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Design of a Nozzle-Height Control System Using a Permanent Magnet Tubular Linear Synchronous Motor

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ABSTRACT

In agricultural spraying, keeping the spray at the correct height reduces pesticide drift and provides uniformly distributed pesticide accumulation on the target plant. In this study, an agricultural nozzle-height control test system was developed using a permanent magnet tubular linear synchronous motor (PMTLSM) that can adjust the height between the spraying nozzle and the plant. The developed system was experimentally tested in the laboratory environment and under field conditions. According to the experimental results, the nozzle height coefficient of variation (CV) value decreased from 16.77% to 5.17%, while the uniformity of distribution in the forward direction increased from 56.57% to 86.11% at 12 km h^{-1} under field conditions. Under test conditions it was found that the developed system keeps the distance between differently sized plants and the nozzle at the set point with minimum error.

Keywords: Agricultural spraying; Nozzle height control; Permanent magnet tubular linear synchronous motor

1. Introduction

The rapid increase in the world population, high-quality food demand and the expectation of maximum yield from accessible agricultural land leads to more intensive farming practices (Matthews 2008). Agricultural diseases and pests reduce product yield, grain size, storage time and quality, and also causes rapid spread of disease (Bisesi & Koren 2003). For this reason, the use of pesticides for high yield and high-quality food is an inevitable tool (De Schampheleire et al 2007; Matthews 2008). Although pesticides have important benefits for the development of agriculture, they also have many negative effects on people, animals and the environment (Belforte et al 2011). During the pesticide application, the required dose throughout the entire area must be properly applied to the target. Incomplete application causes negative effects such as weeds and harmful insects to be sustained by decreasing pesticide efficiency. On the other hand, excessive application leads to contamination of the soil and surface waters, and excessive pesticide residues. Since pesticides contain intense active ingredients, excessive pesticide residues on plants causes crop damage (Ozkan & Reichhard 1993; Marck & Luycx 1993). The quality of spraying is determined by characteristics such as mean diameters, uniformity of distribution, drop frequency and the coating ratio of the droplets collecting on the target surfaces. It is desirable that the amount of pesticide drift to the off-target area must be as low as possible, as the accumulation rate and coating rate is high for each treatment (Ozkan 1995; Gil & Badiola 2007).

For high quality spraying, it is necessary to keep the spraying height constantly at an appropriate value. Spraying at too high a level results in spray drift, while a low-level setting causes untreated slivers and excessively sprayed strips in areas underneath the nozzle. The total effect appears to be very poor accumulation and deterioration in uniform distribution (Yoshida & Maybank 1971). For this reason, it is of utmost importance that the treatment height is kept at a reasonable value to provide treatment in one go, to reduce pesticide drift, to obtain a more uniform pesticide distribution, to avoid disruption of the spray pattern and to provide adequate coverage (Wang et al 1993; Womac et al 2001; Wen & Kidd 2005; Qasem 2011).

In published literature, the distance between the nozzles and also the nozzle angle is taken into account. For wide-angle nozzles, a lower spray height is preferred. For example, for a nozzle spacing of 50 cm, a spray height of 50 cm is recommended at a 110° nozzle angle (Langenakens et al 1999; Wilson et al 2008). However, when the spray is being applied, the spray height is constantly changing due to fluctuations in the land structure, to hills, tyres and vertical vibrations. Thus, the quality of the spraying is adversely affected (Langenakens et al 1995; Ramon et al 1997; Langenakens et al 1999). Based on a study conducted by Langenakens et al (1995), the spray deposit can vary between 0% and 1000% for vertical boom vibrations. When passive and active suspension systems are used, the level of spraying quality is increased by reducing the vertical vibrations and height errors (Ramon et al 1997). Passive suspension systems are based on balance, central rotation and damping suspension systems and do not require any power source (Frost 1984; Klein & Kruger 2011). On the other hand, active suspension systems use sensors and actuators to balance the boom arm. If a height deviation is detected by the sensor, the actuator adjusts the set point by moving the boom in a downward or upward direction (O' Sullivan 1986; Klein & Kruger 2011).

Many theoretical and experimental studies have been carried out on passive and active suspension system applications (Musillami et al 1982; Frost 1984; O'Sullivan 1986; Frost & O'Sullivan 1986; Marchant & Frost 1989; Kennes et al 1999; Deprez et al 2002; Deprez et al 2003; Anthonis et al 2005; Sun & Miao 2011; Koc & Keskin 2011; Pontelli & Mucheroni 2012). These systems control the vertical height of all or parts of the boom arms carrying the spray nozzles, and they keep the boom parallel to the ground. In these studies, hydraulic cylinders were also used as actuators.

