SENSOR-BASED PRECISION HERBICIDE APPLICATION SYSTEM

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ABSTRACT

The smart sprayer, a local-vision-sensor-based precision chemical application system, was developed and tested. The long-term objectives of this project were to develop new technologies to estimate weed density and size in real-time, realize site-specific weed control, and effectively reduce the amount of herbicide applied to major crop fields. This research integrated a real-time machine vision sensing system and individual nozzle controlling device with a commercial map-driven-ready herbicide sprayer to create an intelligent sensing and spraying system. The machine vision system was specially designed to work under outdoor variable lighting conditions. Multiple vision sensors were used to cover the target area. Instead of trying to identify each individual plant in the field, weed infestation condition in each control zones (management zone) were detected. To increase the delivery accuracy, each individual spray nozzle was controlled separately. The integrated system was tested to evaluate the effectiveness and performance under varying commercial field conditions. With the on-board differential GPS, geo-referenced chemical input maps (equivalent to weed map) were also recorded in real-time. The maps generated with this system have been compared with other sensing and referencing systems.

Keywords: machine-vision, multiple sensors, weed, herbicide application rate, spray nozzle.

1. INTRODUCTION

Much research has investigated strategies to control weeds with less herbicide to reduce production costs and to protect the environment. Simple methods have been proposed such as banding herbicide spray on crop rows and cultivating between the rows (Stout, 1992). Models of weed-crop competition can be used to determine a bio-economic threshold for herbicide application (Barritt and Witt, 1987). Many of the post-emergence herbicides that are currently used in the U. S. corn-belt can be applied at reduced rates without a significant impact on crop yields (Marking, 1990). Some researchers even tried to further reduce the dosage and found that a rate of 1/8 of the labeled rate of post-emergence herbicides can still suppress weeds without appreciable yield losses (Willis and Stoller, 1990). The reason of setting up relatively high herbicide application rate is mainly because the in-field weed infestation information is not available and the “worst condition scenario” has to be considered. Chancellor and Goronea (1993) studied the effects of spatial variability of weeds on the site-specific application advantages. They found that at intermediate levels of herbicide application, the input efficiency increased approximately 40% for simulations of spatially modulated application on irrigated wheat. To realize spatial modulated (zone selective) herbicide application, detection based on a simpler, more reliable characteristic is needed for practical spraying systems (Thompson et al., 1991). Many researchers have attempted to detect weeds in crop fields with machine vision systems (Shearer and Holmes, 1990; Woebbecke et al., 1992; Zhang and Chaisattapagon, 1995; Tian et al., 1997), because weed detection at the time of spraying could be very valuable for cutting chemical costs and reducing environmental contamination. However, these vision systems based on morphological or texture parameters generally needed a relatively high image resolution, and the detection algorithms were quite complicated and computationally expensive for real-time systems (Mayer et al., 1998). With the exception of a few recent studies, machine vision recognition of individual plants is still at the stage of studying individual potted plants in the laboratory, or studying the target plants under a controlled indoor lighting environment (e.g., in a greenhouse).

A few real-time field systems have been developed. The photosensor-based plant detection systems (Shearer and Jones, 1991; Hanks, 1996) can detect all the green plants (weed and crop plants) and spray only on the plants. A machine-vision guided precision band sprayer for small-plant foliar spraying (Giles and Slaughter, 1997) demonstrated a target deposition efficiency of 2.6 to 3.6 times that of a conventional sprayer, and the non-target deposition was reduced by 72% to 99%. For high-value crops, high-accuracy machine vision and control systems have been studied for outdoor field applications in California (Tian et. al., 1997, Lee and Slaughter, 1998).

For major crop chemical applications, the current commercial sprayer controllers maintain constant application rate by compensating for ground speed changes, a concept that was researched more than a decade ago (Gebhardt et al., 1974; Dickey-john, 1987). To use GIS or remote sensing information, research was initiated on map-driven variable rate sprayers (Rockwell and Ayers, 1994). Because of the resolution of the weed map, the spatial resolution of those sprayer controllers was relatively low -- the whole boom was controlled at one rate. Current post-emergence sprayers have boom widths of 20 to 50 meters. The timing of weed control was another issue. By the time the weed map was ready, field conditions may have changed.

