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Application Accuracy of a Machine Vision-controlled Robotic Micro-dosing System

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Experiments with a new concept for the precise application of herbicides in a seed line have been conducted. The concept combines plant recognition, micro-dosing and autonomous robotics. A machine vision system recognises objects to be sprayed, and a micro-dosing system targets very small doses of liquid at the detected objects, while the autonomous vehicle takes care of the navigation. The experiments were carried out under controlled indoor conditions. The results show that the spray liquid can be applied at subcentimetre accuracy and that the application rate can be reduced by two orders of magnitude compared to recommendations used for conventional broadcast spraying.

1. Introduction

The most commonly used pesticide application method is the conventional boom sprayer mounted with nozzles at 50 cm spacing across the boom. This technology has been optimised over the years to achieve better spray distribution on the soil surface and optimisation of the droplet size in terms of high biological efficacy and minimum spray drift. After the introduction of precision farming in the beginning of the 1990s, the sprayer was equipped with computerised variable dose technology. This technology is able to control the applied amount of spray according to the site-specific demand in the field based on manually generated spray maps.

The use of alternative technologies enables herbicide to be applied very precisely and accurately on single plants and for specific formulations to be used for the individual weed species. This reduces the pesticide consumption and decreases local as well as global contamination of the environment. This requires a weed recognition system as well as a high-resolution micro-dosing system at the centimetre or subcentimetre scale. Installing this technology on an autonomous vehicle is also labour efficient. Nielsen et al. (2002) described work on the development of a real time kinematic-global positioning system (RTK-GPS)-guided vehicle. One of the potential uses of this autonomous vehicle was reported to be the mapping of the spatial distribution and density of weeds combined with herbicide application with variable rate technology. Southall et al. (2002) and Hague et al. (2002) reported on an autonomous robot that applies machine vision for navigation and discrimination between crops and weeds. The system is designed to operate in transplanted horticultural crops (cauliflower) that are planted in a regular grid pattern.

Optical sensors can be used for recognition of plants and discrimination between plant species by utilising image analysis methods and/or multi-spectra information (Soille, 2000; Perez et al., 2000; Søgaard, 2005; Gerhards et al., 1993; Manh et al., 2001; Southall et al., 2002). These types of sensors and processing methods have been developed intensively during recent years. The reliability of crop and weed recognition under field conditions varies from 60% to 95% (Lee et al., 1999; Søgaard, 2005).

Lee et al. (1999) developed a precision spraying system called micro-spray, which is designed for intra-row weed control. Herbicide is applied to the weed plants, only, and not to the crop plant and the soil. Hence, rather than spraying entire fields, only intra-row areas are considered. Treatments are likely to be done with a broad-spectrum herbicide (e.g. Glyphosate), which, in combination with the micro-spray system, provides a very powerful tool in weed control in the intra-row and close-to-crop areas. Although some work has been performed to investigate the biological effect of small droplets on weed leaves (Graglia, 2004), there is a need for further investigation on the biological benefits in the micro-spray system. The effect of coverage, dosage and placement on the leaves requires to be examined in order to develop the system further.

The objective of this paper is to investigate the performance under controlled indoor conditions of a machine vision-controlled micro-dosing system that is integrated in an autonomous robot vehicle. The aspects considered are the application accuracy and the application rate.

Søgaard and Lund (2005) investigated a first prototype of a 126-mm-wide micro-spray boom with eight spray sections across the seed line. It was concluded that the system was able to target weed seedlings at subcentimetre accuracy but on the other hand higher accuracy and lower application rates were obtained by increasing the 'ground resolution' of the micro-dosing system. Therefore, this paper presents investigations of the spraying accuracy of a new 100-mm-wide micro-spray boom with 20 individually controlled sections.

