1 **Variable rate sprayer. Part 1 - Orchard prototype: design,**
2 **implementation and validation**

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ABSTRACT

Discussions in recent decades about dosage models for applying plant protection products in orchards have failed to reach a compromise solution. Furthermore, canopies are spatially variable, and a uniform dose may not be adequate for the entire orchard. Spraying at an adequate volume application rate on a site-specific basis would help reduce the amount of agrochemicals used in the framework of precision horticulture and precision fructiculture.

An orchard sprayer prototype running a variable-rate algorithm to adapt the volume application rate to the canopy volume in orchards on a real-time and continuous basis was designed, implemented, and validated. An equivalent prototype was designed for vineyards and described in a companion paper ('Variable rate sprayer. Part 2 – Vineyard prototype: design, implementation and validation'). The orchard prototype was divided into three parts: the canopy characterization system (using a LiDAR sensor), the controller executing a variable-rate algorithm, and the actuators. The controller determines the intended flow rate by using an application coefficient (required liquid volume per unit canopy volume) to convert canopy volume into a flow rate. The sprayed flow rates are adjusted via electromagnetic variable-rate valves. The goal of the prototype was to keep the actual application coefficients as close as possible to the objective.

Strong relationships were observed between the intended and the sprayed flow rates ($R^2 = 0.935$) and between the canopy cross-sectional areas and the sprayed flow rates ($R^2 = 0.926$). In addition, when spraying in variable-rate mode, the prototype achieved significantly closer application coefficient values to the objective than those obtained in conventional spraying application mode.

Keywords: precision horticulture, variable rate, LiDAR sensor, orchard sprayer.

43

44 **Nomenclature**

45	C_H	Canopy height (m)
46	C_V	Canopy semi-volume (m ³)
47	C_W	Canopy semi-width (m)
48	$Dv0.1$	Volumetric diameter percentile 10 (μm)
49	$Dv0.9$	Volumetric diameter percentile 90 (μm)
50	i_a	Application coefficient – actual (L m ⁻³)
51	i_o	Application coefficient – objective (L m ⁻³)
52	NMD	Numeric median diameter (μm)
53	p	Working pressure of the system (bar)
54	Δp_{max}	Maximum differential pressure (bar)
55	p_{max}	Maximum working pressure of the system (bar)
56	p_{min}	Minimum working pressure of the system (bar)
57	q	Flow rate for the entire side of the sprayer (L min ⁻¹)
58	q_j	Flow rate at section j (L min ⁻¹)
59	r	Row spacing (m)
60	R	Sampling resolution (samples m ⁻¹)
61	S	Canopy cross-sectional area (m ²)
62	s	Canopy semi-cross-sectional area (m ²)
63	s_j	Canopy semi-cross-sectional area at section j (m ²)
64	SV	Sprayed volume (L)
65	T	Period of the regulation loop (ms)
66	v	Forward speed (m s ⁻¹)
67	V_j	Control signal for the electromagnetic valve j (V)
68	VMD	Volume median diameter (μm)

69

70 **1 INTRODUCTION**

71 Agrochemicals, and more specifically, application techniques of plant protection
72 products (PPP), have been widely analysed because of the economic and environmental
73 costs derived from their use. Initially, agrochemicals were intended to be homogeneously
74 distributed over the orchards, and doses were (and still are) expressed as a per unit ground
75 area dose rate. Several researchers have spent many years analysing and developing dosage
76 models for orchards, groves, and vineyards (Byers *et al.*, 1971; Byers *et al.*, 1984; Furness *et*
77 *al.*, 1998; Walklate *et al.*, 2003a; Walklate *et al.*, 2003b; Planas *et al.*, 2006; Frießleben *et*
78 *al.*, 2007; Siegfried *et al.*, 2007; Pergher and Petris, 2008; Viret and Höhn, 2008; Gil and

Escolà, 2009; Gil *et al.*, 2011; Planas *et al.*, 2011; Walklate *et al.*, 2011; Walklate and Cross, 2012). As early as the 1960s, Morgan (1964) stated the importance of taking into consideration the dimensions and other geometric parameters of canopies. Byers *et al.* (1971) developed a method for estimating the amount of vegetation per unit ground area and named it tree-row-volume (TRV). The TRV was estimated from manual measurements of the height of trees, their width, and the total row distance. A coefficient was applied to determine the water volume application rate to be sprayed as a carrier for PPP spray applications. In a subsequent work, Byers *et al.* (1984) stated that product deposits in canopies were significantly different when spraying TRV-determined doses onto canopies with different foliage densities. Sutton and Unrath (1984) modified the TRV-based volume application rate with an arbitrary coefficient while taking into account canopy density. However, manual measurements imply a degree of inaccuracy, leading to dosage errors. In addition, the results of all previous dose adjustment models in tree crops output an overall dose rate for the entire plot. That is, they do not take into consideration the spatial variability of canopy parameters throughout the orchard, vineyard, or grove. Precision agriculture and site-specific management practices (also referred to as precision crop protection) began to consider this variability and to adapt spraying technologies to the crop variability (also referred to as crop adapted spraying). Precision agriculture has developed rapidly over the last 20 years, but its application in horticulture lags behind.

