the tractor speed profile ranging between 5.5 and 8.5 km per hour was analyzed to evaluate different setpoint deviations. The simulated performance showed a maximum error of 0.04 % of the dosage per hectare and a real time maximum RMS error of 6.21 % with respect to the average setpoint dosage. In all cases the system delay produced underdose per hectare and in all cases the time lapse of underdose was greater than the time lapse of overdose.*

KEYWORDS *automatic control, variable spraying, agricultural automation, agrochemical application, PID control.*

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I. INTRODUCTION

In an orchard, the spraying system, which generates and transports spray droplets with active ingredients to the intended vegetation, has a significant impact on the application efficiency and effectiveness. In the spray application, usually a large portion near 30-50 % of the applied plant protection products, is lost to non-target sites because of run-off and spray drift loss [1]. Spray drift is the quantity of plant protection products that is carried out of the sprayed area by the action of air currents during the application process [2]. The inevitable loss of pesticide during crop management, especially the spray drift, has caused several undesirable consequences like high risk of exposure and inhalation to nearby livestock and residents [3], environmental contamination of surface water and other living organisms, unintentional damage to nearby sensitive crops and plants [4], and excessive toxic residues in agricultural food and products [5]. As there is growing social attention and concern on the environmental contamination and health risk generated from agrochemical applications, two pesticide reduction targets have been proposed as part of the Farm to Fork Strategy in the European Green Deal, to reduce the use and risk of both chemical pesticides and the more hazardous pesticides by 50 % by 2030 [6]. These ambitious objectives have been addressed mainly by developing new equipment and technologies to optimize spray application,improving the educational skills of end-users, and increasing the degree of adoption of new technologies and precision farming. Benefitted from the development and improvement of sensing technologies, the precision spraying system has been developed and implemented [7] . This advanced system can adjust the spray volume and/or air flow rate precisely in real-time based on the obtained comprehensive information on the target vegetation volume,meteorological conditions, and pest and disease infections toachieve site-specific management. The precision spraying system shows a 34–88 % potential savings of spray volume compared with the conventional [8][9].

Usually, farmers use constant-rate sprayers for pesticide applications [10], which requires that the working pressure and travel speed remain unchanged during the entire spraying. With this practice, the same spray volume is applied in the field without considering the variabilities in tree canopy characteristics, tree gaps, or tree population in the field. Moreover, most pesticide labels recommend a single application dosage rate for all situations without taking these variabilities into consideration. Thus, current spraying practices lead to a high risk of wasting pesticides through increased off-target losses to the ground and in the air and the risk is even greater for applications in orchards with young trees. One of the ways to reduce the spray drift risk from constant-rate sprayers is that operators are recommended to use large orifice nozzles to produce large droplets along with the travel speed adjustment accordingly to satisfy the desired application rate. However, in most cases changing either the travel speeds or nozzle sizes is not practical because travel speeds are usually linked to various tractor settings and field conditions therefore cannot be changed freely; and applicators may not always have ready access to more than one size of nozzles during spraying. Another option to reduce spray drift is to decrease the working pressure to increase droplet size, but that can change the nozzle flow rate and increase spray loss to the ground. On the other hand, variable-rate sprayers, supported by sensors to detect canopies, can adjust application rates according to tree structures in real-time [11][12][13][14]. Pulse width modulation (PWM) solenoid valve technology has the potential to solve these problems without need for changes of sprayer parameters [15][16]. The PWM solenoid valves can be coupled with existing constant-rate sprayers, allowing a nozzle to control its output utilizing the duty cycle produced by an electro-valve instead of working pressure. PWM controlled nozzles can also reduce spray drift by decoupling the spray pressure from the flow rate [17][18][19]. This intermittent spray behavior may enhance the biological efficacy of the product coverage on the foliage because the intermittent spray deposition would stimulate the diffusion of active ingredients through cuticles of leaves [20] . This technology, when retrofitted in a conventional constant rate mist-blower, resulted in a 40 % reduction in dose ha^{-1} while maintaining the same efficacy compared with standard full dose [21]. In addition, many experiments show other advantages provided by conventional nozzles coupled with PWM valves, such as nozzle flow rates are allowed to be independent of sprayer travel speeds while maintaining the droplet size and pressure unchanged.