This study differs from previous studies because it uses a PMTLSM to control the vertical motion of the nozzle, and for the independent adjustment of the height of a single spray nozzle and ability to track differently sized plants on a row.

2. Material and Methods

The test bench used to perform laboratory tests is presented in Figure 1. The variable speed conveyor belt with different sizes of artificial plants is 410 cm long and 60 cm wide. The conveyor belt speed is measured by a wheel-type incremental encoder (Autonics ENC-1-1-V-5, South Korea). The data acquisition card (National Instrument NI DAQ 6211, USA) and the graphical programming language (National Instrument LabVIEW 2013, USA) were used to read the distance information from the sensor and to calculate the analog voltage information commands to be sent to the analogue inputs of the motor servo drive. Vertical movement of the nozzle is provided by the high-performance PMTLSM (LinMot P01-23x160H-HP-R20, Switzerland) and is given in Figure 2. In the PMTLSM, high-speed linear motion is produced by direct electromagnetic force, there are no mechanical parts such as a mechanical gear and a belt-pulley system. In addition, there is no need for an oil tank, pump, filter or liquid transmission pipes. In addition, the motor's tubular configuration provides benefits such as easy installation, accuracy, high repeatability, high thrust density, low weight / force ratio and quiet operation from the direct drive linear motion system (LinMot 2016).

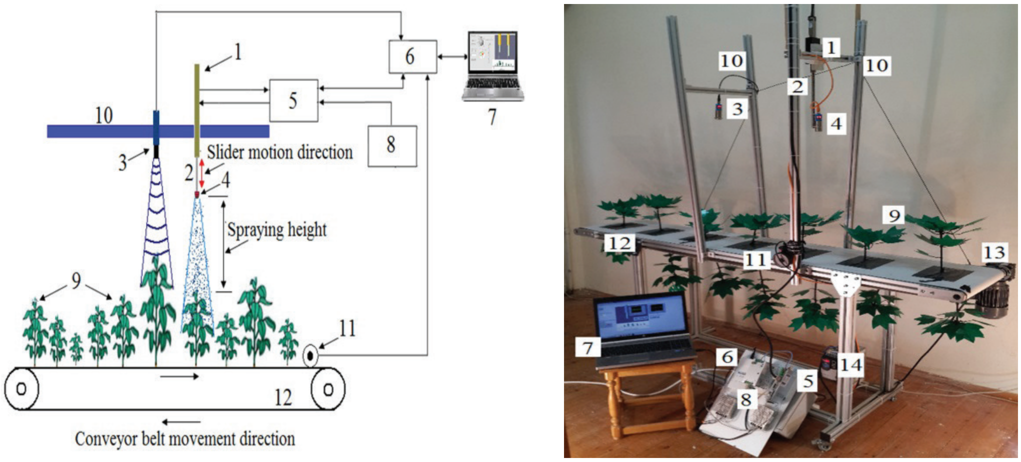


Figure 1- The laboratory test setup (schematic diagram in left, picture in right): 1, PMTLSM; 2, Slider; 3, 1st ultrasonic sensor; 4, 2nd ultrasonic sensor; 5, servo driver; 6, DAQ board; 7, laptop; 8, power supply; 9, artificial plants; 10, bridge; 11, wheel type encoder; 12, conveyor belt; 13, induction motor with reduction gear; 14, frequency converter

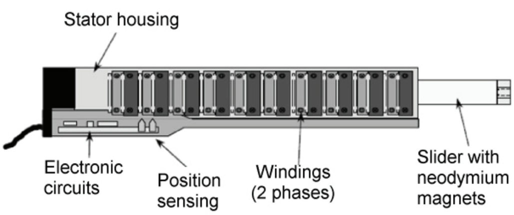


Figure 2- Assembly of PMTLSM

The servo drive (Linmot B1100 GP-HC, Switzerland) has a built-in, internal, proportional integral derivative (PID) controller that controls the linear travel position of the PMTLSM slider. The linear motor-defining parameters, PID controller gains, slider acceleration and maximum velocity information are entered manually into the driver via the servo drive software (LinMot Talk software version 6.0). The servo driver has maximum velocity and limited acceleration interpolation. In this interpolation process, the traditional PID controller output is damped to provide trapezoidal trajectory tracking according to the set acceleration and maximum velocity values (Figure 3). Thus, the slider travels from the current position to the target position at the maximum velocity with limited acceleration thereby avoiding unwanted position deviations. When the acceleration increases, the isosceles trapezoidal angles also increase, as seen in Figure 4. Thus, a motion profile is produced that will enable the target to be reached in a shorter time.