2. Materials and methods

2.1. The autonomous robot

The autonomous robot equipped with a machine vision-controlled micro-dosing system (Fig. 1) was tested in a laboratory hall. The robot is an electrically driven vehicle with four individually driven and steered wheels (Nielsen et al., 2002). The distance between the wheel centres was 1 m in both longitudinal and cross-travel directions. Under outdoor conditions, the robot navigated within an accuracy of about 5 cm by means of RTK-GPS, an electronic compass, and encoders in the wheels that measure the motion. Under indoor conditions, the robot relies on dead reckoning based on the compass and the wheel encoders.

2.2. Camera and micro-dosing system

A web camera and a micro-dosing system were mounted on the robot as illustrated in Fig. 1(c). The camera was centred on the robot in the cross-travel direction as well as in the longitudinal direction. The camera pointed vertically downwards from a height of 247 mm above the floor (height of the lens) and covered an area of 196 mm by 147 mm on the floor (in longitudinal × cross-travel directions). The camera was connected by a universal serial bus (USB) to an onboard laptop computer taking care of the image processing. By means of a transmission control protocol/Internet protocol (TCP/IP) link, the laptop computer-transmitted information about recognised objects to the computers that controlled the robot and the micro-dosing system.

The micro-dosing system was placed 154 mm behind the camera at a height of 50 mm above the floor. The system consisted of a micro-boom with a linear array of 20 evenly spaced tubings covering a 100 mm treatment width across the travel direction. The tubings (polytetrafluoroethylene 1·6 mm by 0·5 mm) were 250-mm-long with an inner diameter of 0·50 mm.Each tubing was controlled individually by a 12 V dc solenoid valve (039T2M, BioChem Valve^{TM} INC.) and covered a deposit width of 5 mm.The tubings produced a liquid jet, which optimised the transport and targeting precision.

2.3. Formulation of the spray liquid

The challenge of working with a liquid jet produced by micro-dosing tubing was to reduce the splashing effect when the spray liquid hits the plant surface. A laboratory study on minimising the splashing effect was

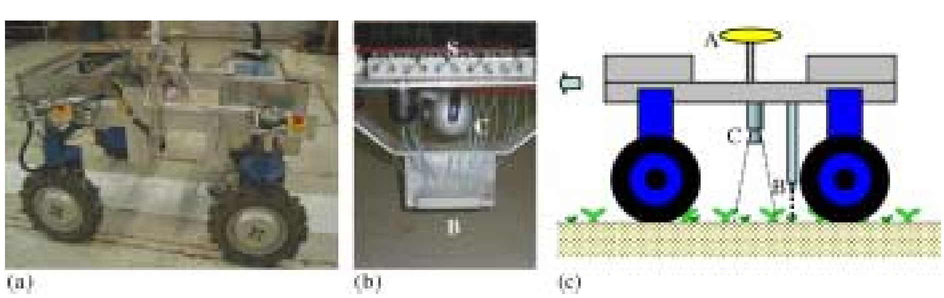

Fig. 1. Autonomous robot with machine vision-controlled micro-dosing system: (a) photo of the vehicle; (b) photo of the micro-spray boom (B) and the web camera (C) from the front; (c) sketch of the vehicle in field; A, global positioning system antenna; B, micro-spray boom; C, web camera; S, solenoid valves

done by Downey et al. (2004). The conclusion from this work was that formulations containing polyethylene oxide polymer proved effective in reducing the splash problem, i.e. 'micro-drift'.

The spray mixture consisted of demineralised water, a polymer and a green spray colourant. The polymer added to the formulation was a polyethylene oxide polymer (Polyox WSR N-60 K, 2 000 000 MW, Union Carbide) at 0·06% v/v. The spray colourant (Clou^R, 158-Dark Green) was added at 0·05% v/v to solutions for spray visualisation on polyvinyl chloride (PVC) sheets. The dispensed volume of spray liquid per 10 ms 'shot' from a single tubing was determined as an average of 500 shots and was found to be approximately 2·5 µl with a liquid pressure of 40 kPa.

