Computers and Electronics in Agriculture 77 (2011) 35–40

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

# Performance evaluation of a crop/weed discriminating microsprayer

Henrik Skov Midtiby [a,*], Solvejg K. Mathiassen [b], Kim Johan Andersson [a], Rasmus Nyholm Jørgensen [a]

[a] University of Southern Denmark, Niels Bohrs Allé 1, 5230 Odense M, Denmark
[b] Department of Integrated Pest Management, Research Centre Flakkebjerg, Forsøgsvej 1, 4200 Slagelse, Denmark

ARTICLE INFO

*Article history:*
Received 23 March 2010
Received in revised form 8 March 2011
Accepted 20 March 2011

*Keywords:*
Machine vision
Weed crop discrimination
Microsprayer
Herbicide reduction
Site-specific
Close-to-crop

ABSTRACT

An intelligent real-time microspraying weed control system was developed. The system distinguishes between weed and crop plants and a herbicide (glyphosate) is selectively applied to the detected weed plants. The vision system captures 40 RGB images per second, each covering 140 mm by 105 mm with an image resolution of 800 × 600 pixels. From the captured images the forward velocity is estimated and the spraycommands for the microsprayer are calculated. Crop and weed plants are identified in the image, and weed plants are sprayed. Performance of the microsprayer system was evaluated under laboratory conditions simulating field conditions. A combination of maize (*Zea mays* L.), oilseed rape (*Brassica napus* L.) and scentless mayweed (*Matricaria inodora* L.) plants, in growth stage BBCH10, was placed in pots, which were then treated by the microspray system. Maize simulated crop plants, while the other species simulated weeds. The experiment were conducted at a velocity of 0.5 m/s. Two weeks after spraying, the fraction of injured plants was determined visually. None of the crop plants were harmed while 94% of the oilseed rape and 37% of the scentless mayweed plants were significantly limited in their growth. Given the size and shape of the scentless mayweed plants and the microsprayer geometry it was calculated that the microsprayer could only hit 64% of the scentless mayweed plants. The system was able to effectively control weeds larger than 11 mm × 11 mm.



## 1. Introduction

Effective weed control is a vital part of agriculture. Conventionally, weeds are controlled by an overall application of herbicides to the field. It has become apparent that herbicides place a heavy burden on the environment. Herbicide usage is already controlled by European laws, but in the future these restrictions are expected to increase significantly. Increased restrictions will reduce the number of herbicides and thus there exists a demand for new weed control methods. With the microsprayer approach developed in this article, herbicides are mainly deposited on weed plants.

In patchspraying, the entire field is divided into smaller patches and then the herbicide is adjusted according to the presence of weeds (Christensen et al., 2009). When the patch size is reduced, the potential reduction in herbicide use is increased (Lund et al., 2008). When the patch size reaches the size of a single plant, the process is denoted microspraying. The microspraying technique has two significant advantages: (1) high reduction of the amount of herbicide deposited on the soil, which minimizes the issue of herbicide leaching and (2) almost no deposition of herbicide on crop plants, which eliminates the potential presence of herbicide residues in the harvested crop plants and potential damages to the crop. In addition microspraying can use both selective and non-selective herbicides. Non-selective herbicides, like glyphosate used in this experiment, harm any plant while selective herbicides are tolerated by specific crop plants but can cause yield loss.

Lee et al. (1999) used a microsprayer to control weeds in tomato. The spraying system moved forward with a continuous velocity of 0.22 m/s. A camera grabbed images of the ground in front of the spraying device. A grid consisting of 8 × 18 cells were imposed on the image, and the cells containing weed plants were marked for spraying. The system was able to spray 47.6% of the weeds while 24.2% of the tomato plants was also sprayed. A similar spraying device was used by Lamm et al. (2002), to spray weeds with elongated leaves in a cotton field. The system sprayed 89% of the weeds and 22% of the cotton plants.

Søgaard and Lund (2005) investigated the accuracy and precision of a robotic system carrying a microsprayer hitting weed markers (circles with a diameter of 12 mm). The robotic system switched between two modes: image analysis and forward motion while spraying the detected circles. During the image analysis step where a single image was acquired, targets were identified and marked in a spray plan. The spray plan was represented as an 8 × 16 grid and each cell could either be marked for spraying or not. After the spray plan was generated, the robotic system moved 180 mm forward with a velocity of 0.2 m/s. During this motion the microsprayer was activated according to the spray plan. When the

* Corresponding author. Tel.: +45 21 35 61 05; fax: +45 65 50 73 54.
*E-mail addresses:* hemi@kbm.sdu.dk (H.S. Midtiby), Solvejg.Mathiassen@agrsci.dk (S.K. Mathiassen), kja@kbm.sdu.dk (K.J. Andersson), rasj@kbm.sdu.dk (R.N. Jørgensen).