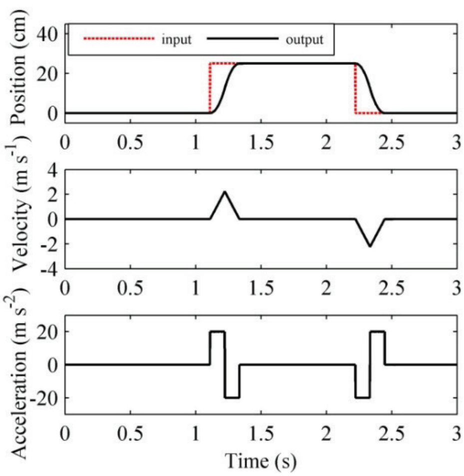


Figure 3- PMTLSM trapezoidal motion profile (for 25 cm position, 2.3 m s^{-1} velocity, 20 m s^{-2} acceleration)

The first of the two ultrasonic distance sensors (Sick UM30 213113, Germany) in the system measures the profile of the plant while the second ultrasonic distance sensor measures the distance between the plant and the slider following the height control process. Tests were performed to determine the calibration characteristics of the ultrasonic sensor with an analog output voltage from 0 to 10 V, a detection range from 20 to 130 cm. The calibration characteristics obtained from distances measured using a fixed object is shown in Figure 5. The mathematical equation obtained by using the calibration characteristic of the ultrasonic distance sensor is given in Equation 1.

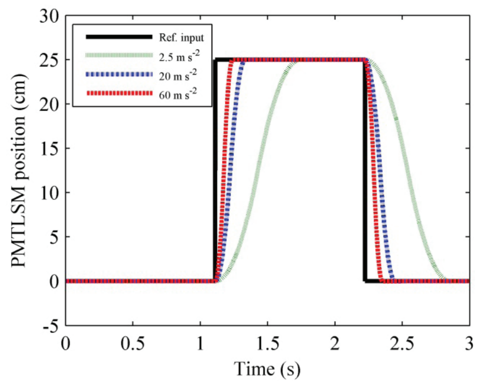


Figure 4- Trapezoidal motion profile for different acceleration values (Reference input, 0.45 Hz square wave signal)

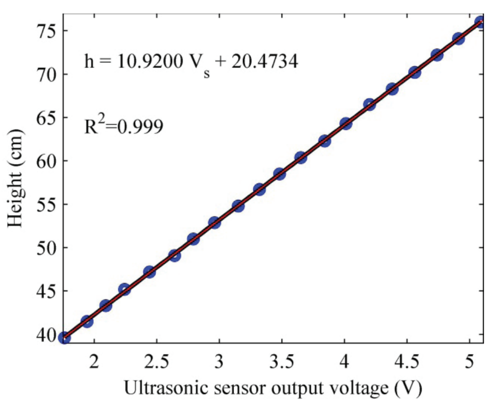


Figure 5- Calibration characteristic of the ultrasonic distance sensor

$$h = 10.9200V_s + 20.4734 \tag{1}$$

Where; V_s is the voltage (in volts) read from the sensor, and h is the height (in cm). This equation is used to calculate the distance between the sensor and the object according to the voltage measured from the sensor output. For synthesis of the drive signal a test was performed using a measured height. The characteristic figure obtained according to the test result is given in Figure 6. Using this characteristic, Equation 2 was obtained.

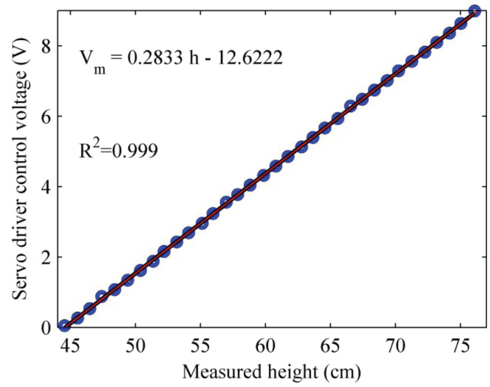


Figure 6- Servo driver analog control signal characteristic according to height

$$V_m = 0.2833h + 12.6222 \tag{2}$$

Where; h is the height (in cm) and V_m is the control signal (in volts). This equation provides a calculation of the analog control signal to be applied to the servo drive inputs to achieve the slider's 50 cm reference height using the distance information obtained from the sensor. Since the servo drive inputs are suitable for a 0 to 10 V analogue voltage, the control signal is limited between these values. In the PID position controller, the proportional gain, integral gain and derivative gain parameters significantly affect the performance of the control. These parameters are set 2.5 A mm^{-1}, 0 A mm^{-1} s^{-1} and 7.5 A s m^{-1} respectively. Since there is an oscillation risk in the slider position at steady-state conditions, integral gain is set to the zero as recommended by the PMTLSM manufacturer.