Although new advanced spraying systems integrated with different technologies are encouraged for orchard applications, their advantages and characteristics need to be demonstrated for specific tree crops that have great variability in vegetation structures. On the other hand, adequate field tests are necessary to quantify and classify the potential improvement in spray drift for the advanced spraying systems such as the precision and optimized system. Thus, the goal of this research was to theoretically simulate the performance of the design of an automatic flow control system which can avoid or reduce flow variations due to the limitations of tractor-driver control capabilities that can generate unwanted drift and offset application rates.

II. METHODOLOGY

Spraying system design

A preliminary design concept was developed and simulated by means of a block model implemented in the matlab-simulink environment, whose basic schematics are presented in the flow diagram of Figure 1.

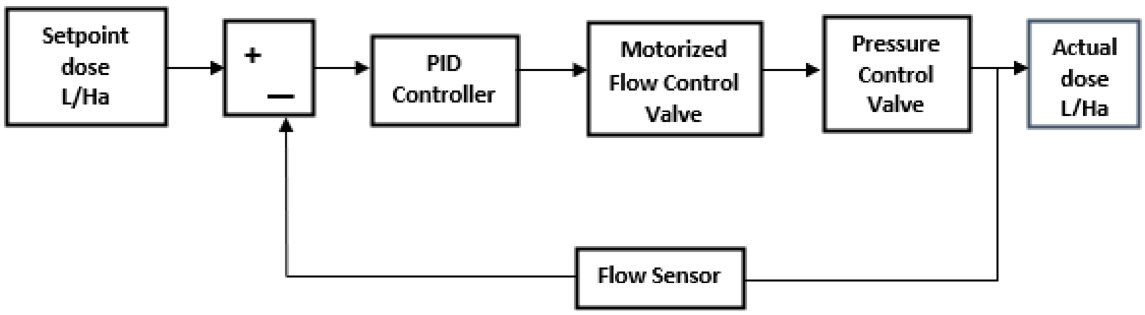


Fig. 1. Schematic flow diagram of spraying control system.

The system is composed of a motorized valve for controlling the pesticide flow, followed by a pressure control valve to be able to regulate the drop size in the liquid flow, since it is well known that there is an optimum drop size to minimize drift, a feedback flow sensor and a Proportional Integral Derivative (PID) controller. To implement the design simulation, a linear proportional Coax RMQ 32 motorized of linear throttling flow control valve with 0-10 V output control signal from fully closed to fully open was considered. To regulate the spraying pressure, we incorporated a CSV1A stop valve, 1-25 GPM, constant pressure 15-150 psi that automatically can adjust pressure output to match variable demands. To sense the feedback flow, a magnetic inductive NMID-16, 0.4-120 L/min, 0-10 V of output was considered and also a typical universal PID controller model Select PID500 with input-output 0-10 V was chosen for the design simulation.

Design simulation modelling

The computing simulation model developed in matlab-simulink programming platform corresponding to the design concept of Figure 1, is illustrated in Figure 2. The setpoint calculation shown in figure 2 assumed a theoretical dosage of 1000 L ha^{-1}. With that condition the algorithm evaluates real time setpoint and actual flowrate, since the tractor speed is variable and therefore the setpoint will be also time variable. Following this calculation diagram, both the setpoint and the actual spraying flowrate are converted to a voltage of 0-10 V which is the control signal to operate the motorized valve.In the simulation routine a desired setpoint dose flow FSP in L min^{-1} was evaluated by means of the following expression:

$$FSP = \frac{Q \cdot A \cdot V}{600} \qquad (1)$$

Where:
Q=Theoretical desired flow dosage of 1000 (L ha^{-1})
A=Sprayer working width of 6 (m)
V=Tractor speed (km h^{-1})