2.4. The test course

For the experiments, two dull white PVC sheets of 3·00 m by 0·40 m by 0·004 m each were used as a spraying surface. Placed end-to-end on a horizontal floor, the PVC sheets constituted the test course for the experiments (Fig. 2). The objects to be recognised on the sheets were black circles. The circles were placed randomly at different densities from 50 to 400 circles per m^2 (Fig. 2). The area of each circle was 110 mm^2, corresponding to the mean size of weed seedlings with up to two true leaves. The reason for deciding to work with regular objects (circles) instead of realistic plant shapes was that this choice would make the experimental work easier, and at the same time it would lead to results that could be transferred to real plants as far as spraying precision is concerned.

2.5. Image processing

Figure 3(a) shows a graphical illustration of an image taken by the robot when passing over the PVC sheet with circles on it. The image processing identified the black circles by looking for circular objects with the expected size. First, the black areas in the image were segmented by thresholding of the grey-level intensities. Subsequently, each connected black region was identified and characterised by its area and its eccentricity. The area was measured as the filled area, i.e. the area of the black region including potential white holes in the region. Thus the area of a circle would be the area of the black ring plus the area of the white interior of the circle. Black regions with filled areas between 84 and 159 mm^2 were accepted as potential circle candidates. The expected area of the filled circles was 110 mm^2.

To decide if a black region was circular (or rather had similar second-moments as a circle) its eccentricity was determined as

$$e = \sqrt{1 - \left(\frac{b}{a}\right)^2} \tag{1}$$

where: e is the eccentricity ($0 \leqslant e < 1$); a is the length of the major axis and b is the length of the minor axes of the ellipse that has the same second-moments as the black region. For circular regions the eccentricity will be low (0 for a perfect circle). In image processing algorithm regions with eccentricities between 0 and 0·6 were accepted as circular (i.e. the ratio of the minor axis to the major axis is between 0·8 and 1).

When the circles were identified, the image was overlayed with a grid of 20 by 20 square cells covering 100 mm by 100 mm [Fig. 3(b)]. Depending on the locations of the circles, the cells in this grid were then marked for spraying to produce a 'spray map'. The criterion for spraying a cell was that at least 50% (12·5 mm^2) of the cell should be covered by circle objects. Each of the 20 horizontal cell rows in Fig. 3(b) had a width of 5 mm and corresponded to one of the 20 micro-dosing tubings.

The images were taken with a certain mutual overlap in the longitudinal direction in such a way that the spray maps would be placed adjacent to each other. The reason why the system operated with overlap between successive images was that it was designed to form the basis for robotic weed control between the crop plants in the seed line. In order to identify the crop plants, each of them must be fully covered by at least one image, and this will be ensured by image overlapping.

Figure 3(c) illustrates the spray map obtained when using the micro-dosing system presented by Søgaard

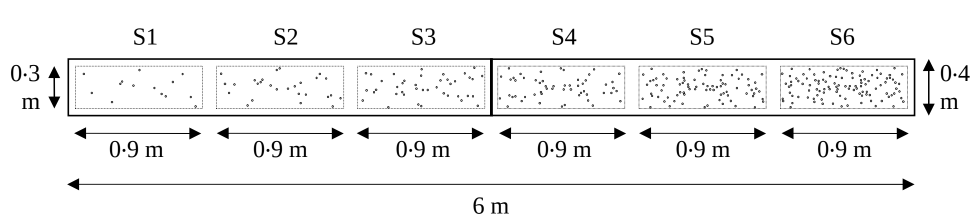

Fig. 2. Illustration of the sheets used as spraying surface: S1, 50 circles m^{-2}; S2, 100 circles m^{-2}; S3, 150 circles m^{-2}; S4, 200 circles m^{-2}; S5, 300 circles m^{-2}; S6, 400 circles m^{-2}