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doi:10.1016/j.compag.2011.03.006

movement ended a new image was acquired and the entire process repeated. The system was able to hit the weed markers with an average position error of 2.8 mm.

Nieuwenhuizen et al. (2010) evaluated a microspraying system consisting of five nozzles used for controlling volunteer potatoes in sugar beet. Average color information was calculated for $11 \times 11$ pixel bins and used to distinguish between crop and weed plants using an adaptive Bayesian classifier. With a forward speed of 0.8 m/s the system controlled growth of 77% of the volunteer potatoes and killed up to 1% of the crop plants.

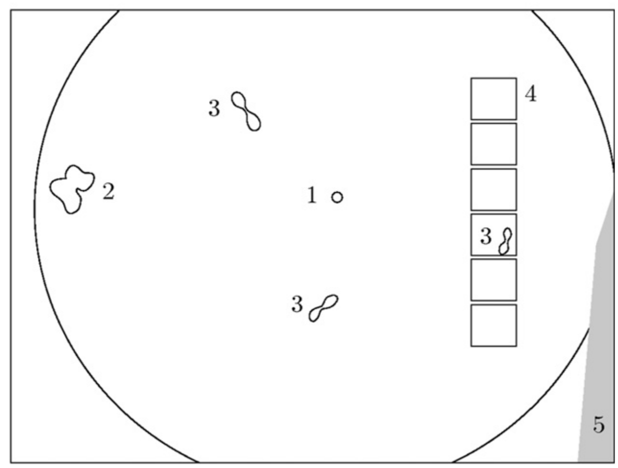
In present paper a spray targeting system that does not rely on a fixed cell grid is evaluated. By avoiding the fixed grid, the ability to hit small targets is expected to increase. When controlling a microsprayer it is important to trigger the sprayer when it is directly above the target. Using a fixed grid, the set of possible activation-times is reduced. None of the above mentioned microspray systems can move at a speed above 0.3 m/s and maintain a weed control efficiency higher than 90%. The relative low speed of the spray systems severely limits the number of plants that can be processed in a given period and a low weed control efficiency renders the systems economically unattractive. Compared to other microspray systems, our system has a higher speed relative to the treated plants and can therefore control weeds more efficiently.

Present article covers: (1) a detailed description of the vision control system and microsprayer setup, (2) calculations of the achievable hit rate given the geometry of the microsprayer and size and shape of the treated plants and (3) a performance evaluation of the entire system conducted under laboratory conditions.

## 2. Materials and methods

The system is a combination of three separate subsystems, (1) vision system, (2) spray planner using the acquired images and (3) physical microsprayer. The vision system captures images (Fig. 1a) which are processed by two different subsystems: a plant recognizer and a velocity estimator. The velocity estimator compares two consecutive images and determines the displacement of their common content. The plantrecognizer analyses each image and locates green objects in the image. These objects are then classified as crop or weed plants, in this process a crop and weed map is generated (Fig. 1b). The map is an interpreted version of the input image covering the same area. Based on this map and the estimated forward velocity spraycommands are generated and sent to the microsprayer controller.

(a) Image acquired by the vision system.




(b) Annotation of the elements in Fig. 1a.

**Fig. 1.** An example of the images acquired by the vision system. The numbers in (b) describes the elements at the shown locations. (1) Maize, (2) oilseed rape, (3) scentless mayweed, (4) target areas of the six spraynozzles and (5) part of the microsprayer. One of the scentless mayweed plants is located in the target area of spraynozzle 4. Part (4) and (5) are fixed in the image while (1)–(3) moves from left to right.

### 2.1. Vision system

Homogeneous illumination of the field of view is provided by 18 3W white LEDs (ProLight PG1X-3LXS-SD) that are directed on the white inner surface of a half cylinder placed over the spray location. When placed in direct sunlight, the half cylinder ensures that the area to be captured is kept free of hard shadows and the homogeneous illumination eliminates specular highlights. These properties have been verified in small scale experiments with the half cylinder placed approximately 100 mm above the soil surface and exposed to direct sunlight.