In the laboratory experiments, the conveyor belt was operated at speeds of 1, 2, 3, 4 km h^{-1}. At every speed, the PMTLSM acceleration was set manually via the servo drive software to be 2.5, 5, 10, 20, 40, 60 m s^{-2}, respectively.

The coefficient of variation (CV) and linear motor RMS current values (the root mean square values of motor current values calculated for each test) were used to test the performance of the system. CV is taken as the deviation from the average height. The RMS current is an important criterion in determining the amount of energy consumed and the amount of warm-up time for the electric motors. The linear motor RMS current values were calculated using the data received from the servo drive.

Analysis of variance (ANOVA) was used to investigate: 1. Whether there is a difference between the CV averages, and 2. Whether there is a difference between the PMTLSM RMS current averages. When a significant difference occurred, the LSD multiple comparison test was used to identify which subgroups caused the differences.

After laboratory experiments, field experiments were carried out on land where real plants were found in different sizes. For the field test, the system developed in the laboratory was adapted to a tractor (Figure 7). In the field tests the driving speed was set at 4, 8 and 12 km h^{-1} detected by a GPS device (Aselsan ASN3040, Turkey), because Langenakens et al (1995), indicated that the tractor speed changes between 3 and 12 km h^{-1} in spraying applications. The PMTLSM acceleration is set to 20 m s^{-2}, which was found to be the best value in laboratory tests. The 2nd ultrasonic sensor on the test setup was replaced with a conical type nozzle for spray tests on the field. A conventional type of hand pump knapsack sprayer (Basar Memeto, Turkey) was used as the sprayer at 4.9 bar of service pressure. Data for the wind speed, air temperature and average humidity during field experiments were recorded at 5.9 m s^{-1}, 23 °C and 41%. Water-sensitive paper (WSP) cards (26×76 mm, Syngenta, Switzerland) are used to visualize, measure and map out the spray distribution and for analysis of the spray coverage area. Spray droplets leave a blue stain on the yellow surface of the WSP (Salyani et al 2013). In this study, spray distribution was charecterized by measuring spray coverage on the WSP. Evans et al (1994), found a strong correlation between the spray coverage obtained from image analysis and the mass deposits obtained by chemical analysis provided that the spray coverage is fairly uniform. Six WSP cards were located at approximately 30 to 65 cm directly under the nozzle and water was used as the spray liquid. In accordance with previous studies (Salyani et al 2013) only a sample area of 2×2 cm was used at the center of the WSP cards for image analysis. WSP cards were analyzed using the Matlab image processing toolbox. The percentage of wetted area or spray coverage was calculated for the samples after the spray application. WSP card images were converted to binary values by converting the image to gray scale and then a threshold was applied to assign a value of 0 or 1 to pixels based on their intensity. Spray coverage area was calculated as the ratio of the number of pixels exposed to water, divided by the total number of pixels (Sama et al 2016).

