Improvement of spray deposit homogeneity using a PWM spray controller to compensate horizontal boom speed variations.

F. Lebeau [a,*], L. El Bahir [b] - M.-F. Destain [a] , M. Kinnaert [b], R. Hanus [b]

[a] *UMC, Faculté universitaire des Sciences agronomiques de Gembloux,*

Passage des Déportés, 2 B-5030 Gembloux, Belgium

[b] *SAAS, Université Libre de Bruxelles,*

CP165/55 Av. F. Roosevelt, 50 B-1050 Brussels, Belgium

Abstract

Longitudinal spray distribution is mainly affected by the horizontal speed variations of the nozzles. Manufacturers classically try to reduce unwanted nozzles movements using horizontal boom suspension but these methods have performance and price limitations. This paper describes a spray controller aiming to compensate the effect of the horizontal boom movements on the spray deposits homogeneity. The controller is based on three main components: a control law describing the relationship between nozzle speed, nozzle flow and spray deposit; a real time measurement of the boom horizontal speed variations using micro-machined capacitive accelerometers, and Pulse Width Modulation (PWM) nozzle flow actuators. To assess the feasibility of such a controller, a single nozzle prototype was developed and tested in the laboratory, using a nigrosine solution. Spray coverage was measured using image analysis for field representative nozzle speed variations. The spray coverage uniformity using the controller showed about 51% compensation of the variations observed without it.

Keywords: spray controller; horizontal boom movements; spray deposits distribution; Pulse Width Modulation nozzle.

* Corresponding author. Tel: +32 81 62 21 65 Fax +32 81 62 21 67
E-mail address: lebeau.f@fsagx.ac.be (F. Lebeau)

1 Introduction

Chemical spray application remains the main way to insure high yields at low cost in the conventional agriculture. However, increased concern about the environmental pollution and the effect of pesticides residues on human health create a strong need for more efficient application methods to improve spray deposit homogeneity. Furthermore, poor homogeneity has also an impact on farm efficiency; e.g. additional costs because of over-dosing or losses because of under-dosing. For crop sprayers, boom movements are known to have a major influence on the spray deposits distribution. As a result, much work has been devoted to enhancing the stability of booms, with the objective to limit the transmission of rolling and yawing motion to the boom (Nation, 1982). The dynamic behaviour of booms with pendulum or twin link suspensions, either passive or active, was described from the 1980's (Frost, 1984; O'Sullivan, 1986; Nation, 1987a; Nation, 1987b; Frost and O'Sullivan, 1988, O'Sullivan, 1988) until recently when horizontal active suspension was introduced (Anthonis *et al.*, 2000). On basis of these studies, most spraying machines are now equipped with boom suspension. Particularly, recent sprayers are sometimes equipped with horizontal passive suspensions to limit relative nozzle speed variations by reference to the mean sprayer speed. Horizontal active systems have also been developed but remain at the prototype stage. This may be due to the complexity of the proposed designs, including supplementary mechanical parts, such as links and cylinders, that have to be included in a feedback loop.

However, with the increased width of the present sprayers booms (up to 50 m), the need for reducing the unevenness of spray distribution remains crucial. Indeed, a test of recent sprayers in field conditions showed that the coefficients of variation (CV) of the boom speed would be between 4 and to 6 % when taking into account all the nozzles of a boom and could reach values as high as 15% for nozzles located at the end of the boom, in the 0.2 – 1 Hz frequency range (Ooms *et al.*, 2002). As a result, the yawing and jolting of the boom, and the consequent nozzle speed variations, were found to be the main cause of spray deposits heterogeneity in field conditions (Ooms *et al.*, 2003). Indeed, the longitudinal spray distribution (in the forward direction) is highly affected by the horizontal speed variations of the nozzles, as illustrated in Fig. 1a. High nozzle speed results in local under-application while low nozzle speed results in local over-application.

This paper presents another way to reduce the undesirable effects of the horizontal boom movements on the spray deposits. Instead of using complex filtering mechanical components to restrain the boom movements, a new form of controller acting on the hydraulic circuit of the sprayer is described. Electronic spray controllers are usually designed to compensate the effect of sprayer speed variation by varying the flow rate of the nozzles depending on changing vehicle ground speed (Al-Gaadi and Ayers, 1994). They do not take into account the unwanted horizontal nozzle movements caused by yawing and jolting: the flow rate correction is equal for all nozzles throughout the boom length. The new concept is to improve the precision of the controller by acting at the nozzle level rather than at the sprayer level. This implies adaptation of the flow rate of each nozzle (or of the nozzles belonging to a boom section) to compensate the local boom movements as shown in Fig. 1b. The feasibility of such a controller was investigated for a nozzle subject to speed variations.

2 Materials and methods

The structure of the controller components described in the next sections is represented in Fig. 2. It includes the control law, the signal processing of the sprayer-mounted sensors for the real-time measurement of boom movements and the actuators to adapt the nozzle flow.

2.1 Control law

The control law employed for calculation of the nozzle flow needed to produce a uniform spray distribution in the presence of nozzle speed variations was in the simple form:

$$q_d(t) = k(\tau_d)V(t) \qquad [1]$$

where:

τ_d is the desired application rate (l/m²),

$q_d(t)$ is the flow setpoint needed to get τ_d (l/s),

$V(t)$ is the absolute nozzle speed (m/s),

$k(\tau_d)$ is a constant depending on τ_d (l/m).