A first step to deal with canopy variability was the implementation of either ultrasonic sensors (Giles *et al.*, 1987; Roper, 1988; Giles *et al.*, 1989a; Giles *et al.*, 1989b; Balsari and Tamagnone, 1997) or optic sensors (Wangler *et al.*, 1994; Doruchowski *et al.*, 1997; Jaeken *et al.*, 1997; Wenneker *et al.*, 2003) to only spray in the presence of a canopy. It has been shown that these ON/OFF or selective sprayers achieve an important reduction in PPP use and in drift pollution (Ganzelmeier and Rautmann, 2000; Koch and Weisser, 2000;

Brown *et al.*, 2008; Giles, 2008). However, selective applications do not quite represent a dosage system, because the flow rate remains constant while spraying, as does the applied dose. Recent research projects have considered canopy variability and adjusting the amount of sprayed PPP by using electronic sensors and actuators. Moltó *et al.* (2001) implemented a sprayer able to apply three dose rates: full dose, half dose, and no dose. This dosage model considered the canopy size, estimated by one ultrasonic sensor on each side of the sprayer, and with the model, a threshold was established for changing from full to half dose rates. The results reported important savings (37%) without compromising the treatment efficacy. A project known as Precispray implemented a sprayer prototype to adjust both liquid and air flow spraying rates at a constant distance from the tree canopy according to previously defined contour maps (van de Zande *et al.*, 2001; Meron *et al.*, 2003; van de Zande *et al.*, 2003). Results indicated that it was possible to save PPP by 20% to 36% while maintaining the efficacy or even increasing it in some specific situations. In another important research project named Isafruit, one of the outputs was a variable-rate sprayer prototype able to adjust the dose rate to the canopy size and foliage density (Balsari *et al.*, 2009; Wenneker *et al.*, 2009; Doruchowski *et al.*, 2011). All the listed sprayer prototypes achieved liquid flow rate variation by turning on and off groups of nozzles in a discrete (non-continuous) manner.

The initial development phase of the prototype presented in this paper is described in Solanelles *et al.* (2006). That prototype used ultrasonic sensors to estimate the canopy width at two heights and reduced a conventionally determined full dose rate according to the ratio of actual canopy width to maximum canopy width. The novelty of that prototype was the use of an electromagnetic high-frequency solenoid variable-rate valve to modify the sprayed flow rate in a continuous way. In 2004, a second development phase improved the prototype, and a vineyard sprayer prototype was also implemented to test the system with that specific crop (see the companion paper “Variable rate sprayer. Part 2 – Vineyard

prototype: design, implementation and validation'). In this second phase, a new prototype with several improvements was implemented. A new control algorithm was developed to vary the volume application rate on a continuous (non-discrete) and real-time basis in the framework of precision agriculture or precision horticulture/fructiculture. The algorithm was somehow based on TRV because it takes into consideration the canopy volume. However, the way the canopy volume was estimated is different because of the use of sensors for high spatial and temporal resolution measurements.

In this context, as described in the present paper, we sought to determine whether it is possible to implement a sprayer fitted with the required technology for real-time volume application rate adjustment in fruit tree orchards according to an external control signal (such as a voltage signal related to the canopy volume estimated by electronic sensors) in a more accurate manner than the previous prototype. Therefore, this paper does not deal with the canopy characterization subsystem or with the development and validation of a dosage model. Specifically, the objectives of this work are (i) to design an orchard sprayer for variable volume application rate treatments based on an up-to-date commercial sprayer, (ii) to validate the selected components for this purpose, and (iii) to implement all components in a sprayer prototype for laboratory and field validation.

2 MATERIALS AND METHODS

2.1 Elementary hydraulic circuit for the prototype

An elementary hydraulic circuit was mounted in the laboratory to test the various elements and to determine the best working parameters for an individual section. The components of the circuit were a tank, pump, pressure regulator, and three nozzles resembling those found in commercial sprayers. In addition, we mounted an electromagnetic and a turbine flowmeter, an electromagnetic high-frequency solenoid variable-rate valve to vary the

sprayed flow rate, and an electromagnetic ON/OFF solenoid valve to help the variable-rate valve cut off the flow rate (Fig. 1). Additionally, a pressure sensor was used to verify the collected data. All components are listed in Table 1 and detailed in the following sections.

Fig. 1. Diagram of the elementary hydraulic circuit mounted in the laboratory with its tank (1), filters (2), pump (3), pressure regulator (4), electromagnetic flowmeter (5), turbine flowmeter (6), pressure gauge (7), cut-off valve (8), variable-rate valve (9), antidrip valves (10), and nozzles (11).

Table 1. Technical specifications of the components used in the preliminary circuit and in the prototype