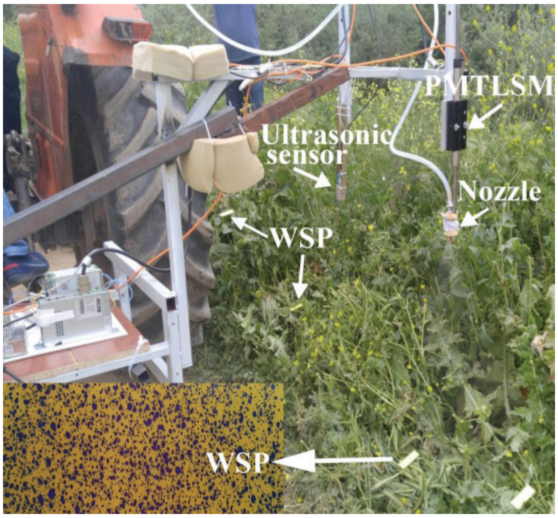


Figure 7- The field test setup

3. Results and Discussion

3.1. Laboratory tests results

The CV value was calculated using the data in Figure 8 at 10.79% for the average height of 50 cm when control was not applied to the system. Some graphs related to the data obtained from the experiments are given in Figures 9 to 11. It can be seen from the figures that the system tries to keep the nozzle at about the 50 cm set height for different accelerations and conveyor speed values. The tests were performed for three repetetions at 4 different conveyor belt speeds and 6 different PMTLSM accelerations. The results of the variance analysis for the data obtained in all experiments are shown in Table 1. This table indicates that the change in PMTLSM acceleration and conveyor speed, and the interaction between them, had a statistically significant effect ($P<0.05$) on the CV and PMTLSM RMS current. The statistical importance of interaction is that it indicates how the effect of increasing acceleration differs according to the changing conveyor speed values. According to the LSD test shown in Table 2, the CV value decreased when acceleration was increased. This decrease was not statistically significant ($P>0.05$) between 20 m s^{-2} and 60 m s^{-2}. Variations of the CV values according to accelerations and conveyor belt speeds are shown in Figure 12. It is seen from the figures that the rate of decrease of CV varies according to the speed. The effect of acceleration is more visible at higher conveyor speeds. When the acceleration is increased from 20 m s^{-2} to 60 m s^{-2}, the CV values decrease only for 4 km h^{-1} of speed, while others are changed little. It can be said that the increase in the amount of vibration generated in the motor causes a reduction in the acceleration effect after 20 m s^{-2}. According to the conveyor belt speed, if the speed was further increased in value by over 2 km h^{-1}, the increase in the CV value became statistically significant ($P<0.05$). It can be said that this is caused by the ultrasonic sensor which is negatively affected by the increasing conveyor speeds (Iida & Bursk 2002; Zaman et al 2007; Koc & Keskin 2011). The effect of PMTLSM acceleration and conveyor speeds on the PMTLSM RMS currents are presented in Table 1, Table 2 and Figure 13. The results of Table 1 indicate that the change of PMTLSM acceleration and conveyor speed, and the interaction between them, affect the PMTLSM RMS current ($P<0.05$). From the results of Table 2 it was found that the effect of conveyor speed was found to be statistically significant ($P<0.05$) for acceleration values greater than 10 m s^{-2}. The PMTLSM RMS current increases as the acceleration increases. The increase in the RMS current was found to be significant ($P<0.05$) when the acceleration was increased from 5 m s^{-2} to 60 m s^{-2}. This is due to the fact that PMTLSM tries to respond very quickly to the measured height, which changes very rapidly. RMS current increases when the conveyor speed increases, When the speed increases from 2 km h^{-1} to 3 km h^{-1}, the increase in the RMS current is not statistically significant ($P>0.05$). A current value of 2.48 in Figure 13 represents the maximum allowed RMS current for the PMTLSM. It can be seen from the figure that the PMTLSM RMS current increases at the 40 m s^{-2} and 60 m s^{-2} acceleration values as the belt speed increases, but there is no increase for smaller acceleration values. The maximum allowed instantaneous current value of the motor used in this study is 11 A, but the maximum continuous current is 2.48 A. Because the warming of the motor windings (caused by losses in the copper) is proportional to the square of the current (Wang et al 2012), the increase in the RMS current after the limit value causes the motor windings to overheat and damage the winding insulation and demagnetize the permanent magnets in the slider. For this reason, the RMS current has a limiting factor as the motor acceleration value increases. This means that the acceleration value must be kept less than 60 m s^{-2} in the system. According to statistical analysis results obtained, the PMTLSM acceleration and conveyor belt speed were found to be important variables affecting the CV and the RMS current values.

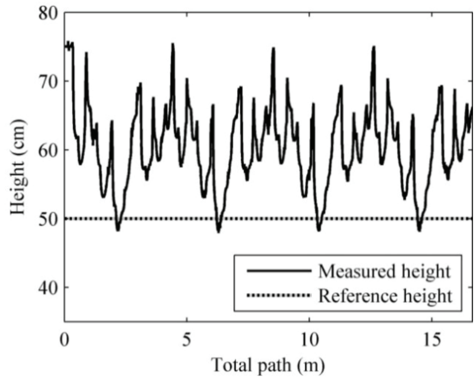


Figure 8- The measured height between by 2nd ultrasonic sensor and artificial plants along the total path (artificial plant profile)

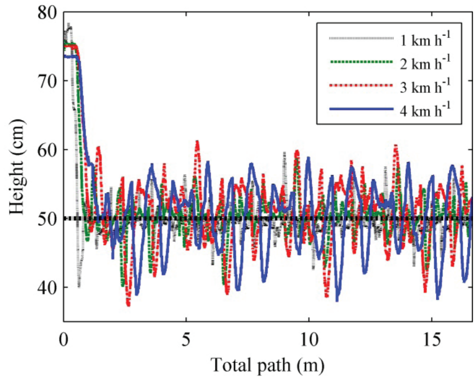


Figure 9- The height measured by 2nd ultrasonic sensor at all speeds for acceleration of 2.5 m s-2

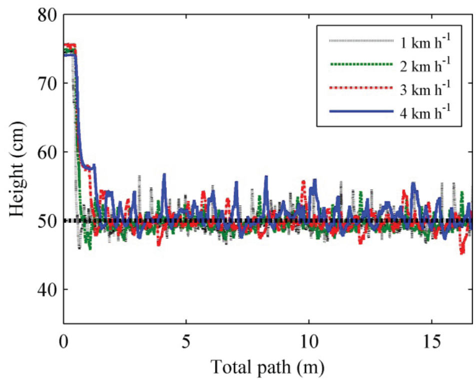


Figure 10- The height measured by 2nd ultrasonic sensor at all speeds for acceleration of 20 m s-2