Images were acquired by a CMOS camera (PixeLINK PL-B742F-R) pointing downwards. The field of view was 140 mm $\times$ 105 mm and was acquired as an 800 $\times$ 600 pixel image. The spray system consisted of six nozzles each with a fixed location and all pointing directly downwards. The six areas that could be targeted by the spraynozzles were all within the captured area, as well as the soil and plants that would pass below the microsprayer during the next 100 mm of movement. To determine the spraycells, the spraynozzles were activated while the sprayer was at rest and an image was acquired. The spraycells were then set to the sprayed locations in the acquired image. Images were acquired with a short exposure time of 9 m/s to reduce motion blur and 40 images were captured per second. The acquired images were transferred to the image processing computer via a Firewire connection. Image processing were performed on a Lenovo ThinkPad W700 laptop equipped with an Intel Core 2 Duo T9600 2.8 GHz processor and 4 GB ram running Windows XP. The software was developed using the C++ programming language and consisted of three separate threads which handled image acquisition, image analysis and sprayplanning, respectively. The software library OpenCV (Bradski and Kaehler, 2008) was used for the implementation of the image processing methods.

### 2.2. Ground velocity estimation

Velocity of the spray system relative to the soil surface was estimated from the acquired sequence of images, based on the assumption that perspective distortions can be ignored. After image $N$ has been captured, it was compared to image $N - 1$ and the relative motion between the two images was estimated. Using the relative motion and the difference between the time of image acquisition for the two images the velocity was calculated.

Initially both images were scaled down to a resolution of $200 \times 150$ (from $800 \times 600$). An area measuring $100 \times 125$ pixels was extracted from the central part of image $N-1$, this part of the image was used as a template. The cross correlation between the template and image $N$ was determined, as a function of the relative position of the template with respect to image $N$. The location where the template has the highest correlation with image $N$ was determined. Then the offset between the template location in image $N-1$ and the best matching location in image $N$ was determined. This offset was used as an estimate of the velocity of the field of view, e.g. how fast one object moved across the field of view measured in pixels per unit of time. The template matching can be calculated efficiently using Fast Fourier Transforms. Template matching used on average 5.1 m/s per frame. If no objects are present in the images, the best matching location is not well defined which then will result in a random location being selected as the best matching location.

### 2.3. Plant detection

To locate plants in the acquired image, the excess green color index (ExG) introduced by Woebbecke et al. (1995) was used:

$$\text{ExG} = 2G - R - B \tag{1}$$

where $R$, $G$ and $B$ are the red, green and blue pixel values of the current pixel. The pixel values are stored as integer values in the range $[0; 255]$. The generated excess green image is then smoothed and binarized using a threshold value of 55. The threshold value was chosen based on the images acquired by the vision system.

Connected regions in the segmented image are located, and for each of the regions the size and some shape descriptors are determined. The shape descriptors used are the seven scale, translation and rotation invariant moments introduced by Hu and February (1962). Regions that intersect the border are considered incomplete and therefore discarded.

### 2.4. Classifier

For classification between crop and weed plants a nearest neighbor Bishop (2007) classifier was used. As the calculated features have different magnitudes (size ~1000 and Hu1 ~0.1) the features are rescaled before classification. The rescaling consists of multiplying the features with the weights given in Table 1. The weights were chosen based on the typical magnitude of the features. Features with high noise levels were given a decreased weight to decrease the influence of the noise. Performance of the classifier was not investigated directly, but small experiments on the experimental setup showed a relative high classification accuracy.

After classification the presence of crop and weed plants are stored in a crop/weed map. The crop/weed map is an image with similar dimensions as the original image where pixels belonging to a weed plant have the value 1 and crop plant pixels have the value 255. Areas with no plants present are identified by the value 0.