The constant $k(\tau_d)$ can be made proportional to the desired application rate as follows:

$$k(\tau_d) = \alpha\tau_d \qquad [2]$$

The constant α can be evaluated experimentally for a nozzle by measuring the spray coverage obtained for a set of trials at constant speed and flow.

This form of feed-forward control avoids the need for on-line measurement of the spray deposits as it relies on the assumption of a direct relationship between the nozzle speed and the application rate. Of course, the restriction is that this controller is unable to compensate sources of spray deposit variations other than the horizontal nozzle speed variations and that incorrect nozzle speed estimation will affect the result.

2.2 Real time measurement of the boom movements

The accuracy of the measured nozzle speed $V(t)$ in real time is crucial for the determination of the flow setpoint delivered by the controller. Several methods have been developed to measure absolute boom movements. They are either based on acceleration or displacement measurements. In this work, accelerometers were chosen to measure the relative speed of the nozzle because of their potential ease of implementation and their low weight which does not affect the boom dynamic behaviour significantly (Lebeau and Destain, 2000). Their main drawback is the drift of the sensor signal at low frequencies and their sensitivity to gravitational acceleration. Signal processing therefore included integration to obtain the speed; filtering of low frequencies to eliminate drift and of high frequencies to avoid aliasing. Micro-machined capacitive accelerometers CXL02LF3 (Crossbow) were chosen as their frequency and amplitude ranges [0 - 125 Hz, ± 20 m/s²] were suited to that of the boom movements in the most detrimental frequencies for the spray distribution. Furthermore, the cost of this technology offers a practical solution from commercial considerations. The mean speed of the boom was measured using a doppler effect speed sensor of a type commonly used on agricultural vehicles (RGSS-201, Philips automotive electronics Co). Its pulse output is transformed to an analogue signal.

2.3 Nozzle flow actuator

The nozzle flow actuator has to operate at the nozzle level in such a way that both high frequency capability and nozzle flow individualisation can be ensured. In fact, the horizontal boom movements to be compensated lie in the 0.2 – 1 Hz frequency range and differ from one nozzle to the other. Pulse Width Modulation (PWM) flow actuators developed for precision farming satisfy these requirements with negligible influence on spray pattern and droplet size distribution (Giles and Comino, 1990). The actuator static characteristics can generally be described with the following linear equation:

$$q_r = a\, duty + b \qquad [3]$$

where

a and *b* are constants,

qr is the nozzle flow (l/s),

duty is the PWM duty cycle.

2.4 Controller implementation and experimental set-up

The prototype controller was implemented using Simulink (Mathworks) models and a DS1102 controller board (dSpace). The next steps are performed by the controller.

The nozzle acceleration is integrated and filtered by a band-pass filter to obtain an estimate of the nozzle speed relative to the spraying machine (mean speed is removed by the filtration). The need for real-time filtering of the signal limited the filter order to avoid excessive phase distortion. Therefore a first order [0,15 – 10] Hz band-pass Butterworth filter was chosen. The pulse signal of the speed meter was processed and low-pass filtered. The absolute speed of the nozzle was obtained by summing the sprayer speed and the nozzle relative speed. In the second step, the actuator static characteristic characterised by equation [3] was integrated in the control laws (equations [1] and [2]). The absolute speed was transformed using the resulting equations to a PWM control signal that was amplified to act on the PWM nozzle.

2.5 Actuator characteristics

The flow of the PWM actuator equipped with a teejet XR 11006 nozzle depends on the PWM duty cycle and frequency. Measured actuator static characteristics at 3 bars showed that the width of the linear zone, described by equation [3], decreased with increasing PWM frequency (Fig. 3). Indeed, a high PWM frequency is needed to assure the continuity of the spray coverage while sufficient linearity is needed. Trials conducted to determine the dynamics of the actuator showed that bandwidth was only limited by the PWM frequency. 16 Hz PWM frequency was chosen as the best compromise, with corresponding constants $a = 37.5$ and $b = -4.35$.

2.6 Test bench

The controller performance was tested and analysed on a specially designed test bench (Fig. 4) in the laboratory to avoid perturbation by environmental factors. A nozzle was mounted on a small beam that could be moved horizontally by a linear translation table controlled by a computer. This system was able to reproduce the speed variations around the mean value of the nozzle, these variations being measured in the field in a previous step. The mean speed of the boom was simulated by a band conveyor moved at a constant speed. The nozzle was connected to a hydraulic circuit similar to that used in sprayers. The distributions resulting were analysed using the method described by Enfält *et al.* (1997) which consisted in spraying a dye (0.3 % nigrosine solution) on paper and measuring the deposit with image analysis. The measured parameter was the grey level at 25 cm² resolution which could be correlated with the application rate. In the present case, the paper spray collector was attached on the conveyor. After spraying, it was scanned in 256 grey levels at 100 dpi with a large-format scanner. The numerical images were treated to find the spray coverage at 6,45 cm² resolution (squares with 25 mm long sides). An accelerometer was mounted on the horizontal linear translation table near the nozzle. To simulate the sprayer mean speed, the conveyor was maintained at a constant 1 m/s.