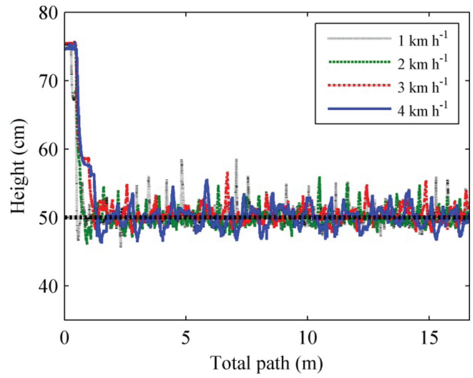


Figure 11- The height measured by 2nd ultrasonic sensor at all speeds for acceleration of 60 m s-2

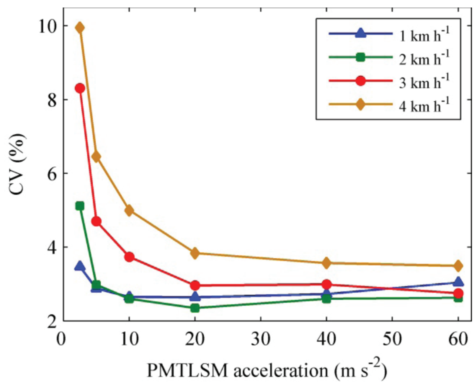


Figure 12- The relationship between PMTLSM acceleration and CV for different conveyor speed

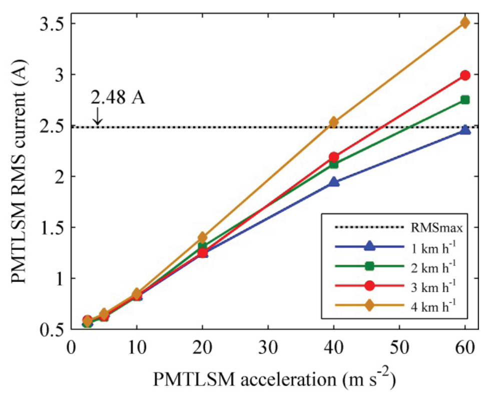


Figure 13- The relationship between PMTLSM acceleration and PMTLSM RMS current for different conveyor speed

Table 1- The results of variance analysis of the mean values of the CV and PMTLSM RMS current

Source of variation	*CV*			*PMTLSM RMS current*	
	Degree of freedom	*Sum of squares*	*F ratio*	*Sum of squares*	*F ratio*
Acceleration (A)	5	0.983	95.96*	54.64	1691.60*
Speed (S)	3	0.687	111.72*	0.91	47.08*
A×S	15	0.247	8.04*	1.49	15.36*
Error	48	0.098		0.31	
Total	71	2.015		57.35	

*, significant at $P<0.05$

Table 2- Mean values and significance groups of CV and PMTLSM RMS current

Acceleration	*CV (%)*					*PMTLSM RMS current (A)*				
	1 km h⁻¹	*2 km h⁻¹*	*3 km h⁻¹*	*4 km h⁻¹*	Mean	*1 km h⁻¹*	*2 km h⁻¹*	*3 km h⁻¹*	*4 km h⁻¹*	Mean
2.5 m s^{-2}	0.54^{efg}	0.71^{d}	0.92^{b}	1.00^{a}	0.79^{A}	0.57^{j}	0.56^{j}	0.59^{j}	0.58^{j}	0.58^{E}
5.0 m s^{-2}	0.46^{h}	0.47^{gh}	0.67^{d}	0.81^{c}	0.60^{B}	0.65^{j}	0.62^{j}	0.63^{j}	0.65^{j}	0.64^{E}
10 m s^{-2}	0.42^{hi}	0.41^{hi}	0.57^{e}	0.70^{d}	0.52^{C}	0.82^{i}	0.82^{i}	0.83^{i}	0.85^{i}	0.83^{D}
20 m s^{-2}	0.42^{hi}	0.37^{i}	0.47^{gh}	0.58^{e}	0.46^{D}	1.24^{h}	1.31^{gh}	1.25^{h}	1.40^{g}	1.30^{C}
40 m s^{-2}	0.44^{hi}	0.41^{hi}	0.47^{gh}	0.55^{ef}	0.47^{D}	1.94^{f}	2.12^{e}	2.19^{e}	2.53^{d}	2.20^{B}
60 m s^{-2}	0.48^{fgh}	0.42^{hi}	0.44^{hi}	0.54^{efg}	0.47^{D}	2.45^{d}	2.75^{c}	2.99^{b}	3.51^{a}	2.92^{A}
Mean	0.46^{C}	0.47^{C}	0.59^{B}	0.70^{A}		1.28^{C}	1.36^{B}	1.41^{B}	1.59^{A}	
$LSD_{0.05}$	A: 0.037 S: 0.030 AxS: 0.074					A: 0.066 S: 0.054 AxS: 0.132				