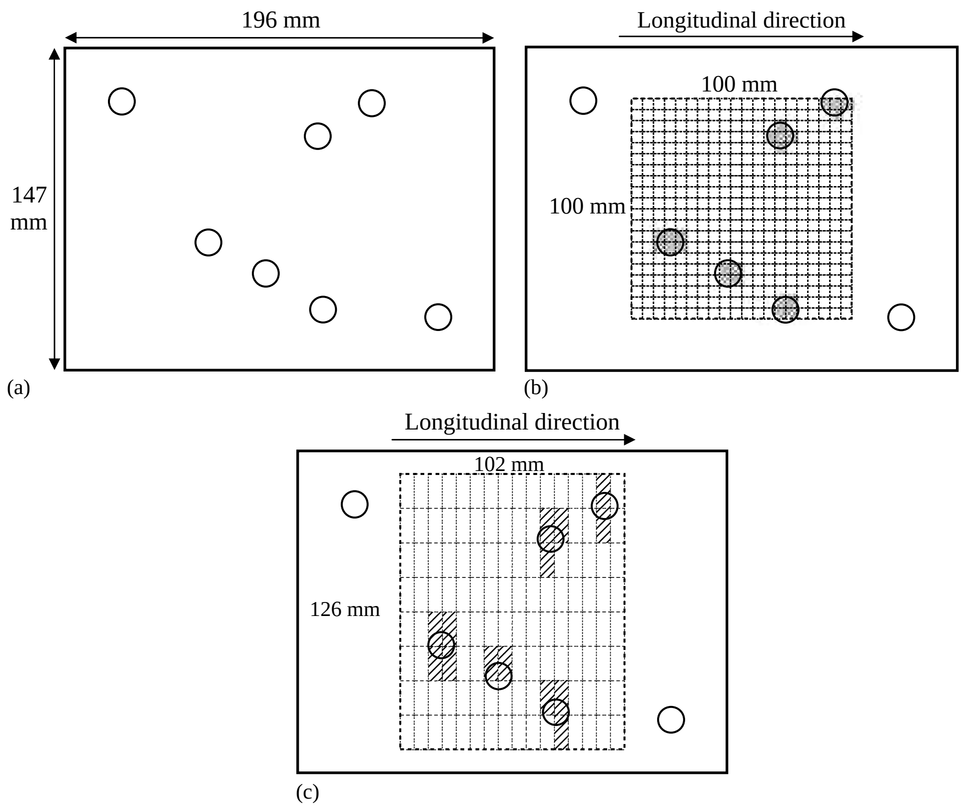

Fig. 3. Illustration of an image taken by the autonomous robot: (a) image of circles on the sheet; (b) image overlayed with a grid of 20 by 20 square cells; (c) image overlayed with a grid of 8 by 16 rectangular cells; ▨, cell marked for spraying

and Lund (2005). For this system the criterion for spraying a cell was that at least 20% (20 mm^2) of the cell should be covered by circle objects. It appears that due to lower map resolution the area marked for spraying is substantially larger than in Fig. 3(b). Thus the potentials for higher accuracy and lower application rates with the system presented in this paper should be obvious.

2.6. Experiment

Because of the distance between the camera and the micro-dosing system and because of the latency of image acquisition, processing and valve activation, the delay between image capture and valve activation was calibrated prior to the actual experiments. First, an initial setting of the delay was chosen and then the autonomous robot was programmed to traverse the test course while spraying the circles. The distances between corresponding liquid droplets and circles on the PVC sheets were measured, and based on the mean distance an optimal delay setting could be calculated and used for the subsequent experiment. The delay setting was optimal in the sense that the mean distance between corresponding droplets and circles was minimised for the specific forward speed used in the experiment.