Components	Manufacturer/ Model	Characteristics	Signal characteristic s	Accuracy	Power supply
Variable-rate valve	Asco Joucomatic SCG202A052V	Internal diameter 2.4 mm	0÷10 V _{DC}	3.00 %	24 V _{DC}
ON/OFF valve	Asco Joucomatic SC8374S402	ON/OFF	12 V _{DC}	-	24 V _{DC}
Pressure sensor	GEMS Sensors 1000BGB2502A3UA	0÷25 bar	4÷20 mA	0.25%	8÷30 V _{DC}
Electromagnetic flow meter	Endress+Hauser Promag 30 A	0÷30 L min ⁻¹	4÷20 mA	0.50%	12 V _{DC}
Turbine flow meter elementary circuit	Badger Vision 2008 2F 66	0.50÷7.5 L min ⁻¹	4,600 pulses/litre	3.00%	5÷24 V _{DC}
Turbine flow meter sprayer prototype	Arag Rapid Check 4623811	3÷40 L min ⁻¹	4,200 pulses/litre	3.00%	12 V _{DC}
Compact Field Point controller	National Instruments cFP-2120	188 MHz processor 128 MB SDRAM	1 Ethernet port 3 RS-232 ports	-	11÷30 V _{DC}
Analogue input module	National Instruments cFP-AI-100	8 voltage or current input channels	-30÷30 V _{DC} -20÷20 mA	-	11÷30 V _{DC}
Analogue output module	National Instruments cFP-AO-210	8 analogue output channels	0÷10 V _{DC}	-	11÷30 V _{DC}
High-speed counter module	National Instruments cFP-CTR-502	8 counter input channels	5÷30 V _{DC}	-	0÷30 V _{DC}
Digital input/output module	National Instruments cFP-DIO-550	8 input channels 8 output channels	11÷30 V _{DC}	-	11÷30 V _{DC}
Ultrasonic sensors	Siemens Sonar-Bero CII 3RG6115-3GF00	Range 40÷300 cm	0÷10 V _{DC}	1.50%	24 V _{DC}
LiDAR sensor	SICK LMS200	181 measurements @ 1° resolution	Array of distance data	10 mm	220 V _{AC}

2.1.1 Electromagnetic valves

The prototype was fitted with two types of electromagnetic valves. The key element of the prototype for continuously varying the flow rate was the electromagnetic high-frequency solenoid variable-rate valve. The mission of this valve was to modify the flow rate in a continuous manner according to an external control signal from 0 to 10 V provided by the controller depending on the canopy volume (all voltages referred to in this paper are DC). The chosen valve was a normally closed Posiflow ¼" (ASCO/JOUCOMATIC, Rueil Malmaison, France). The solenoid of the valve was supplied with a 300 Hz pulse-width modulation 24 V signal with a duty cycle proportionally modified according to the external 0 to 10 V control signal. This operation was performed by the driver of the valve, resulting in a continuous variation of the position of an internal plunger, causing variation in the flow rate.

The other electromagnetic valve was a regular ON/OFF valve and was mounted for two reasons. The first reason was to better control the antidrip function previously performed by inaccurate mechanical antidrip devices in the first prototype version, so as to stop spraying when the working pressure, p , goes below 1.50 bar (which was too low to offer correct spray jet formation). The second reason was to help the variable-rate valve cut off the flow rate when spraying becomes unnecessary. This second function was a new feature in this phase of the prototype and was implemented to increase the working pressure range. The variable-rate valve tolerates a maximum differential pressure, Δp_{max} , of only 8 bar, implying that this value must also be the maximum working pressure, p_{max} . Increasing this maximum spraying pressure was important for increasing the volume application rate range, but it becomes a problem when attempting to close the variable-rate valve. The selected ON/OFF electromagnetic valve was a two-way normally closed valve able to

operate up to 16 bar. It was placed immediately ahead of the variable-rate valve to help it cut off the flow rate.

2.1.2 Controller

Both the elementary circuit implemented in the laboratory and the field sprayer prototype were equipped with a programmable automation controller, Compact FieldPoint 2120 (cFP) (National Instruments, Austin, USA). The cFP consists of a central processing unit with a backplane with slots to connect the required function modules. We used an analogue input module to acquire data from the pressure sensor and the electromagnetic flowmeter, a counter module to acquire the pulses of the turbine flowmeter, an analogue output module to command the variable-rate electromagnetic valves, and a digital I/O module to control the cut-off electromagnetic valves. The light detection and ranging (LiDAR) sensor used in the canopy characterization communicated with the controller through a RS-232 port. The programming language of the cFP was LabVIEW (National Instruments, Austin, USA), a graphical language that allows software modifications to be rapidly implemented.

2.1.3 Flowmeters in the elementary circuit

Two flowmeters were implemented in the elementary hydraulic circuit. One was the electromagnetic flowmeter used in previous version of the prototype (Solanelles *et al.*, 2006), and the other was a small turbine flowmeter. The purpose of mounting two flowmeters was to determine which was the most suitable device to mount in the prototype in terms of time response.

2.1.4 Nozzles and droplet size

The nozzles mounted in the elementary circuit and in the prototype were hollow cone nozzles model ATR (Albus Saint-Gobain Solcera, Evreux, France). The nozzle model and

working pressure were established from the laboratory trials. Once we decided on the nozzle model, the droplet size distribution obtained in dynamic conditions was studied. To evaluate the droplet size of the sprayed droplet population, we compared the droplet size obtained at a constant pressure with that obtained at variable pressure. A Dantec Dynamics A/S (Skovlunde, Denmark) phase-Doppler particle analyser was used following the method described in Nuyttens *et al.* (2005). In the constant-pressure trial, the working pressure was set to 8 bar. In the variable-pressure trial, a simulated control signal from real canopy measurements was sent to the variable-rate valve in the range of 0 to 8 bar. In both tests, two repetitions were performed. The numeric median diameter (*NMD*) and the volumetric median diameter (*VMD*) were calculated together with the percentile 10 and 90 of the volumetric diameters ($D_{v0.1}$ and $D_{v0.9}$, respectively). The Span ($D_{v0.9}-D_{v0.1}$) and Relative Span ($Span/VMD$) were also calculated to compare both populations.