A system that could make use of the spatial weed distribution information in real-time and apply only the necessary amounts of herbicides to the weed-infested area would be much more efficient and minimize environmental impact. Therefore, a high spatial resolution, real-time weed infestation detection system seems to be the solution for site-specific weed management.

2. METHODS

The concept design of the machine-vision-controlled sprayer is shown in Fig.1 and the system included a multiple cameras vision system, a ground speed sensor and a nozzle controller. The application rate for each nozzle on the spraying boom is controlled separately based on local weed infestation condition. Three prototypes of smart sprayer have been built and tested in University of Illinois since 1996. The design and test of the latest prototype is reported in this paper.

Prototype system setup

The latest prototype was built on a Patriot XL sprayer (CASE-Tyler Industries Inc., Benson, MN). This self-propelled map-driven ready sprayer was equipped AIM control system with a differential GPS receiver with 10 pps (positions per second) position updating rate. Nozzle drops 0.381 m (15 in.) long were connected to the nozzle bodies on the spray boom so that the nozzles (TeeJet 8006VS, Spraying Systems Co., Wheaton, IL) were 0.36 to 0.38 m (14 to 15 in.) above the ground. The boom pressure was set at 172 kPa (25 psi) to achieve a flow rate of 1.8 L/min (0.47 gal/min) per nozzle which resulted in a spray deposition pattern which was visible over the range of travel velocities. The sprayer traveled at 3.2 to 18 km/h (2 to 11 mph) during the experiments.

Video images were acquired from two color CCD cameras (Pulnix TMC-7EX) mounted in the nadir position over the crop on a camera boom 4 meter (10 feet) above the ground (Figure 2). The field-of-view (FOV) of each camera covered a 2.44-m by 3.05-m area with the longer side perpendicular to the crop rows. The machine vision system has a resolution of 640 by 480 pixel for each camera. There for, each pixel in the image represents an area smaller than 0.005 m by 0.005 m on the ground. A dual processor (Pentium 300 MHz CPU) portable computer was used as the main image-processing computer. A high speed CX-100 frame grabber (ImageNation, Inc., Beaverton OR) was used for field image acquisition.

On a conventional chemical broadcast application sprayer, the nozzle spacing and the boom height chosen mainly depend on the overall spray pattern uniformity requirement. For the new precision sprayer, the sensing system spatial resolution was considered as the major factor in the nozzle spacing selection. For each individual nozzle to be controlled separately, the size of the field-zone which one nozzle covered should be equal to, or slightly larger than the detection zone of the vision system. The height of the boom was adjustable so that the image view area and the spray

overlap could be fine-tuned to crop conditions. Corresponding to the vision system FOV, a 6.1 m (24 ft) wide section on the spraying boom was modified for individual nozzle rate control. Twelve solenoid valves were mounted on this boom section with a uniform 0.51-m (20-in.) interval between them.

Based on the vision system design and the spraying nozzle arrangement on the boom, the spraying area was divided into control zones (management zones). The FOV of one camera (2.44-m by 3.05-m) is split into 24 control zones and each control zone has a dimension of 0.508 m by 0.61 m. The control zone is arranged into four rows in one image FOV area on the ground. Figure 3 shows the geometry relationship between the FOV of a camera and the spraying area in any instant.

Table 1. Physical measurements for the prototype smart sprayer system.

Physical	Value
Image height / width	2.44 m / 3.05 m
Vision system spatial resolution	0.005 m by 0.005 m / pixel
Number of control zone rows / columns	4 / 6
Number of control zones per image	24
Distance between camera and spray boom	3.09 m
Control zone area	0.508 x 0.61 m ²
Sprayer boom width / nozzle spacing	6.1 m / 0.508 m

To relate the FOV of camera to spraying area, a nozzle controller is used. The nozzle controller was built around a V-25-based (NEC Electronics Inc, Mountain View, CA) embedded micro-controller. This controller received the commands from the main computer and a square-wave pulse train proportional to the ground speed of the vehicle from the ground speed sensing radar. To turn the nozzles on and off, Synchro (Capstan Ag Systems, Topeka, KS) solenoid valves were mounted on the check valve ports of standard nozzle bodies on the spray boom, and the nozzle controller directed a 12 VDC signal to the solenoid valves through solid state relays (Potter & Brumfield Model Number ODC-15, Totowa, NJ). A ground speed radar gun (Dickey-John Model No. 45640-1910, Auburn, IL) was used to measure the distance traveled. This device produced approximately 98 pulses per traveled meter (30 pulses per foot).