The purpose of the experiment was to evaluate the accuracy of targeting the circle objects with the micro-dosing system. The spray mixture containing demineralised water, a polymer and a green spray colourant was used. The autonomous robot was programmed to traverse the test course four times. Furthermore, the robot was programmed to stop each time an image was acquired and processed. The forward speed between the image takings was 0·2 m s^{-1}. After each passage, the test course was photographed, and the distance between the centre of each target circles and the centroid (two-dimensional centre of mass) of the corresponding drops of spray liquid was determined by digital image analysis.

3. Results and discussion

Figure 4(a) shows a 203 mm by 401 mm section of a PVC sheet after one of the spraying trials and Figs 4(b) and (c) shows two corresponding images taken and processed by the robot immediately before spraying. Comparing Fig. 4(a) with Figs 4(b) and (c) it can be seen

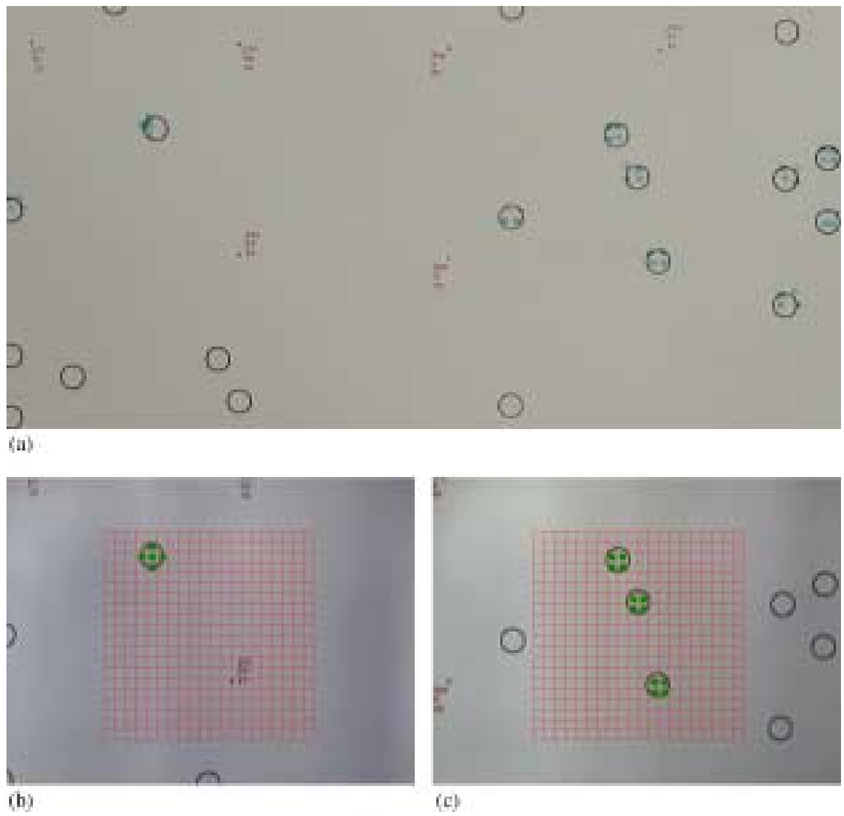

Fig. 4. Example of the spray result: (a) a 203 mm × 401 mm section of the sheets after spraying the circles with green spray liquid (the red numbers and dots are distance markers); (b) and (c), two examples of corresponding images taken by the robot immediately before spraying (overlayed with spray maps); □, a cell in the spray map; ●, cells marked for spraying

that there is a good correspondence between realised and planned spraying (spray maps).

The results from the entire experiment appear from Figs 5(a) and (b). The figure includes all the results from the four replicates (four passages with the robot) and consists of measurements from 404 sprayed circles. There was no significant difference between the replicates and between different densities of the circles.