2.2 Prototype implementation

The field prototype was implemented on a Hardi Arrow F 1000 commercial sprayer (ILEMO HARDI S.A.U., Lleida, Catalonia-Spain) in such a way that only one of the sides was able to spray in variable-rate mode. We made the necessary modifications in the original sprayer and added new components such as the sensors, the controller with its specific software, and the electromagnetic valves (Fig. 2).

Fig. 2. Variable-rate orchard sprayer prototype implemented with three ultrasonic sensors (1) and one LiDAR sensor (2) in an apple orchard in 2005.

The sprayer prototype consists of three subsystems: a canopy characterization system, an electronic controller with its monitoring sensors to execute the control algorithm, and actuators to conveniently spray the intended volume application rate. In this development phase, the prototype was operational from only one side. Firstly, the canopy characterization system acquires data from the vegetation sensors and estimates the required parameters. Secondly, a variable-rate control algorithm was executed to convert the canopy parameters into an intended flow rate to be sprayed in each specific location. Finally, a control signal was calculated and sent to command the valves to spray the intended flow rate on a site-specific basis. All the information was recorded for subsequent analysis of the applications and for traceability purposes.

2.2.1 Sprayer modifications

The prototype hydraulic circuit consists of three independent elementary circuits at various heights with common elements such as the tank, pump, and pressure regulator (Fig.

3). We designed the hydraulic circuit in such a way that the modified side was able to spray in both a variable-rate mode and a conventional constant flow rate mode. The user was able to change the spraying mode via a set of manual valves and the controller software. In the conventional spraying mode, the variable-rate and the cut-off electromagnetic valves are isolated and the entire spraying boom was connected so as to act as a whole, as in a conventional sprayer. In the variable-rate spraying mode, the boom was divided into three independent sections with their own variable-rate and cut-off valves receiving independent control signals from the controller.

Fig. 3. Diagram of the hydraulic circuit of the prototype showing the modifications on the right spraying boom and the required components: tank (1), filters (2), pump (3), pressure regulator (4), distributors 1 and 2 (5 and 6), turbine flowmeter (7), manual isolation valves (8), cut-off valves (9), variable-rate valves (10), pressure gauge (11), and antidrip valves (12).

2.2.2 Flowmeter in the sprayer prototype

The flowmeter mounted in the prototype was used to measure the overall flow rate sprayed by the modified side. The flowmeter was a turbine-type Rapid Check (Arag, Rubiera, Italy) used to estimate rapid variations in the flow rate (Table 1).

2.2.3 Prototype operation

The electronic controller was the same programmable automation controller used in the elementary circuit running specifically programmed software. To operate the sprayer in the field without the need for a laptop, we designed a set of switches and LEDs connected to the controller. From the control switches, it was possible to start and stop the software, to select the spraying mode (variable rate, or constant rate for conventional application), to start a performance test, and to start or stop the treatment and the data acquisition. The software of the controller was programmed according to the flow chart shown in Fig. 4. The prototype was able to spray in variable-rate mode or in conventional mode according to the position of the controller switches. In the conventional mode, a constant flow rate was sprayed throughout the treatment. This was achieved by sending a constant 10 V control signal to the variable-rate valves and a digital ON signal to the cut-off valves. In the variable-rate mode, the control signal sent to the variable-rate valves was determined by the inverse function between the applied voltage and the sprayed flow rate. These functions were experimentally determined in the laboratory trials in an open-loop controller mode. The cut-off valves were closed when the proportional valves received a control signal of 0 V.

The performance test consisted of two verifications depending on the spraying mode selected. When running a test while constant rate mode was selected, the controller sent a 10 V control signal to fully open the variable-rate valves and an ON digital signal to the cut-off valves. This procedure tested whether the valves opened correctly. When running the test in

variable-rate mode, an ON digital signal was also sent to the cut-off valves, while the control signal sent to the variable-rate valves was equal to the voltage acquired from their respective ultrasonic sensors in real time. This procedure tested the variable-rate ability of the valves when objects were detected at various distances from the sensors.

To change the sprayed flow rate at a given sampling resolution (i.e. 5 or 10 samples per metre), the regulation loop execution time in the software automatically adapted to the forward speed of the prototype according to Eq. (1).

$$T = \frac{1000}{R \cdot v} \quad (1)$$

where T is the period of the regulation loop (ms sample^{-1}); R is the sampling resolution (samples m^{-1}); v is the forward speed of the sprayer (m s^{-1}).

Another important aspect is the delay between data acquisition from the canopy sensors and prototype actuation. This delay depends on the distance between the sensors and the nozzles (2 m) and on the forward speed of the sprayer. In addition, the actuation of the valves must take place in such a way that the spray cloud reaches the canopy in the exact location of the canopy semi-cross-sectional area estimation. This means that time of flight of the droplets should be taken into consideration and that the actuation for a given sample must begin before the nozzles reach the location where the sensor readings took place. For this purpose, the software included the option to set the actuation a number of program loops forward according to experimental observation. Incorrect synchronization between canopy characterization and spraying could result in treatment failure because of a mismatch between canopy volume and spraying volume.

Fig. 4. Flow chart of the program to control the sprayer prototype.

Every program loop, the software registered all the signals from the sensors, the control signals sent to all the valves, and the values from the working parameters previously introduced by the user (row spacing, canopy height, forward speed, sampling resolution, and spraying mode). The delay between the canopy estimation and the spraying was taken into consideration when recording the data so that the signals were stored in such a way that the sprayed flow rate was paired with its corresponding canopy estimation. The recorded data are used to validate the performance of the prototype.