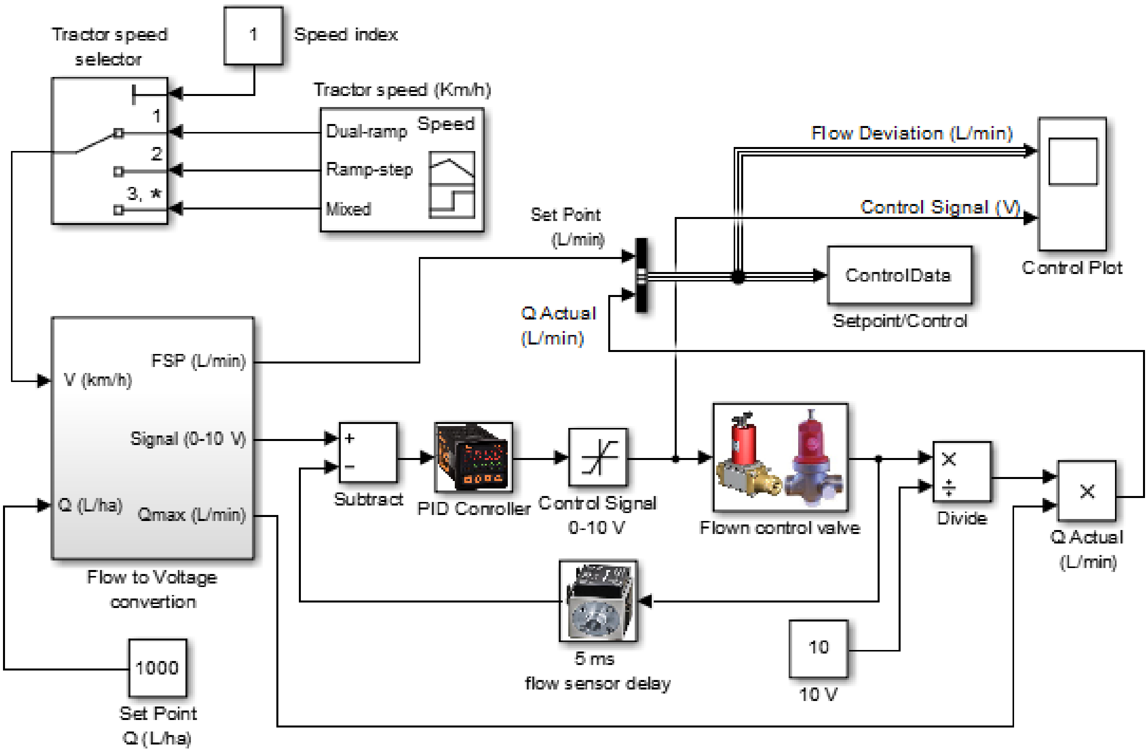


Fig. 2. General matlab-simulink block diagram for spraying control simulation.

The setpoint output with a value of 0-10 V correlated to flow control valve position, was calculated according to the simulink diagram of Figure 3. The simulation assumed a regulation of the main manual valve of the spraying equipment to deliver 25 % over the maximum operation flowrate corresponding to a maximum tractor speed of 8.5 km/h used in the simulation, in order that the actual flowrate can be controlled within the range of tractor speed. The calculation also considered a 6 m of spraying working width, which is a typical spraying width used in fruit orchards and a flow sensor signal delay of 5 ms. To run the simulation of diagram of Figure 2, the input of three different variable tractor speed profiles were tested named Dual-ramp, Ramp-step, and Mixed as a combination of Dual- ramp and Ramp-step speed profiles, with a range of variation between minimum and maximum of 5.5 to 8.5 km h^{-1} and ramp acceleration of ± 10 m s^{-2} as shown in Figure 4. For those speed tractor profiles, a variable real time flowrate setpoint in L min^{-1} corresponding to the desired dosage of 1000 L ha^{-1} was calculated.