2.7 Trials

In a first stage, the accuracy of the reconstructed absolute nozzle speed derived from the combination of speed meter and accelerometers signals was analysed in field conditions. The absolute speed computed by sensor data fusion was compared with absolute speed measurements performed using a laser distance sensor (DME 2000, Sick Optic Electronics). The trials were performed on a hard uneven meadow inducing high amplitude vibrations during the vehicle's rolling.

An illustrative example is presented in Fig. 5. The small discrepancies appearing just after the starting were caused by the high acceleration of the sprayer and rapidly disappeared, and thus would not affect the quality of the measurement in operating conditions.

The second stage was performed on the laboratory test bench. Fig. 6 shows examples of the power spectral function of the right extremity acceleration of the boom for two different sprayers in field conditions. There were two main frequencies which could affect the spray coverage, 0.5 Hz and 0.9 Hz in the first case (a 1000 litre tractor-mounted sprayer equipped with a 18 m boom); 0.75 Hz and 0.85 Hz in the second case (a 2500 litres trailed sprayer equipped with a 27 m boom). To mimic such boom movements, a multi-frequency speed variation (Fig. 6) was applied to the nozzle by the linear translation table. The desired spray coverage was fixed to the one obtained with 0.5 duty-cycle and 1 m/s mean speed.

The nigrosine solution spray coverage was measured using image analysis for these multi-sine nozzle speed variations.

To further assess the effectiveness of the method to improve the quality of the spray deposits, the effect of the controller on the ground spray deposits distribution was simulated using a model based on a convolution of the nozzle trajectory with the nozzle dynamic spray distribution (Lebeau, 2003).

3 Results and discussion

Results showed about 51% compensation of the spray coverage variations (Fig. 8). The actuator was found suitable for this application as it was effective in the most detrimental frequencies, even if the spray coverage was slightly overcompensated. Trials conducted at different constant speeds, with corresponding duty-cycles, to ensure constant dose showed that the application rate - spray coverage relationship was unexpectedly not linear with duty-cycle, which explained most of the discrepancies.

Fig. 9 presents the simulation of the spray deposits caused by the movements of a 18 m wide boom of a sprayer equipped with flat-fan nozzles (2 bar, 0.99 l/min.) spraying in a wheat field, at 1.5 m/s mean speed. The local application rate (varying from 12 to 41 ml/m²) differed greatly from the mean value (22 ml/m²) and the spray deposit heterogeneity was characterised by a 9.2 % coefficient of variation. Fig. 10 shows that, at the present development stage, the 51 % compensation resulted in a significant decrease in the heterogeneity of the spray deposits distribution. In fact, the coefficient of variation of the application rate decreased to 5.8 % with the controller (25 cm² resolution). Although encouraging, this result leaves some place for further improvement. A simulation indicated that a 100 % compensation of the horizontal boom movements by the controller would further reduce the coefficient of variation of the application rate to 4.0 %. The remaining variability would result from the height variations and the incorrect overlap between adjacent nozzles sprays which were not compensated by the horizontal controller.

For the practical implementation of the single nozzle regulator described here into a complete system, issues such as pressure variations, controller configuration or cost still need to be addressed but are not obviously major hurdles. Pressure variations in the entire system must be limited as the sprayer mean application rate remains unchanged. The cost of the system could be relatively affordable as the PWM actuators are emerging on commercial agricultural sprayers equipped for precision farming (e.g. Case IH AIM Command Spray System), low cost micro-machined accelerometers now commercially available (about $2 for a suitable accelerometer chip) and current DSP controllers are powerful enough for the task.

4 Conclusions

The spray controller limited the effect on spray distribution of the nozzle speed variations caused by unwanted boom movements. These results showed promise for the development of an industrial prototype of spray controller to equip all the nozzles of a sprayer in order to conduct field trials of the controller performances and to analyse its potential on future sprayers.

Acknowledgement

This research was funded by the Federal Ministry of Agriculture of Belgium. Project n° S-5926-section 1.

References

Al-Gaadi K. A., Ayers P. D. 1994. Monitoring controller-based field sprayer performance. Applied Engineering in Agriculture. 10(2), pp. 205-208.

Anthonis J., Ramon H., De Baerdemaeker J. 2000. Implementation of an active horizontal suspension on a spray boom. Trans. ASAE, 43(2), pp. 213-220.

Enfält P., Enggvist A., Alness K. 1997. Assessment of the dynamic spray distribution on a flat surface using image analysis. Aspects of Applied Biology, 48, pp. 17-25.

Frost A. R. 1984. Simulation of an Active Spray Boom Suspension. Journal of Agricultural Engineering Research 30, pp 313-325.

Frost A. R., O'Sullivan J. A. 1988. Verification and Use of a Mathematical Model of an Active Twin Link Boom Suspension. Journal of Agricultural Engineering Research 40, pp 259-274.

Giles D. K., Comino A. 1990. Droplet size on spray pattern characteristics of an electronic flow controller for spray nozzle. Journal of Agricultural Engineering Research 47, pp. 249-267.

Lebeau F. 2003. Modélisation de la répartition dynamique des produits phytopharmaceutiques sous une rampe de pulvérisation (Modelling the distribution of spray deposit of phytopharmaceutical products under a spray boom), PhD Thesis, Gembloux, Faculté universitaire des Sciences agronomiques, 197 pp.