2.2.4 Variable-rate algorithm

The control algorithm for variable-rate operation mode is an important improvement on the previous prototype version (Solanelles *et al.*, 2006). The algorithm is based on electronically determining the canopy volume and applying a coefficient to convert it into the volume application rate to be sprayed, in a way similar to and based on the TRV method. In this paper, this coefficient is called the application coefficient and is denoted by i_a or i_o depending on whether it is the actual or objective value, respectively. Specifically, the application coefficient is the liquid volume required to distribute correctly the active ingredient in a specific unit canopy volume. The application coefficient is empirically determined for each orchard either from field tests or by previous experience. In this work described in the present paper, the application coefficient was determined from the empirical experience of several deposition trials performed by the Centre de Mecanització Agrària from the Department of Agriculture of the Catalan Government (Spain).

The goal of the control algorithm was to take sensor readings at constant increments along each row (according to the user requirements and the sensors used) to adjust the volume application rate accordingly so as to maintain as far as possible a constant amount of active ingredient deposited per unit leaf area. The canopy characterization system was also improved by designing it to use either ultrasonic (Escolà *et al.*, 2011) or LiDAR sensors

(Rosell *et al.*, 2009a; Rosell *et al.*, 2009b; Sanz-Cortiella *et al.*, 2011). We used a new data acquisition system and a new processing unit, implemented different flow rate monitoring sensors, and expanded the flow rate regulation range. Therefore, the resulting prototype is a more accurate real-time sensor-based variable-rate orchard sprayer.

The instantaneous semi-cross-sectional areas estimated by the canopy characterization system multiplied by the forward speed of the sprayer give the volume of vegetation passing in front of the nozzles per unit time. The introduction of the objective (intended) application coefficient and a constant to harmonize the units enables estimation of the instantaneous flow rate that should be sprayed at a certain moment and location in the orchard by one side of the sprayer prototype. To increase the sprayer vertical resolution, the sprayer boom was divided into three independent spraying sections, each spraying a corresponding section or level of the canopy. This solution enabled spraying at various flow rates according to Eq. (2).

$$q_j = 60 \cdot s_j \cdot v \cdot i_o \quad (2)$$

where q_j is the flow rate to be sprayed by section j (L min^{-1}); s_j is the fraction of the semi-cross-sectional area associated with the independent section j (m^2); v is the forward speed of the sprayer (m s^{-1}); i_o is the objective application coefficient (L m^{-3}).

2.2.5 Canopy characterization

The canopy characterization system will not be described in detail in this part of the paper because its design and validation are worthy of separate publication. However, some details are explained here to enable better understanding of the field validation trials. The prototype was designed to use either ultrasonic or LiDAR sensors in its canopy characterization system. In the work described in the present paper, results are displayed when scanning the canopy with a LiDAR sensor (see section 2.4 for details). The LiDAR sensor was attached to a vertical pole in the front part of the sprayer prototype facing the

rows of trees to be treated. Because a conventional orchard sprayer treats the two halves of both rows facing the alleys, the canopy characterization system only measures the half facing the operational side of the sprayer. Specifically, the system estimates the semi-cross-sectional area of the canopy, denoted by s , every 10 to 20 cm along the row from the readings of the sensors (Fig. 5); this is a sampling resolution, R , of 5 to 10 samples per metre. These instantaneous canopy semi-cross-sectional areas were the output of the canopy characterization system and one of the inputs of the sprayer prototype controller used to execute the variable volume application rate algorithm and determine the flow rate to be sprayed according to canopy variability.

Fig. 5. Orchard diagram of a cross-sectional area (S) and a semi-cross-sectional area (s) of the canopy, the canopy semi-width (C_W), the canopy height (C_H), and the row spacing (r).

2.3 Laboratory validation trials

2.3.1 Response time

One of the most important issues in variable-rate equipment is response time, which determines the working frequency and the minimum distance for various actuations. The method for establishing the maximum response time of the elementary circuit consisted of

378 sending a 0–10 V step control signal to the variable-rate electromagnetic valve with the cut-
379 off valve completely opened, and recording the readings of all the sensors. The maximum
380 response time would be the minimum response time of any of the sensors in providing a
381 steady response signal. It is to be considered that this response time also includes the
382 response time of the sensor, and thus, the elementary circuit could be quicker in its response.
383 The turbine flowmeter was calibrated to achieve an update rate of 10 Hz so that rapid
384 variations in flow rate could be detected.

385 2.3.2 Flow rate range increase

386 To increase the flow rate range of the elementary circuit, it was necessary to increase
387 the working pressure of the variable-rate valve and to mount the cut-off valve. Several trials
388 were carried out to evaluate the performance of the hydraulic circuit when sending to the
389 variable-rate valve a triangular control signal from 0 to 10 V using various combinations of
390 ATR hollow cone nozzle models (green, red, and orange), working pressures ahead of the
391 variable-rate valve, and opening thresholds. This last parameter was determined by the
392 actuation of the cut-off valve. This valve actuation was tested under three possibilities: 1)
393 always open (allowing spraying at any given variable-rate valve control signal), 2) open
394 only for variable-rate valve control signals higher than 1 V (to prevent spraying at low
395 pressures), and 3) open only for variable-rate valve control signals higher than 2 V.