**Table 1**
Feature weights used in the classifier.

| Feature | Weight |
|---|---|
| Size | 0.001 |
| Hu1 | 6.667 |
| Hu2 | 8.403 |
| Hu3 | 71.428 |
| Hu4-7 | 100.000 |

### 2.5. Sprayplanning

Sprayplanning was performed once for each of the individual spraynozzles. For each nozzle, the area that the nozzle was expected to pass, was examined in the crop/weed map. Presence of crops and weeds were determined as a function of the distance to the current nozzle. Regions where only weeds were present were marked for spraying. When a weed was found in the course of the nozzle, a command is sent to the microsprayer controller that the nozzle should be opened at the time $t_{\text{spray}}$, which was calculated based on the acquisition time of the processed image $t_{\text{img}}$, the distance to the weed $d_{\text{weed}}$, the current forward velocity $v$ and the delay $t_{\text{delay}}$ caused by the entire system. The relationship is:

$$t_{\text{spray}} = t_{\text{img}} - t_{\text{delay}} + \frac{d_{\text{weed}}}{v} \tag{2}$$

The delay parameter was adjusted during the calibration phase before the experiment.

### 2.6. Spray system

The spray system was based on a Willett 3150 Si/800 inkjet printer head. Off the shelf the printer head has seven nozzles which can be controlled individually; six of these were used, as one was malfunctioning. The six nozzles are spaced evenly over a distance of 53 mm, which corresponds to a distance of 10.5 mm between two adjacent nozzles. In the experimental setup there was a distance of ~100 mm between soil surface and nozzle.

The computer sends spraycommands to a microcontroller via a USB connection. After receiving the commands, the microcontroller immediately opens the requested nozzles for 1 ms and 0.2 μL spray liquid is ejected. The spray liquid consists of water mixed with RoundUp Bio (360 g/L glyphosate as an isopropylamine salt, Monsanto Europe) with a concentration of 5 g/L. This ensures that in one spray application there will be enough glyphosate to effectively control the growth of the weed seedling. According to Søgaard et al. (2006), 0.8 μg of glyphosate is enough to effectively control the growth of *Solanum nigrum* L. seedlings. Unpublished results show that oilseed rape seedlings are effectively controlled by a similar amount of glyphosate.

### 2.7. The experimental setup

Crop and weed plants were seeded in pots with a diameter of 130 mm and a volume of 1 L. The plants were raised in glasshouse. The pots had to be moved below the spray system with a small error in the transversal direction as the plants are placed in a 50 mm wide band inside the pots and the spray system can only treat a 60 mm band. To run the experiments, the microsprayer including illumination, vision and control systems was mounted above a conveyor belt, such that the distance between spraynozzles and soil surface in the pots was approximately 100 mm. The purpose of the conveyor belt was to move potted plants below the operating microsprayer system in a steady motion.

### 2.8. Experimental method

Three species were used: maize, oilseed rape and scentless mayweed. At the time of the experiment, the cotyledons had just emerged, which equals growth stage 10 on the BBCH scale (Meier, 2001). Weed control should be performed before growth stage BBCH12 according to Danish recommendations (Petersen and Jensen, 2010). One crop (maize) plant was placed near the pot centre, while 1–2 oilseed rape and 2–3 scentless mayweed plants were placed randomly in a 50 mm wide band centred on the maize plant. The plants were placed such that no leaves overlapped other plants.

Four pots were randomly selected as control pots. These pots received no treatment by the microsprayer system and the plants inside the pots were used to train the classifier. The classifier database was filled with the control plants, where maize was marked as crop and oilseed rape and scentless mayweed were marked as weeds. In total four maize, eight rape and 10 mayweed plants were present in the four control pots. The 33 remaining pots were placed on a conveyor belt, which carried the pots below the microsprayer at a velocity of 0.5 m/s, while the spray system was activated. In total 33 maize, 54 oilseed rape and 76 scentless mayweed plants were treated by the microsprayer.

Two weeks after the microspraying, the status of each individual plant was visually evaluated using two categories: plants following the expected growth rate and plants severely behind the expected growth rate. The expected growth rate was estimated using the observed growth in the four control pots. Dry weight measurements of the oilseed rape plants were made directly after the visual evaluation.

### 2.9. Interpretation of experimental results

The experiment consisted of exposing a number of plants $n$ to the microsprayer treatment. Two weeks after the treatment, the number of normal growing plants $k$ was determined. The normal growth fraction $f$ of the plants exposed to treatment can be estimated from $f = k/n$. In addition to the normal growth fraction, the uncertainty of this fraction was estimated. The credible interval is used to describe the uncertainty of the determined normal growth fraction. Using the Binomial distribution, the experimental support for a given normal growth fraction hypothesis can be expressed as being proportional to

$$p(f|n,k) \propto f^k \cdot (1-f)^{n-k} \tag{3}$$

Note that this value is maximized for $f = k/n$. We assume that $p(f|n,k)$ is normalized, such that

$$\int_0^1 p(f|n,k)\,df = 1 \tag{4}$$

The probability $q$, that the real plant growth fraction is inside the interval $[f_l;f_h]$ is then

$$q = \int_{f_l}^{f_h} p(f|n,k)\,df \tag{5}$$

The shortest interval $[f_l;f_h]$ that covers a given fraction $q$ was used as a credible interval at the $q$ level, this approach was described by Ross and Nov. (2003).