Lebeau F., Destain M.-F. 2000. Sensor data fusion for the measurement of horizontal sprayer boom displacement. In: Ramon H., Hostens I. (Eds.), Proceedings of the 1st International workshop on noise and vibration in agricultural and biological engineering, ISMA 25, Leuven, pp. 1615-1618.

Nation H. J. 1982. The dynamic behaviour of field sprayer booms. Journal of Agricultural Engineering Research 27, pp. 61-70.

Nation H. J. 1987a. The design and performance of a gimbal-type mounting for sprayer booms part 1: Development procedure. Journal of Agricultural Engineering Research 36, pp. 233-246.

Nation H. J. 1987b. The design and performance of a gimbal-type mounting for sprayer booms, part 2: Optimisation model and validation. Journal of Agricultural Engineering Research 36, pp. 247-260.

Ooms D., Lebeau F., Ruter R., Destain M.-F. 2002. Estimation of horizontal displacement of boom sprayer by sensor fusion. Computers and Electronics in Agriculture 33(2), pp. 139-162.

Ooms D., Ruter R., Lebeau F., Destain M.-F. 2003. Impact of the horizontal movements of a sprayer boom on the longitudinal spray distribution in field conditions. Crop Protection 22, pp. 813-820.

O'Sullivan J.A. 1986. Simulation of the behaviour of a spray boom with an active and passive pendulum suspension. Journal of Agricultural Engineering Research 35, pp 157-173.

O'Sullivan J. A. 1988. Verification of passive and active version of a mathematical model of a pendulum spray boom suspension. Journal of Agricultural Engineering Research 40, pp 89-101.

List of Figures

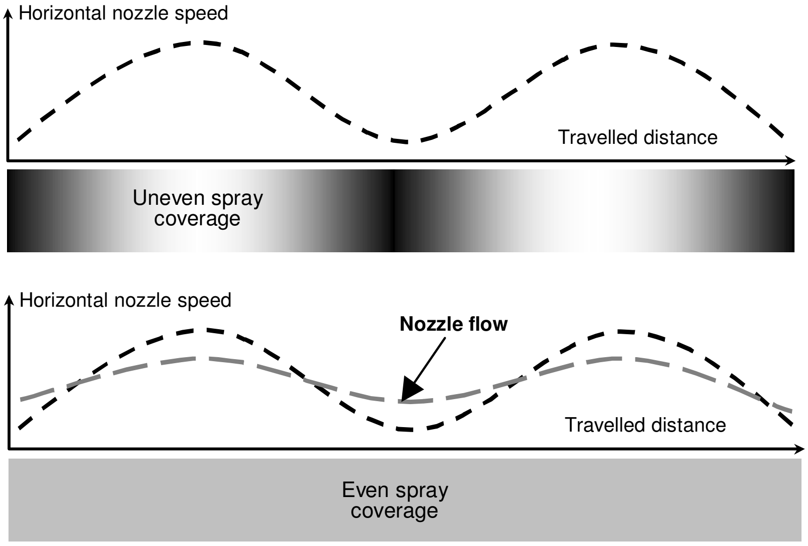
Horizontal nozzle speed
Travelled distance
Uneven spray coverage
Horizontal nozzle speed
Nozzle flow
Travelled distance
Even spray coverage

Fig. 1.

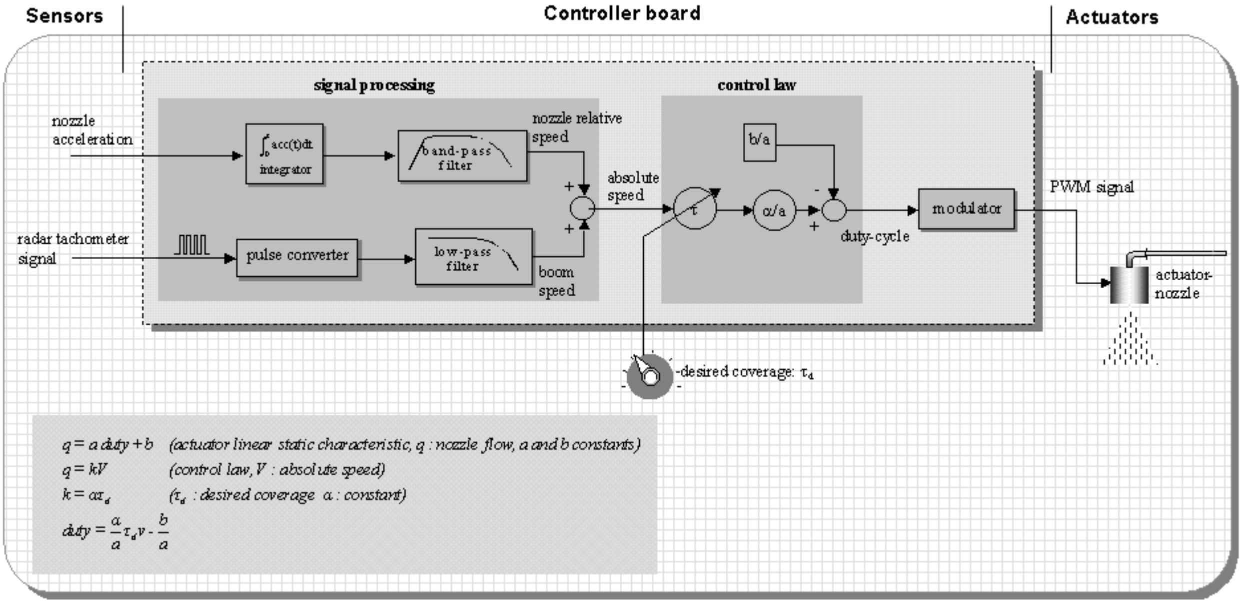
Sensors
Controller board
Actuators
signal processing
control law
nozzle acceleration
integrator
band-pass filter
nozzle relative speed
absolute speed
radar tachometer signal
pulse converter
low-pass filter
boom speed
b/a
α/a
duty-cycle
modulator
PWM signal
actuator-nozzle
-desired coverage: τ_d
$q = a\,duty + b$ (actuator linear static characteristic, q : nozzle flow, a and b constants)
$q = kV$ (control law, V : absolute speed)
$k = \alpha\tau_d$ (τ_d : desired coverage α : constant)
$duty = \frac{\alpha}{a}\tau_d v - \frac{b}{a}$