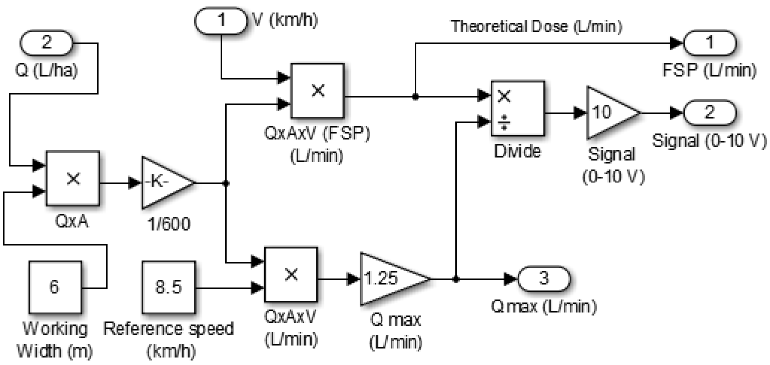


Fig. 3.Diagram of setpoint and real time flowrate calculator.

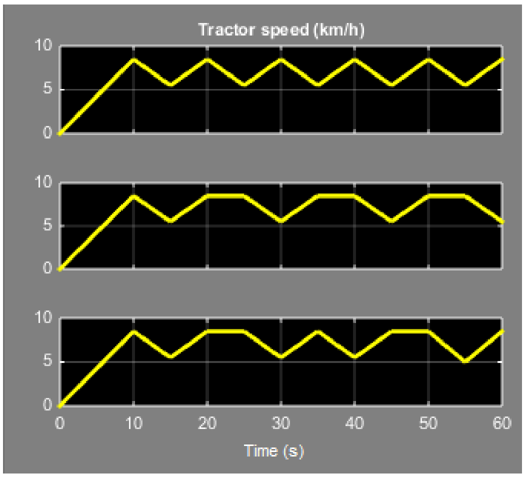
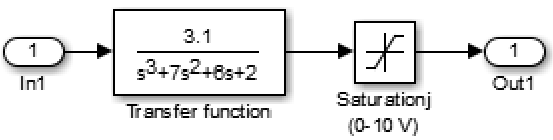


Fig. 4. Tractor speed profiles of the simulation (km h-1).

With respect to the motorized flow control valve, a transfer function was developed in the simulink environment, according to its technical operation specifications which states a 3.5 second period from closed to full open throttle as shown in Figure 5, that corresponds to a typical third order frecuency domain transfer function used in automatic control theory.The Proportional Integral Derivative controller of the closed loop control system of figure 2 was tuned up according to the plant transfer function corresponding to the valves transfer function of figure 4, to optimize the value of controller constants whose expression is shown in the following equation for a PID controller signal:

$$PID = P + \frac{I}{s} + Ds(2)$$

Where: P = Proportional constant = 2.0831, I = Integral constant = 0.5798 and D = Derivative constant = 1.8502 obtained from PID controller tuning. In the general diagram of simulation, the PID controller output is saturated to a maximum value of 10 V, according to its electrical input-output characteristics.



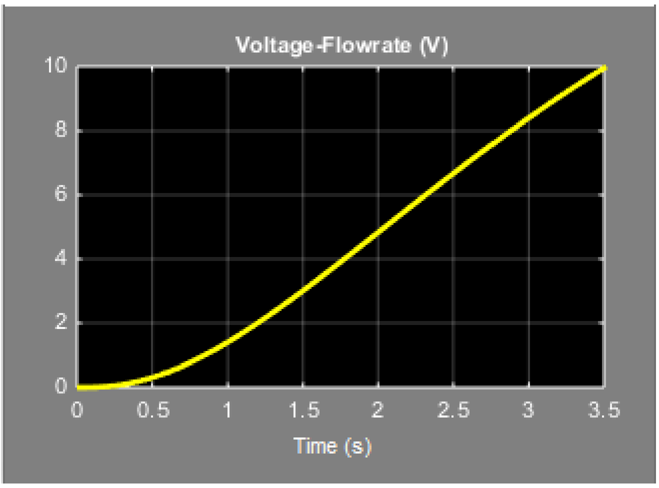


Fig. 5. Flow control valve transfer function.