396 The chosen combination for the prototype would be the one providing the widest
397 flow rate range at adequate working pressures for spray application techniques (from 3 to 15
398 bar with a recommended pressure of 10 bar from the manufacturer) ahead of the variable-
399 rate electromagnetic valve. With this chosen combination and spraying at the chosen
400 working pressure, the resulting scatter diagram (sprayed flow rate versus control signal) and
401 the residuals could be analysed so as to adjust a polynomial model. This polynomial

function could be subsequently used as a calibration for the regulation algorithm of the sprayer prototype.

2.3.3 Prototype sprayed flow rate

The final laboratory trial tested the homogeneity of the flow rate sprayed by every single nozzle and establishing a new function relating control signals and sprayed flow rates if differences with the elementary circuit were important. This test was performed with the help of an AAMS electronic flow rate meter (AAMS NV, Maldegem, Belgium). This device consisted of several test tubes with connectors attached to each nozzle and an electronic unit connected to a laptop to control the test process (Fig. 6). The trial consisted of sending a known control signal between 0 and 10 V to the variable-rate valves and an ON digital signal to the cut-off valves to analyse the response and to establish a relationship between those control signals and the sprayed flow rate of each independent section.

Fig. 6. Laboratory trial setup to validate the sprayed flow rate of the operational side of the prototype using an automated test bench.

2.4 Field validation trials

The field validation trials comprised two applications of pure water in a *Pyrus communis* L. cv. ‘Conference’ orchard. The characteristics of this orchard are listed in Table 2.

Table 2. Description of the *Pyrus communis* L. cv. ‘Conference’ orchard where field trials were performed.

Parameter	Approx. value
Phenological stage	BBCH 92
Row spacing	4.0 m
Tree spacing	1.6 m
Canopy width	1.9 m
Tree height	4.0 m

The first treatment was carried out in a conventional constant flow rate mode, whereas the second was a variable-rate mode application. The variable-rate application was controlled by the designed algorithm to automatically vary the sprayed flow rate and, therefore, the volume application rate according to the canopy volume estimated by using the LiDAR sensor. The sensor used was a LMS 200 (SICK, Waldkirch, Germany) LiDAR sensor. A scan was taken every 20 cm along the tree row, and the objective application coefficient was 0.125 L m^{-3} , established for canopy estimations performed with a LiDAR sensor from our experience in previous trials.

After the treatments, data were retrieved, analysed, and processed to obtain information on the canopy and the sprayed flow rates. The parameters directly registered were the instantaneous canopy semi-cross-sectional areas and the instantaneous sprayed flow rate. From these parameters, other relevant information was calculated such as all instantaneous canopy semi-volumes (Eq. 3), total canopy semi-volume, sprayed volumes in each canopy semi-volume (Eq. 4), total sprayed volume, actual instantaneous application coefficients (Eq. 5), and average application coefficient (total sprayed volume/total canopy semi-volume).

$$C_V = \frac{s}{R} = \frac{\sum s_j}{R} \quad (3)$$

$$SV = \frac{q}{60 \cdot v \cdot R} = \frac{\sum q_j}{60 \cdot v \cdot R} \quad (4)$$

$$i_a = \frac{SV}{C_V} \quad (5)$$

where C_V is the canopy semi-volume ($\text{m}^3 \text{ sample}^{-1}$); s is the canopy semi-cross-sectional area (m^2); s_j is the canopy semi-cross-sectional area at section j (m^2); R is the sampling resolution (samples m^{-1}); SV is the sprayed volume (L sample^{-1}); q is the flow rate sprayed by the entire side of the sprayer (L min^{-1}); q_j is the flow rate sprayed by section j (L min^{-1}); v is the forward speed of the sprayer prototype (m s^{-1}); i_a is the actual application coefficient (L m^{-3}).

These data were used to assess the correlation between the theoretical flow rate to be sprayed and the actual sprayed flow rate, and the correlation between the instantaneous sprayed flow rate and the instantaneous canopy semi-cross-sectional area. The statistical technique consisted of visually analysing the scatter and residuals diagrams and attempting to fit a linear regression model to assess the relationship between the variables. In addition, we compared the actual instantaneous application coefficients of both treatments with those obtained from the variable-rate mode with its programmed objective application coefficient (which was 0.125 L m^{-3}). For this purpose, we applied descriptive statistics and compared the actual instantaneous application coefficient means obtained in conventional and variable-rate modes with an analysis-of-variance test.

3 RESULTS AND DISCUSSION

3.1 Laboratory validation trials

3.1.1 Response time

Fig. 7 shows a diagram of a rising and falling edge of a 10 V step control signal sent to a variable-rate valve and the responses of the pressure sensor, the electromagnetic flowmeters, and the turbine flowmeter. The quickest response was that from the pressure sensor, the next quickest was that from the turbine flowmeter, and far behind that was the response from the electromagnetic flowmeter. The time between the control signal step and attainment of the stabilized value of the flow rate was approximately 400 ms for the turbine flowmeter and 3 s for the electromagnetic flowmeter. It should be noted that this maximum step will rarely occur in real treatment, owing to the characteristics of the canopies. The pressure sensor required approximately 300 ms to reach the stabilized value of its response. When analysing the falling edge, the responses of the two flowmeters were similar to the rising case, whereas the pressure sensor required only 200 ms to stabilize. Because hydraulic pressure depends on the flow rate, it can be said that the real flow rate change is quicker than that registered by the turbine flowmeter. Therefore, the response of the basic circuit is faster than 300 ms because this is the maximum time required by the valve to change the delivered flow, plus the time needed by the sensors to develop their response, plus the time required by the controller for acquiring and recording the responses of the sensors. For smaller steps, such as those taking place in real working conditions, the response times will be shorter.