### 2.10. Probability of hitting small plants

When a small plant passes below the microsprayer between two of the nozzles, it is not always possible for the spray system to hit the plant. This can be explained by the geometry of the spray system, where the distance between two adjacent nozzles is larger than the width of the sprayed area of one nozzle. The area between two nozzles that cannot be sprayed is denoted the deadzone (Fig. 2). If a plant is in the deadzone throughout the entire passage, the spray system has no chance of hitting it. The following values are used to describe the setup: $w$ is the distance between two adjacent nozzles, $w_s$ is the width of the area that are sprayed by a single nozzle, $\theta$ is the plant orientation and $w_{\text{eff}}(\theta)$ is the effective width of the plant (Fig. 2). The effective width of a plant is its width measured in the direction perpendicular to the moving direction. If the effective width is larger than the deadzone width

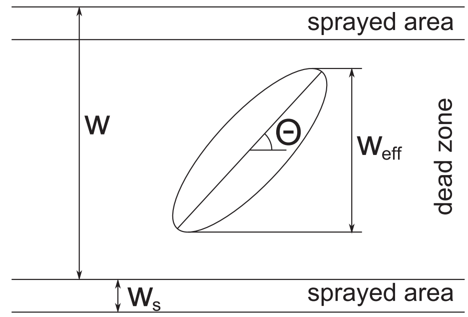



**Fig. 2.** Illustration of the effective plant width $w_{\text{eff}}$ and the parameters $w$ and $w_s$ for the microsprayer setup.

($w_{\text{eff}} > w - w_s$), some part of the plant will always overlap an area that can be sprayed and thus it is possible to hit the plant. In the other case where $w_{\text{eff}} < w - w_s$ the probability of hitting the plant with random location is given by the fraction $\frac{w_{\text{eff}}+w_s}{w}$. To calculate the probability of hitting a plant with random orientation and location the following expression is used.

$$p_{\text{hit}} = \frac{w_s}{w} + \frac{1}{\pi}\int_0^{\pi} \frac{\min\left(w - w_s, w_{\text{eff}}(\theta)\right)}{w}\,d\theta \tag{6}$$

To simplify the calculations, the plant shape is described by an ellipse, with the major axis $a$ and the minor axis $b$. The ellipse shape parameters were chosen such that the ellipse covered the entire plant. Eq. (6) can then be evaluated numerically using the values relevant for the used microsprayer setup ($w = 10$ mm,$w_s = 2$ mm), and the parameters describing the plant shape. Note that the calculated values are based on two assumptions: (1) that all the plants have the same shape and size and (2) that all the plants are located and oriented randomly. The estimated hit probability is a statistical upper bound of the performance of the optimal vision and spray control system.

The difference between the observed normal growth fraction and estimated probability of not being able to hit the plant species, $f - p_{\text{miss}}$, is a measure of the performance of the spray system. A low value indicates that the system can effectively target the given plant species at this growth stage, and a high value shows that the system did not hit all plants that it should be able to. Using this measure it is possible to compare the targeting performance of the spray system when targeting different objects, varying in size and shape.

## 3. Results and discussion

Table 2, lists the plant shape parameters used for the estimation as well as the obtained hit probabilities. The hit probabilities reveals that the geometry of the microspray system is suitable for targeting plants larger than 11 mm × 11 mm but is unsatisfactory for smaller plants.