The nozzle controller was connected to the main computer by three links. First, a trigger line was used by the nozzle controller to command the main computer to take an image. This trigger line was connected directly to a trigger input line on the frame grabber. After initialization or processing of the prior image, the frame grabber was commanded to wait for a trigger. After the trigger was received, a time delay occurs as the frame grabber cannot grab the image until the start of the next image field. Immediately after the image was acquired, a strobe signal was sent back to the nozzle controller on the strobe line, the second link between the two computers. This strobe signal was also produced by a frame grabber digital output line. The third link was a RS-232 serial communication line which allowed the main computer to send individual nozzle commands after the completion of processing for a control zone row. The nozzle commands directed the nozzle controller to turn individual nozzles on or off.

Image Processing System

The image processing software was developed using Microsoft Visual C and the Windows application program interface (API) to create a graphical user interface which made possible a graphical display of the image processing results and ease in changing the software settings. Image

was first segmented with an environmentally adaptive segmentation algorithm (EASA, Tian and Slaughter, 1997). The EASA specifies the boundaries of a region in HSI color space which corresponded to the color of the objects in the outdoor scene through an interactive calibration window. Several variations of EASA program have been developed and tested with this machine vision system; the relative reliable RDC-EASA has been selected for the final system (Steward and Tian, 1999). To separate weeds from crop plants, additional information such as field location (different zones), crop row spacing, crop plant size (age), etc. was used in the image-processing algorithm. The crop rows were identified and the inter-row area was used for weed infestation condition measurement. The hypothesis here is that weed patches are normally distributed across the inter-row and crop row area and the weed density is similar in a relatively near neighborhood (say within one meter). So, the inter-row area weed density can be used to estimate the weed infestation condition in the crop row between plants. After all, we can only control and direct herbicide into unified grids (20 in by 20 in). To increase the image processing speed, several real-time weed density and weed leaf number extraction algorithms have been developed (Steward and Tian, 1999).

Decision-making algorithm

The concept of economic chemical application threshold level was the theoretical foundation for the decision on variable rate weed control. It is known that a crop can tolerate a certain pest level without a reduction in yield or quality (Barritt and Witt, 1987). Therefore, costly (in terms of money and energy) practices need not be employed in all cases when pests are present. One concern of using the threshold level concept is that new seed will be added to the soil each year, since some weeds reach maturity. However, this should not be of major concern with many of the most common weed species because attempts at eradicating weed seed from the soil through weeds control in a field have failed, as evidenced by the percentage of acres treated with herbicides (Barritt and Witt, 1987). In addition, multiple-level thresholds could be realized with the continuous weed density information.

In our decision-making algorithm, a four-level application-rate scheme was selected. Because of the vision system has a limitation of 0.005 m by 0.005 m per pixel, a 10% label rate was selected as the base-rate. This design will eliminate the possibility of over look the infestation areas composed mainly of new germinated weed. Based on the sensed weed infestation conditions, other three levels of chemical dosage were assigned -- 33%, 66%, and 100% of full application rate (from label). The economic chemical application threshold was considered in the calculation of the application rate in the simulation test since information about weed numbers in unit area and average weed size (age) could be used to make the decision to skip some low weed density control zones or to decide between multiple application rates for different weed infestation levels.

Main system control program

The main system control program loop started with the program waiting to receive a trigger signal from the nozzle controller (Figure 3). When a trigger was received, an image field was acquired and the nozzle controller was strobe. The program then started processing the control zone rows starting with the first row (closest to the spray boom). The image-processing algorithm calculates the weed density and weed size of each control zone. Based on image processing results, one of four specific dosages was assigned the corresponding control zone. Then the encoded nozzle command was set for the nozzle controller to adjust corresponding nozzle to a certain duty-cycle (Gopalapalai, et al., 1999). When the entire control zone row was processed, the two byte long encoded nozzle control commands were sent for that control zone row. Processing continued row by row until all the rows were processed. Finally, the program returned to the beginning to wait for the trigger.

On the nozzle controller side, the nozzle control command is received and decoded first. When the distance sensor measured the right distance the nozzles are set to corresponding application

rate. The controller is then counting the distance sensor pulses and waiting for next right distance to arrive.