Figure 5 shows that the centroids of the pools of spray liquid were found within 10 mm from the centres of the target circles. Though, it can be seen from Fig. 5(a) that the longitudinal distances were generally larger than the transversal distances (standard deviations of 2·5 and 1·8 mm, respectively; Table 1). The uncertainty in the longitudinal direction was mainly related to timing errors because of errors in estimation of travel distance following image acquisition. The travel distance was estimated by means of a motion model that took pulses from the wheel encoders as input. The estimation algorithm assumed constant velocity over short periods of time but this assumption was not always true, especially not when the robot stopped and started in connection with image acquisition. The predominant uncertainty in the transversal direction was presumably related to small variations in the directions of the liquid jets released from the micro-dosing tubings. Although the 20 tubes are designed to release liquid jets in a perfect vertical direction, minor misalignments may have caused deviations. This type of errors source may also be a part of the explanation for the uncertainty in the longitudinal direction.

Apart from the sources of uncertainty mentioned above, there is also another and more basic source of uncertainty, which is related to the resolution of the spray maps, i.e. the size of the spray map cells. Due to limited map resolution the cells marked for spraying can generally not be centred exactly on the target circle, cf Figs 3(b) and (c). To quantify the theoretical contribution of uncertainty related to the targeting resolution of the micro-dosing system, a simulation study was performed. A target circle was placed at 2500 different positions within grid of 5 mm by 5 mm cells (2500 positions representing all possible positions relative to a cell). For each placement, the cells to be sprayed were identified (cells covered at least 50% by the circle). Furthermore, the longitudinal, transversal and absolute