System performance indexes

From the simulation output data, which emulates real time spraying application, various performance parameters were assessed for one period of each of the tractor speed profiles. To evaluate the dosage real time error, the Root Mean Square error (RMS) in L min^{-1} was evaluated with the expression:

$$RMS = \sqrt{\frac{1}{n}\sum_{1}^{n}(AFR_i - FSP_i)^2} \quad (3)$$

Where:
RMS = Average root mean square error (L min^{-1})
n = Number of data points
AFR_i = Real time actual flowrate (L min^{-1})
FSP_i = Real time flowrate setpoint (L min^{-1})

The average percentual RMS was also calculated to have an idea of the real time magnitude of the flowrate deviation. Besides, an absolute dosage error per hectare at the central tractor speed of 7 km h^{-1} was assessed along with the percentual time portion while the system delivers over or under dosage.

III. RESULTS AND DISCUSSION

A graphic illustration of the comparison between real time flowrate setpoint and the actual simulated value can be roughly appreciated in Figures 6, 7, 8 where a one-minute simulation shows a yellow line for the setpoint and a white line for the actual simulation output. The plot of Figure 6 that shows the simulated performance when the tractor speed profile follows a Dual-ramp shape, indicates that the simulated actual output has a time delay with respect to the setpoint due to the valve dynamic behaviour, therefore the system can never reach the maximum and minimum flowrate setpoint values and it is also seen that the control signal is always less than 7 volts. In Figure 7 the performance of the control system when assuming a Ramp-step profile for the tractor speed, it is clear that because of the motorized flow control valve delay the output never reaches the minimum setpoint value.

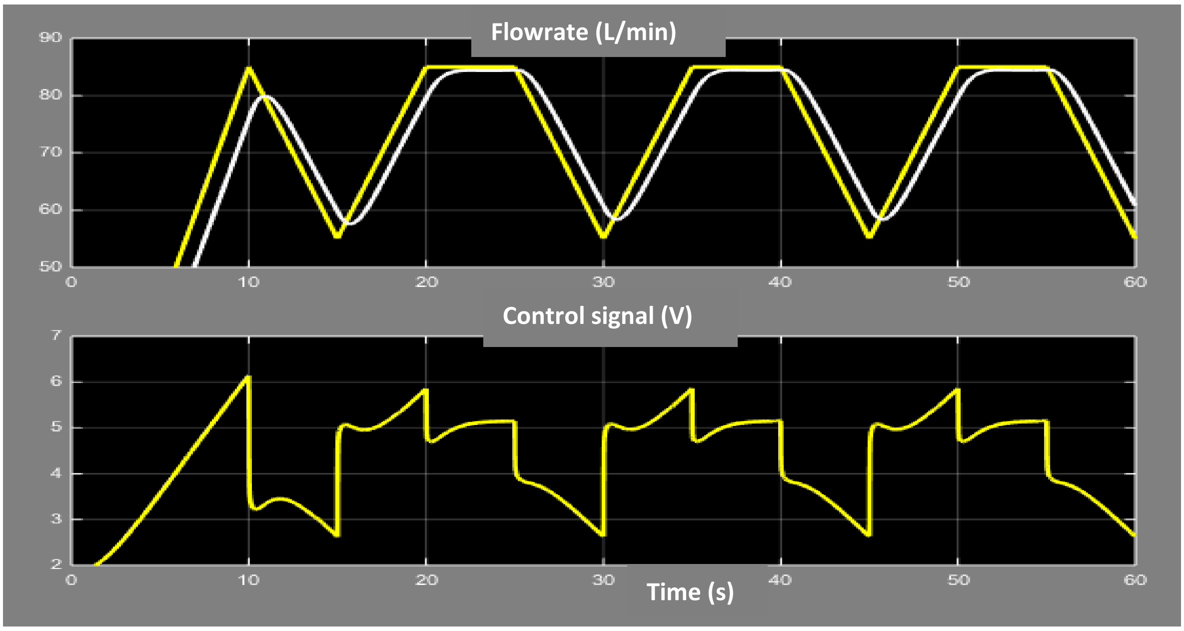


Fig. 6. Setpoint and actual flowrate comparison for Dual-ramp tractor speed profile (L min^{-1}) and PID control signal (V) to the motorized valve.