Fig. 2.

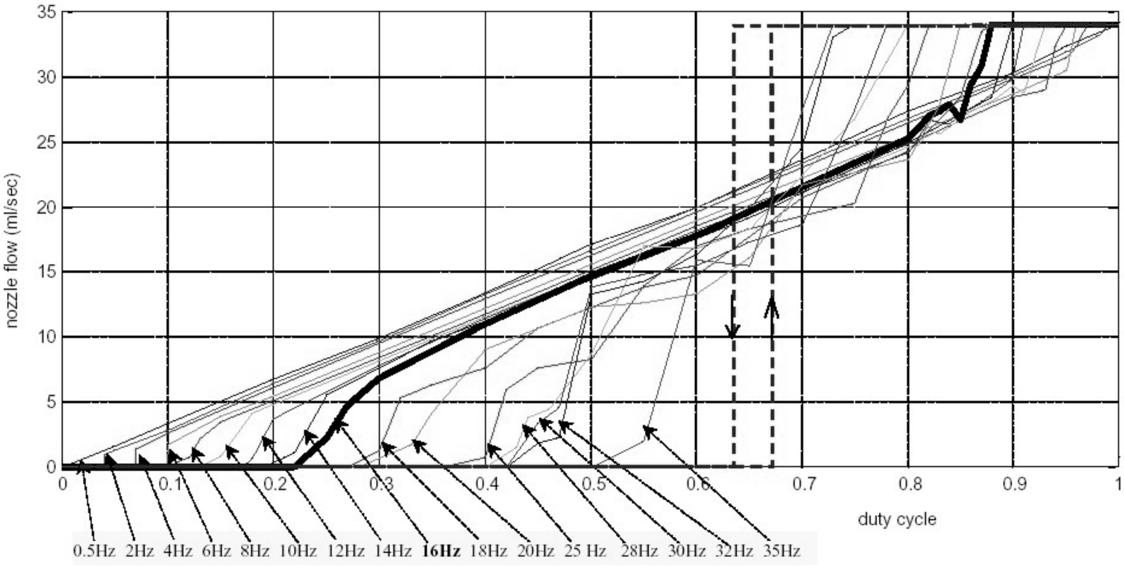
nozzle flow (ml/sec)
duty cycle
0.5Hz 2Hz 4Hz 6Hz 8Hz 10Hz 12Hz 14Hz 16Hz 18Hz 20Hz 25 Hz 28Hz 30Hz 32Hz 35Hz

Fig. 3.

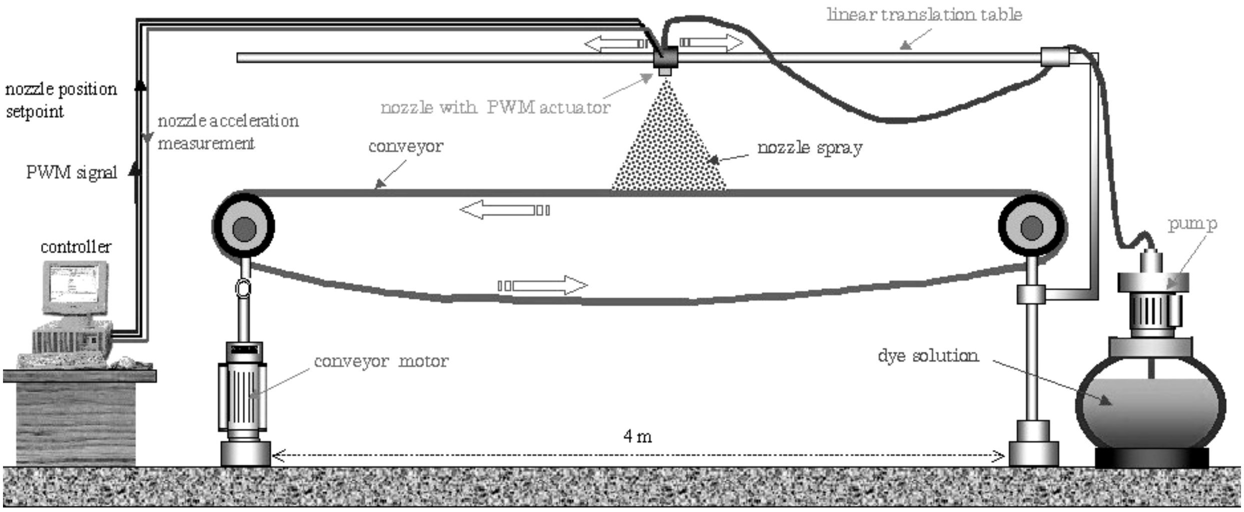
linear translation table
nozzle position setpoint
nozzle acceleration measurement
PWM signal
nozzle with PWM actuator
nozzle spray
conveyor
controller
pump
conveyor motor
dye solution
4 m

Fig. 4.