Fig. 7. Detail of the response signals of elementary hydraulic circuit after the rising (a) and falling (b) edges of a 10 V step control signal sent to the variable-rate valve.

3.1.2 Flow rate range increase

In relation to the selection of the nozzle model, Fig. 8 shows the basic circuit response when spraying with three Albuz ATR orange hollow cone hydraulic nozzles. The initial spraying pressure was between 1.50 and 2 bar, the maximum pressure was approximately 10 bar, and the flow rate ranged from 1.75 to 3.5 L min⁻¹. When mounting the red nozzles, the flow rate ranged from 1.85 to 4.3 L min⁻¹, but the pressure varied between only 1 and 6.75 bar. When spraying with the green nozzles, the initial pressure descended to 0.5 bar, and the highest pressure reached only 5 bar with an initial flow rate similar to that with the red nozzles but with the maximum reaching almost 5 L min⁻¹. Given these results, it was decided to work with the orange nozzles because the manufacturer recommends a working pressure of 10 bar. The working pressure upstream of the variable-rate valve was set to 15 bar, and a cut-off valve was introduced to help the former in the cut-off process. In

496 addition, the use of the cut-off valve allowed spraying to start only with working pressures
 497 above 2 bar, guaranteeing the correct formation of the hollow cone.

498
 499 Fig. 8. Diagram of the response of the elementary hydraulic circuit by flow rate and pressure
 500 for a triangular control signal sent to the variable-rate valve for an upstream pressure of 15
 501 bar for three orange Albuz ATR hollow cone nozzles.

502 Fig. 9 shows the adjustment of a cubic polynomial function to the scatter diagram of
 503 flow rate versus control signal data generated in the elementary circuit equipped with three
 504 orange ATR Albuz nozzles at a pressure of 15 bar immediately prior to the variable-rate
 505 valve.

Fig. 9. Scatter diagram of the control signal and delivered flow rate for the elementary circuit with three orange Albuz ATR nozzles, an upstream pressure of 15 bar, and a cut-off electro valve opening at a 1 V control signal.

The adjusted polynomial function is only valid within the analysed flow rates, and therefore its application must be limited to this range. Eq. (6) allows us to establish the required control signal to be sent to the variable-rate valves so as to spray the flow rate determined by the developed variable-rate algorithm. The coefficient of determination for the adjusted polynomial function is $R^2 = 0.966$, and the root mean square error is $RMSE = 0.479$ after 1,075 observations.

$$V_j = -0.685 q_j^3 + 4.914 q_j^2 - 6.919 q_j + 2.438 \quad (6)$$

where V_j is the control signal sent to the variable-rate electrovalves (V), and q_j is the flow rate to be sprayed by an independent section (L min⁻¹).

3.1.3 Droplet size

The droplet size distribution was measured for the chosen orange hollow cone ATR nozzles. Table 3 lists the values of the various parameters related to droplet size. It is clear that droplet populations are fairly similar when produced at constant and variable-rate pressure conditions.

Table 3. Droplet population characteristics for an orange Albuz ATR hollow cone nozzle in constant- and variable-pressure trials.

Parameter	Constant-pressure trial (@ 8 bar)	Variable-pressure trial (0 to 8 bar)
<i>NMD</i> (μm)	54.16	53.97
<i>VMD</i> (μm)	148.45	156.20
<i>Dv0.1</i> (μm)	73.78	76.40
<i>Dv0.9</i> (μm)	262.14	275.24
Span (μm)	188.36	198.85
Relative Span	1.27	1.27

3.1.4 Prototype sprayed flow rate

Although we implemented the prototype attempting to mimic the preliminary circuit in all three sections, differences were observed in the relation between control signals and sprayed flow rates, so that new polynomial functions were fitted for each individual section (Table 4).

Table 4. Adjusted functions for determining the control signal V_j , in volts, to be sent to the variable-rate valves of the various sections (j) of the sprayer after the intended flow rate determined by the variable-rate controller algorithm, in $L \cdot min^{-1}$.

Section	Adjusted function	R^2
Top section (3)	$V_3=0.184q_3^5-1.644q_3^4+4.859q_3^3-4.754q_3^2+2.210q_3+0.020$	0.99
Central section (2)	$V_2=0.003q_2^3-0.606q_2^2+6.598q_2-6.277$	0.99
Bottom section (1)	$V_1=0.628q_1^5-7.258q_1^4+33.613q_1^3-79.671q_1^2+101.340q_1-53.130$	0.98

The total flow rate applied by the prototype was the sum of the flow rates applied by each of the three independent sections of the modified side of the spraying boom. Fig. 10 presents the overall flow rate response of the prototype in the case of a simulated uniform

542 tree canopy so that the control signals sent to the three variable-rate valves were the same,
 543 ranging from their minimum to their maximum values. Fig. 10 shows the maximum flow
 544 rate capacity of a sprayer side and the entire range of flow rate regulation. In that specific
 545 simulated case, the sprayed flow rate ranged from a minimum of 3.75 L min^{-1} to
 546 11.25 L min^{-1} , allowing a wide range of volume application rates. The minimum sprayed
 547 flow rate was no lower than 3.75 L min^{-1} , to ensure that spraying did not occur at lower
 548 working pressures, which would fail to guarantee the correct formation of the jet cones. This
 549 safety minimum flow rate may cause overdosing when spraying PPP where there is little
 550 vegetation, but prevents the incorrect formation of droplets.