Nevertheless, since there is a constant speed portion of the tactor speed profile, the system can partially reach the maximum setpoint value while the control signal is always inferior to 7 volts. When simulating the control system performance with an input tractor speed of the type mixed which includes ramps and a constant speed sections, in Figure 8 we see that the simulated actual flowrate exhibits the proper behaviour of these two kind of inputs, where for the dual ramp the output never reach the minimum and maximum setpoint values, and for the constant section of the input, the output flowrate can partially reach the maximum setpoint value during part of the constant tractor speed section.

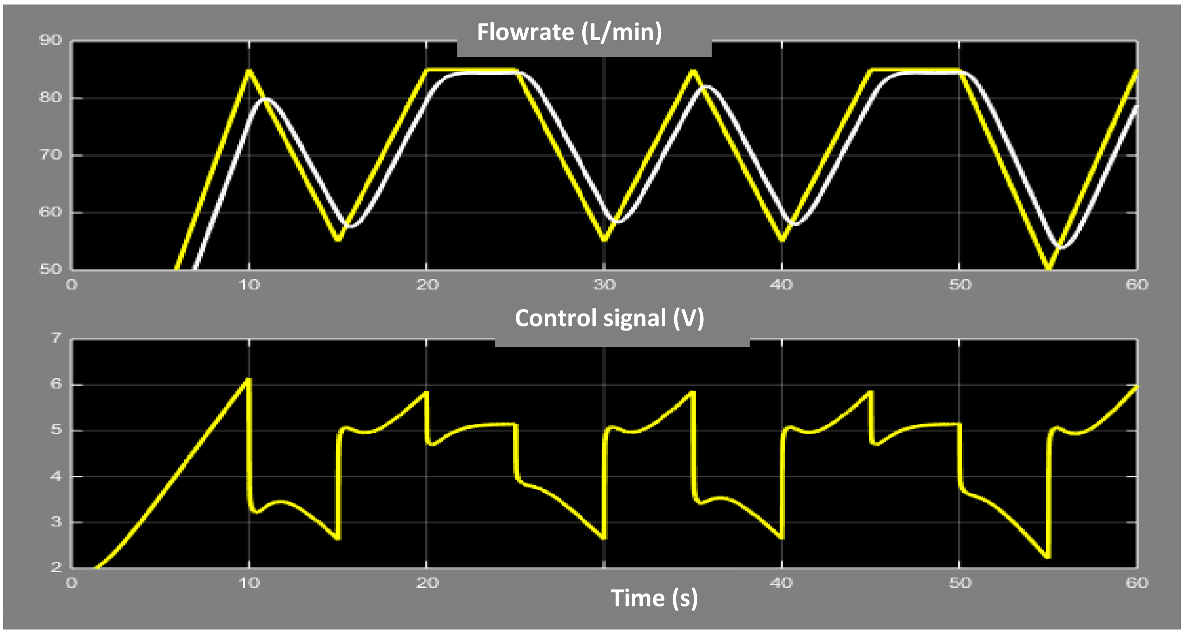


Fig. 7.Setpoint and actual flowrate comparison for Ramp-step tractor speed profile (L min^{-1}) and PID control signal (V) to the motorized valve.