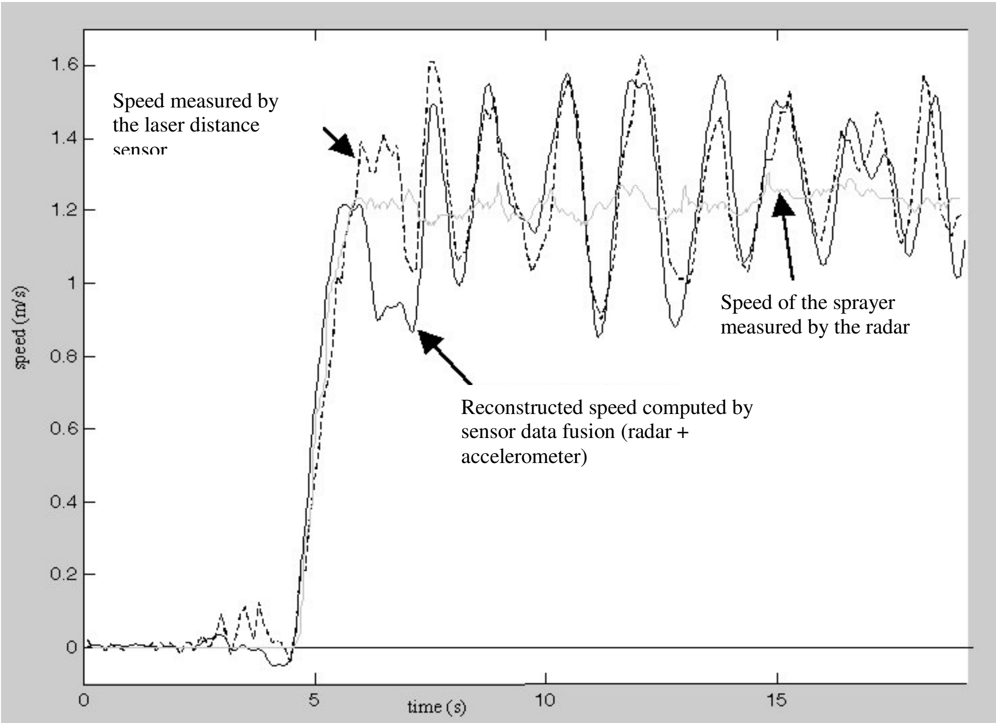
Speed measured by the laser distance sensor
Speed of the sprayer measured by the radar
Reconstructed speed computed by sensor data fusion (radar + accelerometer)
speed (m/s)
time (s)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15

Fig. 5.

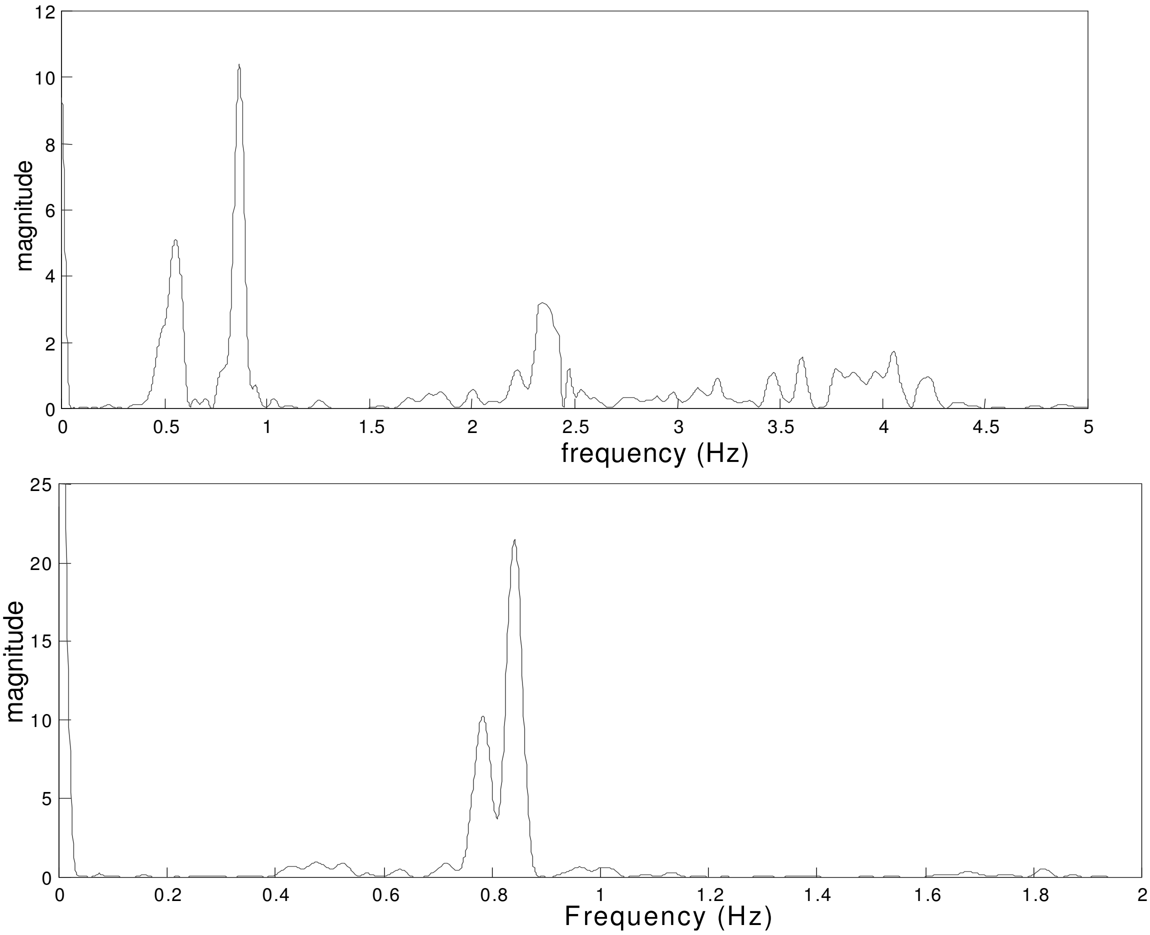
magnitude
frequency (Hz)
magnitude
Frequency (Hz)