There was a clear difference between control and treated group. All plants in the control pot, Fig. 3a, were now in a more developed growth stage than at the time of spraying. For the treated pot in Fig. 3b, the maize plant and a single scentless mayweed plant had evolved into a more developed growth stage. For the maize and oilseed rape plants, there were no doubt of which category to place the plants into, as they either grew as expected or their growth were stopped at the BBCH 10 stage. The scentless mayweed plants were more difficult to classify, as only a part of the plants grew as expected (48 plants) or stopped their growth at the BBCH 10 stage (18 plants). The remaining fraction (10 of 76) were somewhere between these two stages. Table 2 lists the number of treated plants and the number of the ones that followed the expected

**Table 2**
Short summary of the experimental results. ($a$ and $b$): major and minor axes of the ellipse shaped plant model ($p_{miss}$): probability of the system not being able to hit the plant model ($k$): number of plants that grow unaffected after the microspray treatment. ($n$): number of plants treated by the microsprayer system. ($f$): normal growth fraction. (95% CI): the shortest credible interval for the rate of normal growth. ($f - p_{miss}$): miss rate that cannot be explained by plant size.

| Plant | Spray probability | | | Experimental results | | | | $f - p_{miss}$ |
|---|---|---|---|---|---|---|---|---|
| | $a$ [mm] | $b$ [mm] | $p_{miss}$ | $k$ | $n$ | $f$ | 95% CI | |
| Maize(crop) | 3.5 | 3.5 | 0.55 | 33 | 33 | 1.00 | [0.92; 1.00] | 0.45 |
| Scentless mayweed | 8.0 | 2.5 | 0.34 | 48 | 76 | 0.63 | [0.52; 0.73] | 0.29 |
| Oilseed rape(weed) | 13.7 | 11.0 | 0.00 | 3 | 54 | 0.06 | [0.01; 0.14] | 0.06 |

(a) Control pot (b) Sprayed pot

**Fig. 3.** Comparison of a control pot and a sprayed pot. In the sprayed pot, the oilseed rape plant is severely damaged by the herbicide while the maize plant appears unaffected. Of the two scentless mayweed plants that are present in the sprayed pot one is severely injured while the other grows unaffected.

growth pattern. Three of the treated oilseed rape plants had a dry weight comparable to the control plants. The weight distribution of the control and the treated plant populations are visualized in Fig. 4.

The oilseed rape plants, which had the largest leaf area per plant, were effectively controlled by the microsprayer. Only 6% of the treated plants followed the expected growth pattern for untreated plants, while 94% was effectively controlled. In comparison only 37% of the scentless mayweed plants were sprayed, which is much less than the expected hit probability of 66%. This difference indicates that the system is not able to locate and target small objects effectively. The reason could be timing problems of the microsprayer control system, imprecise calibration of the delay parameter $t_{\text{delay}}$ or faulty classification of the plants as crop plants. The $f - p_{\text{miss}}$ measure is not relevant for the maize plants, as they were not targeted for spraying. All of the 33 treated maize plants followed the expected growth pattern, this indicates the system was able to correctly classify the plants as crops.

A main disadvantage with the experiment is that the input to the vision system was discarded during the experiment. Therefore it is not possible to investigate how the system failed in the cases where plants were not hit. By storing all the acquired images before they are processed, it should be possible to redo the image analysis and the following sprayplanning.

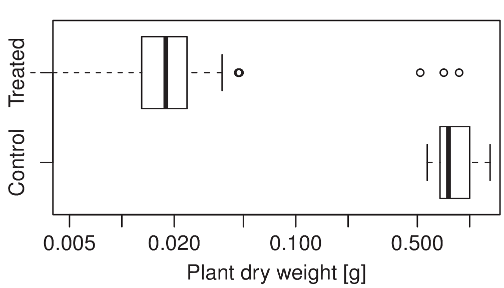



**Fig. 4.** Measured dry weight of the oilseed rape plants (representing weeds) in the control ($n = 8$) and treated ($n = 53$) groups two weeks after microspraying. Three outliers can be identified in the treated group, these are the plants that the microsprayer missed during the treatment.

The system by Søgaard and Lund (2005) relies on controlling the motion of the vision and spray system, this makes the system infeasible to mount on an existing platform. Our system is self contained and needs only to be moved in a steady motion above the area that should be treated. The volunteer potato controlling system described in Nieuwenhuizen et al. (2010) and our system have many common properties. The main difference is the geometry of the microsprayer setup, the nozzle spacing is narrower in our setup, this increases the resolution of the spray system which can then target weed plants closer to crop plants.

A direct limitation of the described system is the narrow region (60 mm) in which weeds can be controlled. By replacing the microsprayer unit with a larger one, the region can be extended to cover the full range of the vision system $\sim$ 100 mm. If the region should be larger the vision system has to be redesigned.