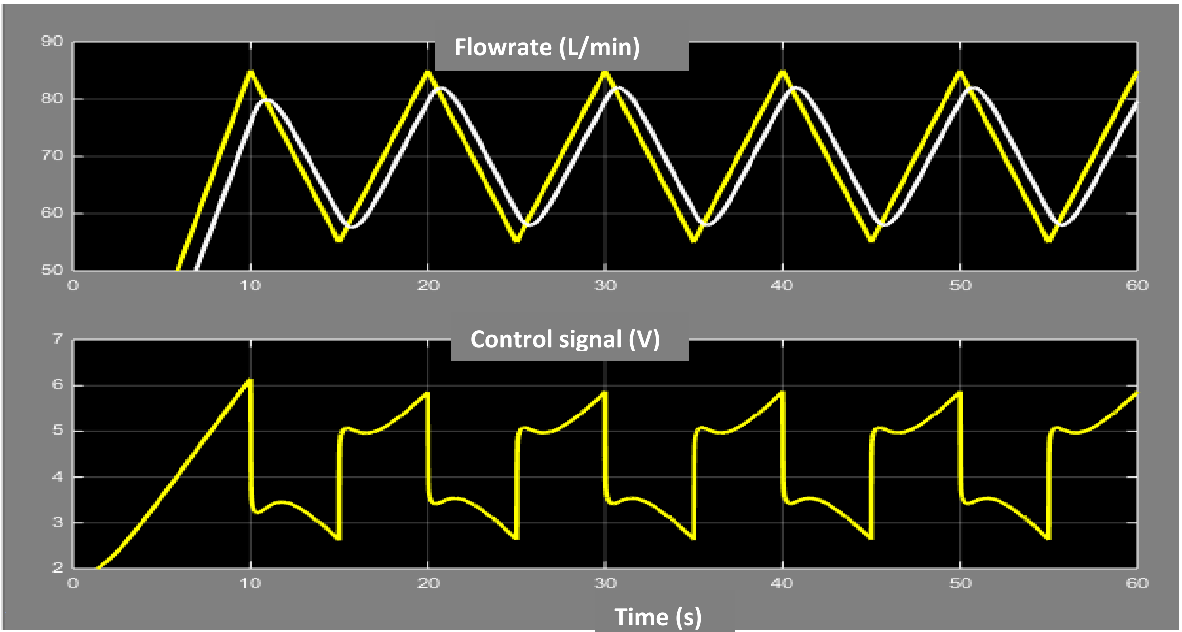


Fig. 8. Setpoint and actual flowrate comparison for Mixed tractor speed profile (L min^{-1}) and PID control signal (V) to the motorized valve.

The resume of the main performance indexes to evaluate the simulated behaviour of the designed control system for one period of each of the simulated tractor speed profiles are detailed in Table 1. We see that the number of data points are consistent with the duration of the simulation period of each of the tractor speed profiles since the period is 10 seconds for Dual-ramp profile, 15 seconds for the Ramp-step speed profile and 25 seconds for the mixed speed profile. The table also indicates that the simulated flowrate setpoint was inside the interval 70-75 L min^{-1}. In terms of real time average flowrate error, a maximum of 284 cm^3 min^{-1} for the Ramp-step speed profile and a minimum of 101 cm^3 min^{-1} below the setpoint dosage in each case. With respect to the absolute dosage per hectare, which is one of the main indicators, the simulated values estimated at a central tractor speed of 7 km h^{-1} showed maximum underdoses of 4.061 Lha^{-1} for the tractor Ramp-step profile and a minimum of 1.447 L ha^{-1} for the Mixed tractor speed profile which also means 0.4061 % and 0.1447 % with respect to the desired 1000 L ha^{-1} setpoint dosage. The RMS real time error turned out to have a maximum of 4.347 L min^{-1} corresponding to 6.21 % of the average flowrate setpoint and 3.884 Lmin^{-1} corresponding to 5.20 % of average flowrate set point. Finally, the table shows that the overdose time is always inferior to underdose one with a small deviation as indicated before, being the higher when a Dual-ramp tractor profile is considered.

Table 1. Resume of automatic control spraying simulation indexes.

	Tractor speed profile 5.5 - 8.5 (km h^{-1})		
Parameter	Dual-ramp	Ramp-step	Mixed
Number of data points	354	499	850
Average setpoint (L min^{-1})	70.013	74.657	72.721
Average deviation (L min^{-1})	-0.176	-0.284	-0.101
Average deviation (L ha^{-1})	-2.508	-4.061	-1.447
Error RMS (L min^{-1})	4.347	3.884	4.026
Error RMS (%)	6.21	5.20	5.54
Time of over dose (%)	49.2	36.5	42.5
Time of under dose (%)	50.8	63.5	57.5

IV. CONCLUSION

The implementation of a theoretical simulation dynamic modelling of an automatic control spraying system may help to preliminary visualize its practical behavior in order to improve and optimize the final system design. The actual experimentally testing of the design is necessary to experimentally assess the validity of the simulation since the operation specification of each component can affect the performance of the whole system.

It is also clear that the selection of a proper flow control motorized valve is relevant since its dynamic response may affect significatively the response delay even when optimizing the tuning of the Proportional Integral Derivative controller.

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