A, PMTLSM acceleration; *S*, Conveyor belt speed; uppercase letters represent groups of A and S means, lowercase letters represent groups of A×S interaction means; ($P<0.05$)

The average height values for each trial in laboratory experiments were found to be between a minimum of 49.47 cm and a maximum of 51.05 cm, as shown in Table 3. It can be seen from the table that the nozzle-height control system developed in this study was able to keep the nozzle within a very close mean of the set point of 50 cm in height.

Table 3- The average height values for each trial in laboratory experiments

Acceleration	*Mean height (cm)*			
	1 km h⁻¹	*2 km h⁻¹*	*3 km h⁻¹*	*4 km h⁻¹*
2.5 m s^{-2}	50.54	50.01	50.03	49.99
5.0 m s^{-2}	50.12	50.01	49.64	49.47
10 m s^{-2}	49.51	50.03	50.68	51.05
20 m s^{-2}	50.12	50.09	50.88	50.95
40 m s^{-2}	50.14	49.70	50.64	50.27
60 m s^{-2}	50.05	48.82	50.98	50.22

3.2. Field tests results

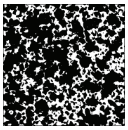
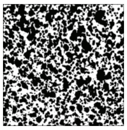
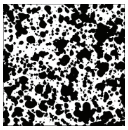
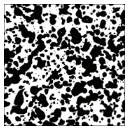
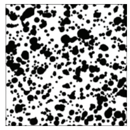
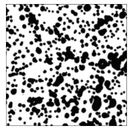
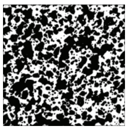
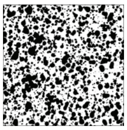
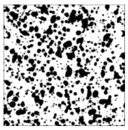
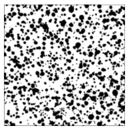
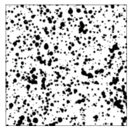
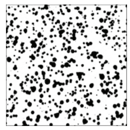
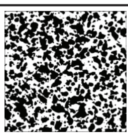
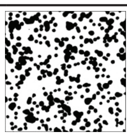
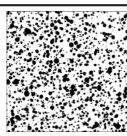
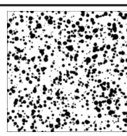
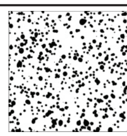
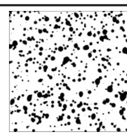
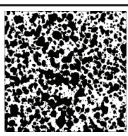
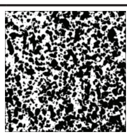
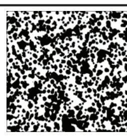
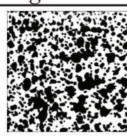
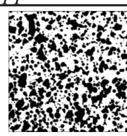
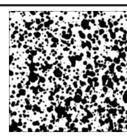
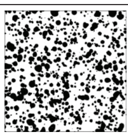
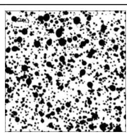
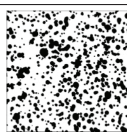
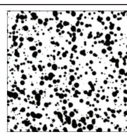
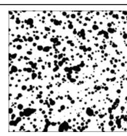
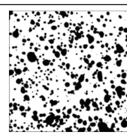
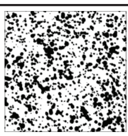
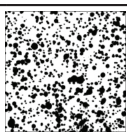
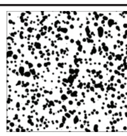
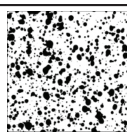
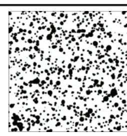
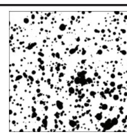
The average height and CV values obtained from experiments are shown in Table 4. CV value of 16.77% were obtained while the nozzle was stationary (without nozzle height control). However, when height control is applied, this CV value decreases to 5.17%, 4.98%, 4.09% respectively for driving speeds of 12, 8 and 4 km h^{-1}. The reason for the increase in CV value with the increase in speed can be explained as follows; The increase in the driving speed reduces the measurement accuracy of the ultrasonic sensor (Iida & Bursk 2002; Zaman et al 2007; Koc & Keskin 2011), causing the test platform vibration to increase (Langenakens et al 1999; Pontelli & Mucheroni 2012). WSP card samples obtained from field trials for three driving speed are shown in Table 5, where the number under each sample represents the percentage of the

Table 4- Mean and CV values of nozzle height for different driving speeds in the field tests