Fig. 6.

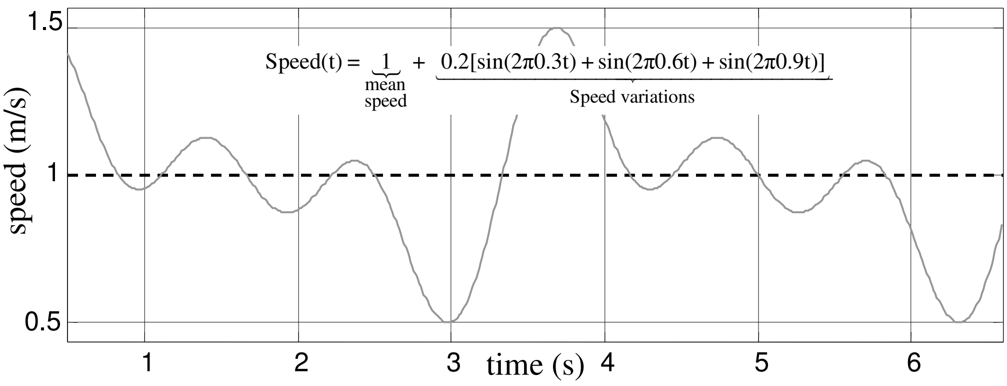
Speed(t) = 1 + 0.2[sin(2π0.3t) + sin(2π0.6t) + sin(2π0.9t)]
mean speed
Speed variations
speed (m/s)
1.5
1
0.5
1
2
3
4
5
6
time (s)

Fig. 7.

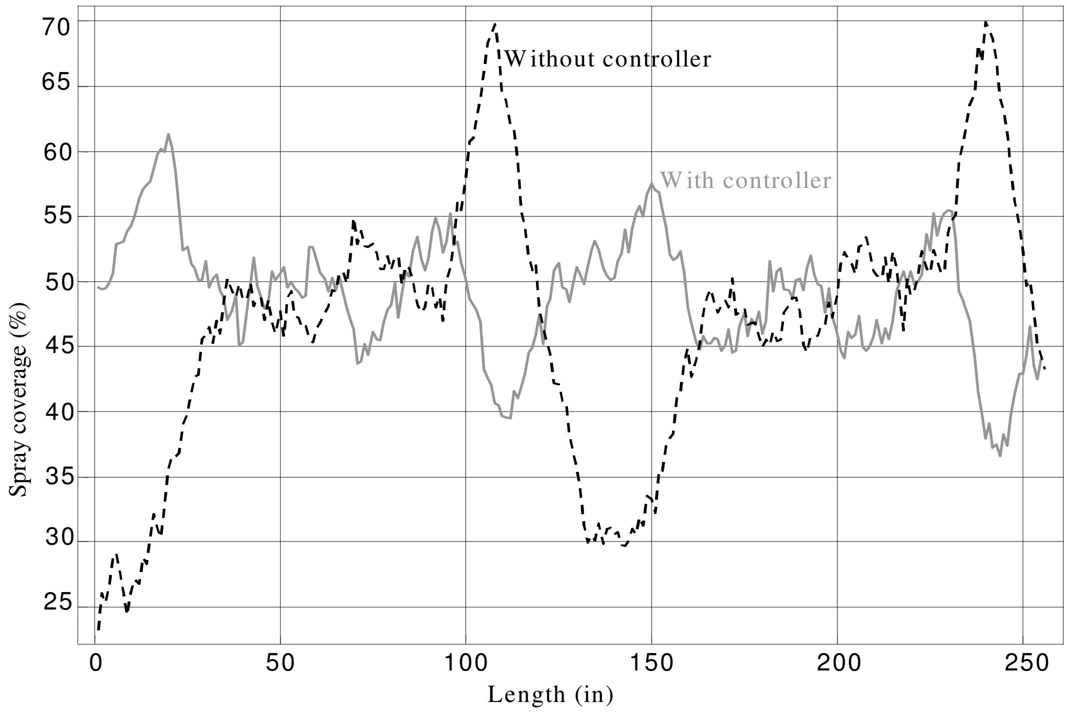
Without controller
With controller
Spray coverage (%)
Length (in)
70
65
60
55
50
45
40
35
30
25
0
50
100
150
200
250

Fig. 8.