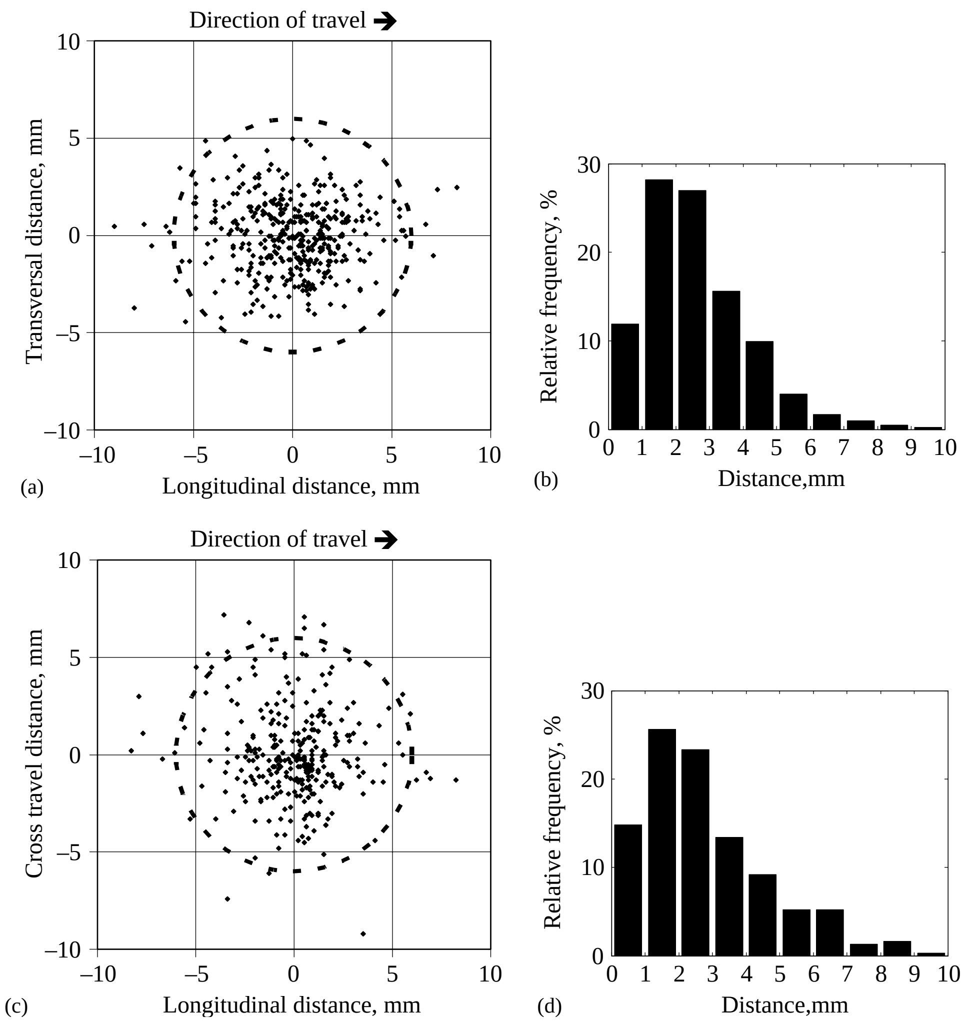

Fig. 5. Distances from centres of target circles to centroids of corresponding drops of spray liquid — results from the present micro-dosing system ((a) and (b)) and earlier micro-dosing system ((c) and (d)); (a) and (c), positions of centroids of spray liquid drops relative to the centres of the corresponding target circles:– –, target circle, ♦, position of pool centroid; (b) and (d), distribution of absolute distances

Table 1
Statistics on distances from centres of target circles to centroids of corresponding drops of spray liquid

Micro-dosing system	Data source	Standard deviation, mm		Average of absolute distances, mm
		Long*	Trans†	
Present system‡	Experiment	2·5	1·8	2·6
	Simulation	0·9	0·9	1·1
Earlier system§	Experiment	2·3	2·4	2·8
	Simulation	1·5	2·9	2·9

*Standard deviation in longitudinal direction.
†Standard deviation in transversal direction.
‡The micro-dosing system described in this paper.
§The micro-dosing system described by Søgaard and Lund (2005).

distances from the centroid of the marked cells to the centre of the target circle were calculated. The standard deviations in the longitudinal and transversal directions were both 0·9 mm and the mean absolute distance was 1·1 mm (Table 1). These numbers are much less than the corresponding numbers found experimentally (Table 1) and hence it can be concluded that the spray map resolution is sufficiently fine and does not significantly limit the targeting accuracy of the micro-dosing system.

To compare the micro-dosing system presented in this paper with the system described by Søgaard and Lund (2005), statistics for the latter have also been listed in Table 1. It can be seen that the present system seems to be more inaccurate in the longitudinal direction than the earlier system. Though, the difference between standard deviations of 2·5 and 2·3 mm, respectively, is not significant (probability value $P > 0{\cdot}1$). On the other hand, the present system has reduced the transversal standard deviation significantly ($P < 0.0001$) and consequently the mean absolute distance have been reduced from 2·8 to 2·6 mm, i.e. 7% (significant reduction, $P < 0.025$).

Table 2 shows that with the micro-dosing system presented in this paper each target circle gives rise to spraying of 4·18 map cells on average. Thus, for each target circle the average area marked for spraying is 4·18 by 25 mm^2 = 105 mm^2, which is very close to the area of the circles (110 mm^2). The average amount of spray liquid applied in each cells is 2·5 µl (one shot from a single micro-dosing tubing) and consequently 4·18 × 2·5 µl = 10·5 µl is applied at each target circle on average. For the micro-dosing system described by Søgaard and Lund (2005), the average area marked for spraying for each target circle was 220 mm^2 and the average amount of liquid applied per target circle was 131 µl. Thus the amount of liquid, especially the amount of off-target liquid, has been reduced dramatically with the present micro-dosing system.

There are two reasons why the average applied liquid volume per target circle was 12-fold higher for the old system than for the present one. One reason is that the old system operated in larger cells (about 100 mm^2) than the present one (25 mm^2) and consequently the old system sprayed more than twice as much area than the present one in order to cover the target circles (220 mm^2 per target circle compared to 105 mm^2, cf Table 2). Another reason, the most important one, was that the new system was improved considerably compared to the old one. New solenoid valves that could be controlled very precisely and longer tubings that gave higher resistance to the liquid flow made it possible to release very small amounts of liquid in each shot.