The future of the microsprayer technique depends on several things. The system presented can reliably detect and control weed plants with a size larger than 11 mm $\times$ 11 mm when in a steady forward motion with a velocity of 0.5 m/s. The forward velocity of 0.5 m/s is probably not enough to make the system economically feasible. The challenge will be to move the system from controlled indoor facilities to more challenging circumstances in the field. Use of controlled illumination and shielding from direct sunlight is expected to make the system more resistent to changes in the natural illumination. The main change will be to go from the steady motion to a more shaky motion. Under a steady forward motion is it possible to predict the weed trajectory relatively to the vision system with high accuracy, when the motion is disturbed the quality of such a path prediction will decline rapidly, deteriorating spray accuracy.

## 4. Conclusion

A machine vision system was developed for controlling a microsprayer system. The goal was to develop a system that can detect, classify and effectively control weed plants while the system was moving with a velocity of 0.5 m/s. The system was tested in a relatively simple situation with two weed species (scentless mayweed and oilseed rape) in maize. With a velocity of 0.5 m/s between the soil surface and the microsprayer system, the system was able to effectively control weeds larger than 11 mm $\times$ 11 mm. But only 37% of the smaller scentless mayweed plants were effectively controlled. The low success rate cannot be explained by the small plant size alone, but may be explained by a sub optimal sprayplanning system, problems related to depositing enough herbicide on the small leaves or a combination of both.

## Acknowledgements

Henning Tangen Søgaard provided a lot of constructive critique during the writing of this paper. During development of the system we had constructive discussions with Ivar Lund (University of Southern Denmark, Department of Industrial and Civil Engineering) and Michael Nørremark (Aarhus University, Department of Biosystems Engineering). Michael also provided access to the used microsprayer device.

## References

Bishop, C.M., 2007. Pattern Recognition and Machine Learning (Information Science and Statistics), first ed. Springer.

Bradski, G., Kaehler, A., 2008. Learning OpenCV. O'Reilly Media.

Christensen, S., Søgaard, H.T., Kudsk, P., Nørremark, M., Lund, I., Nadimi, E.S., Jørgensen, R., 2009. Site-specific weed control technologies. Weed Research 49 (3), 233–241.

Hu, M.-K., 1962. Visual pattern recognition by moment invariants. IRE Transactions on Information Theory 8 (2), 179–187.

Lamm, R.D., Slaughter, D.C., Giles, D.K., 2002. Precision weed control system for cotton. Transactions American Society of Agricultural Engineers (ASAE) 45, 231–248 (shutter speed: 1/250 s).

Lee, W.S., Slaughter, D.C., Giles, D.K., 1999. Robotic weed control system for tomatoes. Precision Agriculture 1, 95–113.

Lund, I., Christensen, S., Jensen, L.A., Jensen, P.K., Olsen, H.J., Søgaard, H.T., Bligaard, J., Jensen, J.E., 2008. Cellesprøjtning af ukrudt i majs. Technical Report, Miljøstyrelsen.

Meier, U. (Ed.), 2001. Growth stages of mono-and dicotyledonous plants. BBCH Monograph, second ed. Federal Biological Research Centre for Agriculture and Forestry.

Nieuwenhuizen, A., Hofstee, J., van Henten, E., 2010. Performance evaluation of an automated detection and control system for volunteer potatoes in sugar beet fields. Biosystems Engineering 107 (1), 46–53.

Petersen, P.H., Jensen, J.E., 2010. Ukrudt i majs. Available from: <http://www.landbrugsinfo.dk/Planteavl/Plantevaern/Ukrudt/Kemisk-bekaempelse/Sider/pl_pn_10_102.aspx>.

Ross, T.D., 2003. Accurate confidence intervals for binomial proportion and poisson rate estimation. Computers in Biology and Medicine 33 (6), 509–531.

Søgaard, H., Lund, I., Graglia, E., 2006. Real-time application of herbicides in seed lines by computer vision and micro-spray system. Transactions American Society of Agricultural Engineers (ASAE), 061118.

Søgaard, H.T., Lund, I., 2005. Investigation of the accuracy of a machine vision based robotic micro-spray system. Precision Agriculture '05, 613–619.

Woebbecke, D.M., Meyer, G.E., Von Bargen, K., Mortensen, D.A., 1995. Color indices for weed identification under various soil, residue, and lighting conditions. Transactions American Society of Agricultural Engineers (ASAE) 38 (1), 259–269.