Control situation	*Driving speed ($km\,h^{-1}$)*	*Mean (cm)*	*CV (%)*
With height control	4	49.77	4.09
	8	49.94	4.98
	12	50.70	5.17
Without height control	--	50.33	16.77

wetted area. The mean of wetted area percentage (WA) and Uniformity of Distribution (UD) were calculated over the six samples for each speed (Table 5). The information in Table 5 reveals that the percentage of wetted area or spray coverage is different in the forward direction when the height control is not applied. At the lowest nozzle height of 30 cm, it could be clearly seen that for all speeds,

Table 5- Mean of wetted area and uniformity of distribution for different driving speeds in the field tests

Speed	*Sample number (Nozzle height)*							
$km\,h^{-1}$	*1 (30 cm)*	*2 (40 cm)*	*3 (50 cm)*	*4 (55 cm)*	*5 (60 cm)*	*6 (65 cm)*	*WA (%)*	*UD (%)*
			Nozzle-height control not applied					
4	 70.54	 54.30	 53.37	 50.69	 38.90	 34.79	50.43	74.83
8	 58.51	 40.65	 32.02	 28.89	 22.24	 20.44	33.79	58.21
12	 51.34	 31.85	 26.82	 25.03	 19.46	 16.73	28.5	56.57
			Nozzle-height control applied					
4	 55.84	 55.67	 52.52	 47.67	 43.25	 42.82	49.59	88.06
8	 32.62	 30.59	 27.55	 27.44	 26.51	 26.66	28.56	91.33
12	 30.35	 29.28	 27.67	 25.79	 23.71	 20.62	26.23	86.11

the wetted area percentage was the largest on the sample card for sample number 1, while for the highest nozzle height of 65 cm the wetted area percentage was the least on sample number 6. It is indicated in the study of (Al-Gaadi 2010) that when the distance between the nozzle and the target was small, the highest volume and application rate was found over a narrow area directly under the nozzle. On the other hand, when the height between the target and the nozzle increases, the spray volume and application rate was decreased directly under the nozzle and a larger area was sprayed. Yoshida & Maybank (1971) emphasized that for shorter distances in droplet movement towards the target, larger droplets at higher speeds can hit the target, and droplet bouncing and fragmentation can occur. This situation may negatively affect the distribution uniformity and the accumulation amount on the target. It may be said that when the distance between the nozzle and the target is large, spray-drift-which means that the sprayed droplets goes out of the target area-is a reason for the wetted area percentage to be small. Balsari et al (2017), pointed out that spray-drift increased significantly when the spraying height was increased from 30 cm to 50 cm, and from 50 cm to 70 cm, and the effect of boom height is independent of the nozzle type. Lardoux et al (2007), indicated that the dose obtained in L ha^{-1} decreases when the height increases. Losses depend on evaporation, drifting and dispersal of droplets. It is shown from Table 5 that, when speed increased, the WA value decreased for all trials. The biggest WA value was obtained at 4 km h^{-1} and the smallest was obtained at 12 km h^{-1}. Wolf et al (1997), reported that increased speed decreased the spray deposit under the nozzle center. Ooms et al (2003), found that there is a strong correlation between horizontal motion and longitudinal spray coverage in the laboratory and under field conditions, and they indicated that spray coverage is inversely proportional to the horizontal speed. They also stated that the speed increase tends to increase the risk of spray-drift. Results from field measurements reported by Miller & Smith (1997), indicated that spray-drift increased aproximately 51% when speed was increased from 4 to 8 km h^{-1}. Langenakens et al (1995), emphasized that at a speed greater than 4 km h^{-1} the amount of the chemical has to be increased to achieve the desired effect. As it can be seen from Table 5, when the proposed nozzle-height control was applied, the Uniformity of Distribution (UD) values were increased in the forward direction according to the fixed nozzle-height condition from 74.83% to 88.06% for 4 km h^{-1} speed, from 58.21% to 91.33% for 8 km h^{-1} and from 56.57% to 86.11% for 12 km h^{-1}. From this, it can be concluded that as the nozzle height control is applied, system produces better spray distribution in the forward direction.

4. Conclusions

In this study, a spray nozzle-height control system developed using a PMTLSM was tested in the laboratory environment and under field conditions. According to the results obtained, it can be said that the developed height control system is affected by the PMTLSM acceleration and speed. For this system, the optimal acceleration value was found to be 20 m s^{-2}, according to the data obtained from laboratory experiments. Both the laboratory tests and field tests showed that the CV value was reduced when the nozzle height control was applied. In the field tests when the height control is applied, the uniformity of distribution increased significantly in the forward direction. According to the results, if this system is mounted on a conventional pesticide sprayer, excessive and incomplete spraying of the pesticides will be reduced when applied in the field.

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