As mentioned above, the average number of cells marked for spraying per target circle was 4·18. However, due to the longitudinal and transversal uncertainties related to the timing of spraying and other technical sources of errors (Table 1), some of the shots 'fired' by the micro dosing system never hit the target circle. The example in Fig. 4 illustrates circles that should ideally be hit by four or five shots each but it can be seen that a few shots ended outside the target circles. To quantify the proportion of shots missing the target, Monte Carlo simulations were performed that took the uncertainty in Table 1 (present system) into account. The simulation showed that the average number of off-target shots per circle was 1·14, i.e. 27% of the average number of cells marked for spraying (4·18). The number of shots hitting the circles ranged from 0 to 5 with an average of 3·04. The percentages of circles hit by 0, 1, 2, 3, 4 and 5 shots were 0·2, 3·5, 24·6, 36·5, 34·1 and 1·1, respectively, i.e. 99·8% of the circles were hit by at least one shot.

Graglia (2004) demonstrated that by using Glyphosate as herbicide for controlling Solanum nigrum, only 1 µg will be needed per plant. Thus, to kill a plant by only one shot (2·5 µl spray liquid), a Glyphosate concentration of 1 µg in 2·5 µl of spray liquid is required. Table 2 shows that the average amount of applied per target circle is 10·5 µl (hitting plus non-hitting fraction). With a weed infestation of 100 weeds m^{-2} or 10^6 weeds ha^{-1}, the amount of applied spray liquid per hectare is 10^6 × 10·5 µl = 10·5 l corresponding to 4 g of Glyphosate. This dosage is well below the official label recommendation, which is 540 g ha^{-1} for newly germinated dicotyledonous weeds (Graglia, 2004). This demonstrates that the robotic micro-dosing system has a great potential for reducing herbicide consumption.

The results presented in this paper are only valid for indoor conditions. However, the micro-dosing system has also been investigated under outdoor conditions and the results from these investigations are described in a planned publication.

Under realistic outdoor conditions, the accuracy of micro-application will be reduced and the efficacy of weed control will be lower than predicted from indoor results. Varying soil conditions may impair the kinematic control of the robot and the liquid jets. Furthermore, wind may also disturb the transportation of liquid from the micro-dosing tubings to the targets, but it is not considered a big problem because of the fact that the liquid is transported through a jet with a high kinetic energy. Potential wind effects on liquid jets and weed plants can be minimised by shielding.

Table 2

Comparison of the micro-dosing system presented in this paper (present system) and the micro-dosing system described by Søgaard and Lund (2005) (earlier system) with respect to targeted area and applied amount of spray liquid

Micro-dosing system	Area of a spray map cell, mm^2	Average number of marked cells per target circle	Average marked area per target circle, mm^2	Average amount of liquid per marked cell, μl	Amount of liquid per target circle, μl
Present system	25	4·18	105	2·5	10·5
Earlier system	101	2·18	220	60	131

4. Conclusions

The objective was to investigate the performance under controlled indoor conditions of a machine vision-controlled micro-dosing system that was integrated in an autonomous robot vehicle. The work should elucidate selected technical aspects of micro-dosing in a robotic weeding context. The experiments demonstrated the ability of the system to target objects with subcentimetre accuracy. The results suggest that a spatial spraying resolution of 5 mm by 5 mm is sufficiently fine when applying herbicides at single objects of size of average weed seedlings. Furthermore, the results indicate that in case of 100 objects m^{-2} the system uses 10·5 l of spray liquid per hectare. Based on this finding, it has been estimated that full control of 100 weed seedlings m^{-2} can be achieved by 4 g Glyphosate ha^{-1}. This is a reduction of two orders of magnitude compared to conventional broadcast spraying of Glyphosate.

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