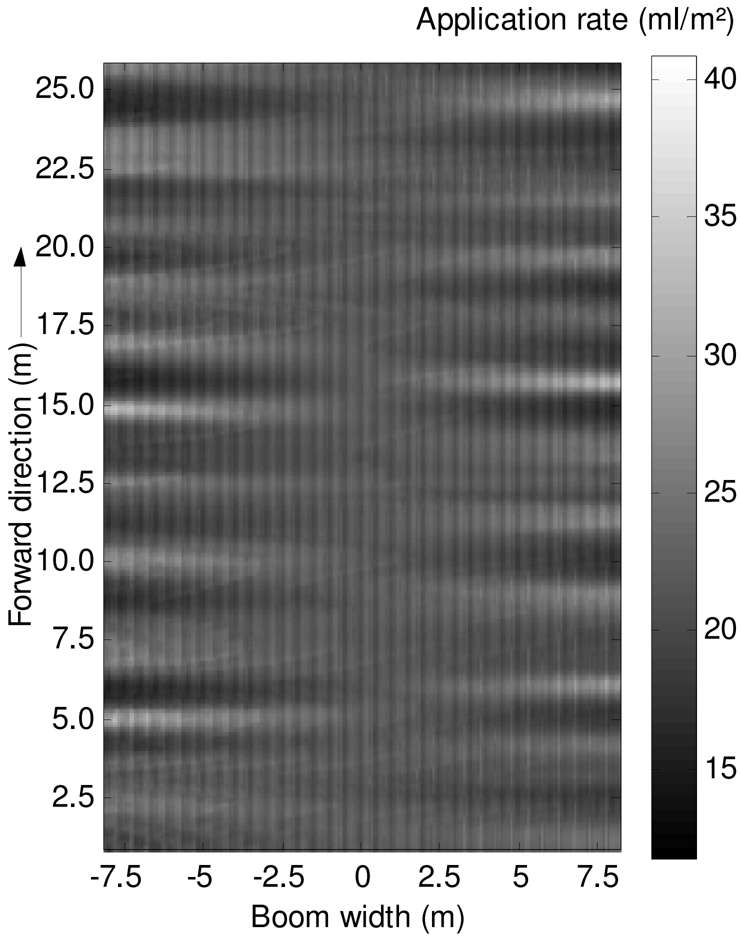
Application rate (ml/m²)
Forward direction (m)
Boom width (m)
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
-7.5
-5
-2.5
0
2.5
5
7.5
40
35
30
25
20
15

Fig. 9.

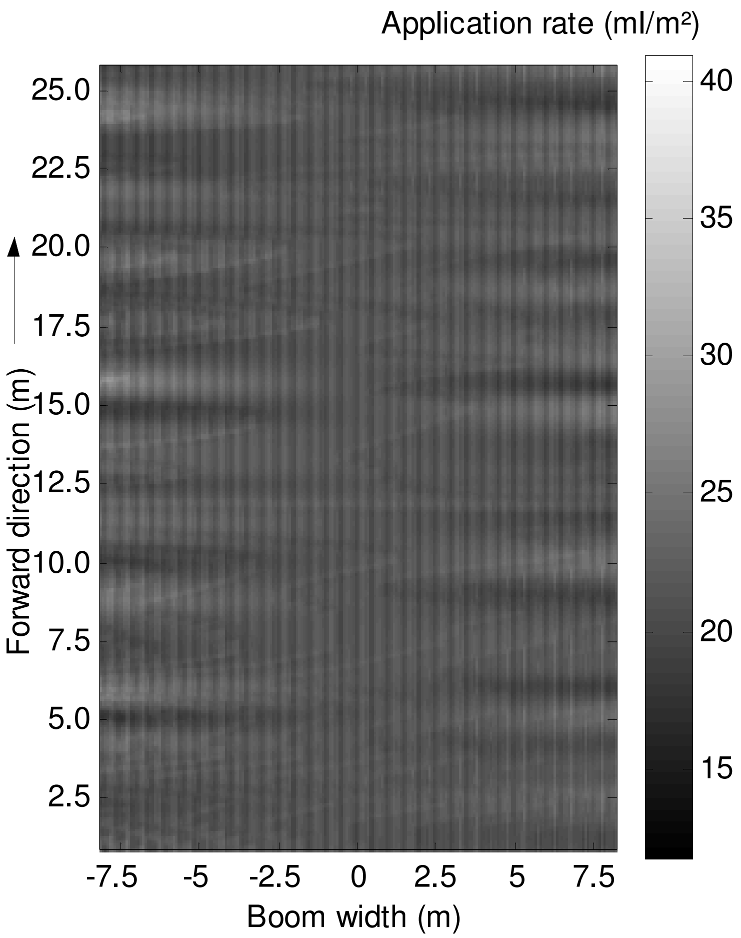
Application rate (ml/m²)
40
35
30
25
20
15
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
Forward direction (m)
-7.5
-5
-2.5
0
2.5
5
7.5
Boom width (m)

Fig. 10.