551
 552 Fig. 10. Diagram of the sprayed flow rate of the three sections of the prototype ranging from
 553 their minimum to their maximum control signal values.

554

3.2 Field validation trials

In Fig. 11, the results of spraying a 40 m row length in constant flow rate mode and in real-time variable-rate mode are shown overlapping the canopy semi-volume.

Fig. 11. Diagram of the estimated canopy semi-volumes obtained with the LiDAR sensor, and the corresponding sprayed volumes in conventional and variable-rate modes in the *Pyrus communis* L. cv. 'Conference' orchard.

3.2.1 Correlation between variables

The linear model fitted to the theoretical flow rate and the actual flow rate data pairs (Fig. 12) explains 93.5% of the variability of the samples. The relationship between the variables is strong according to the high value of the coefficient of correlation ($r = 0.967$), and the residuals do not follow any structured pattern.

Fig. 12. Scatter diagram of the sprayed flow rates as a function of the intended flow rate determined by the variable-rate controller algorithm. The solid line represents the fitted simple linear regression model.

The instantaneous sprayed flow rates of the trial as a function of the semi-cross-sectional area of canopy are displayed in Fig. 13. The result of the conventional application was a constant flow rate of 9.72 L min^{-1} on average regardless of tree canopy size, whereas the prototype working in variable-rate mode gave a point cloud where a linear model can be fitted. This model explains 92.6% of the variability of the sample, and the relationship between both variables is strong according to the coefficient of correlation value ($r = 0.962$). The model better fits the higher flow rates (higher than 5 L min^{-1}) than the lower flow rates. This effect is a consequence of the use of safety flow rates to prioritize proper spray jet formation rather than following a strict linear response to canopy size. Thus, zones in an orchard with little vegetation may be oversprayed considering the proposed variable-rate algorithm.

Fig. 13. Scatter diagram of the sprayed flow rates as a function of the semi-cross-sectional areas estimated by the LiDAR sensor according to the variable-rate controller algorithm. The solid line represents the fitted simple linear regression model.

3.2.2 Application coefficient

In Fig. 14, the actual application coefficient values obtained during the two treatments are displayed as a function of the canopy semi-volumes estimated by the LiDAR sensor. The diagram in Fig. 14 shows that the conventional treatment only achieved the objective application coefficient in areas of the orchard with the highest canopy semi-volumes, moving away when the canopy decreased. In the case of the variable-rate

application mode, the actual application coefficients remained close to the objective in large and average-sized canopies, but moved away when spraying small canopies because of the minimum safety flow rate. When considering acceptable application coefficients in the range of 0.125 to 0.185 L m⁻³, the conventional mode achieved a success rate of 29% of correctly treated samples, whereas the variable-rate treatment was more successful with up to 84% of the samples. Thus, 71% of cases were oversprayed when treated with a conventional sprayer, whereas the variable-rate prototype oversprayed only 16% of cases. As can be seen in Table 5, the application coefficients obtained by the variable-rate application are closer to the objective than those obtained in the conventional application mode. In terms of negative aspects of the operation of the prototype, it should be mentioned that 2.5% of the canopy received a slightly lower application coefficient (0.115 L m⁻³) in relation to the objective (0.125 L m⁻³), whereas in the case of the conventional treatment, the percentage was only 0.5%.

Fig. 14. Scatter diagram of the actual application coefficients (i_a) obtained for conventional and variable-rate applications as a function of the estimated canopy semi-volumes. The red dotted line indicates the objective application coefficient (i_o).

Table 5. Descriptive statistics of the actual application coefficients (i_a) obtained with the prototype in the trials performed in conventional and variable-rate modes.

Descriptive statistics of i_a	Conventional constant operation mode	Real-time variable-rate operation mode
Mean (L m^{-3})	0.364 a	0.177 b
Maximum (L m^{-3})	4.766	1.336
Minimum (L m^{-3})	0.123	0.115
Standard deviation (L m^{-3})	0.496	0.130
RMSE (L min^{-1})	0.035	0.009
Observations	201	201
Variance	0.246	0.017
Coef. of variation (%)	136.06	73.75

* Different letters in means imply differences with a level of significance $\alpha = 0.05$ according to the Tukey–Kramer test.

4 CONCLUSIONS

The field validation trials indicate a strong correlation between the intended flow rates and the sprayed flow rates ($R^2 = 0.935$) and between the estimated semi-cross-sectional canopy areas and the sprayed flow rates ($R^2 = 0.926$).

The sprayer prototype significantly achieved actual application coefficient values closer to the objective. The final result was better adjustment of the sprayed volume application rate to the actual geometric characteristics of the crop canopy.

Modifying the sprayed flow rate through the electromagnetic high-frequency variable-rate solenoid valves did not significantly affect the size of the generated droplets.

The cut-off valves added to the hydraulic circuit, allowing the working pressure of the sprayer to be increased and, consequently, the flow rate range.

The turbine flowmeters showed better performance than the electromagnetic flowmeters in terms of response time (<500 ms), although their accuracy was slightly lower. Analysis of the obtained data verifies that the implemented prototype can be executed with the real-time variable-rate control algorithm.

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