3. FIELD EXPERIMENTS

Field experiments were conducted in 1999 and 2000 in large plots to evaluate the machine-vision controlled precision sprayer. Experiments were carried out at multiple fields, and under normal Illinois commercial farming conditions without pre-emergence herbicide. Three fields having contrasting soil types and weed species infestation were selected. The fields were located at the Agricultural Engineering Research Farm, Urbana, IL. The corn and soybean plots selected for this study contained crop plants which ranged in developmental age from 4 to 9 weeks. Secondary tillage, just prior to planting, removed any early weed plants, so that weeds in the plots were about the same age as the crop plants. No pre-emergence herbicide was applied to the test plots. The precision sprayer traveled at 3.2 to 18 km/h (2 to 11 mph) during the experiment.

Special check plots were prepared for the system calibration. A 3.05 m by 6 m area was weeded manually to create different levels of weed infestation and bare soil zones. The sprayer was driven very slowly and parked at different positions to check the response (spraying water on the weed infestation zone) and to adjust the camera and algorithm parameters to fine-tune the system. To assess system capacity, the sprayer was driven at different speed to test the system response.

The delivery accuracy test was carried out on artificial targets. Opaque white plastic sheeting was placed over the test area as background. The plastic was used so that a visible and measurable spray deposition pattern would result when dyed water was sprayed. Ten 0.19 m by 0.19 (7.5 in.) square yellow-colored paper targets were placed randomly on the plastic covered area. The threshold for turning on a nozzle over a control zone was set so that one fourth of the object being in any one control zone would turn on the nozzle with a factor of safety to allow for segmented object pixel loss. The distances from the start of the first full pattern on the plastic to the start or end of each of the subsequent spray patterns were measured. From these measurements, the lengths of the individual patterns could be determined. A randomized complete block experimental design was used with four replications of the three speed levels.

For chemical saving experiment, both ground truth about weed infestation and remote sensing weed infestation area data were collected at the same time when the sprayer field experiment was carried out. The amount of chemical consumption was recorded for both conventional and precision chemical application. The conventional chemical comparison test was carried out on the same sprayer. Since the smart sprayer only used portion of the boom in one side of the sprayer, the remain part of the spraying boom was set up to simulate conventional uniform rate application. The chemical input from "smart spray" portion is recorded as a map (amount vs. GPS location) and conventional spray chemical input is then equal to the total amount minus smart spray amount. Weed distributions data from the weed map were plotted and analyzed with respect to these control zones (sampling grids). Weed-free or weed-infestation areas at different threshold levels were calculated. The result of this analysis demonstrated how different weed control methods affect sprayer's performance.

4. RESULTS AND DISCUSSION

The data collected belong three categories: (1) system capacity test, (2) delivery accuracy test, and (3) chemical saving test. In the system capacity test, the maximum travel speed of the sprayer was measured. Table 4 showed the image processing time and the sprayer travel speed. With current system design, the sprayer can travel up to 15 km/h. The spray pattern lengths produced while the main computer was operating in the test mode were approximately normally distributed with a mean of 0.605 m (1.98 ft) and a standard deviation of 0.0487 m (0.160 ft). The analysis of variance F-test revealed no statistical evidence that the length of the pattern was dependent on speed. This revealed that the system was measuring speed accurately and initiating the control according to the 0.610 m (2 ft) control zone specification. Errors caused by the introduction of distance delay by the video timing were negligible (Table 2).

The overall hit accuracy of the system was 91% (Table 3). Two types of errors were observed. In five cases, no spray pattern was observed anywhere in the vicinity of the target suggesting that the target was not correctly segmented as a target by the main computer. This could be due to specula reflections of the plastic bag covering the target or orientation of the target relative to the camera. In the remaining cases of missed targets, there was a spray pattern near the target, but the spray did not hit the target. The hit accuracy was 96% for the lowest speed level. The hit accuracy decreased with increasing speed with 90% for the middle speed level and 86% for the highest speed level. From the Chi-squared test, however, there was no statistical evidence to reject the hypothesis that the hit accuracy of the system was independent of speed.

Table 2. Mean length measurements from field tests of the sprayer.

Speed Level (Km/h)	Pattern Length Test Mode (m)	Distance Fore (m)	Distance Aft (m)	Distance Left (m)	Distance Right (m)	Pattern Length (m)	Pattern Width (m)
3.2 to 3.9	0.601 ^a (0.070) ^{**}	0.478a (0.241)	0.332a (0.209)	0.285a (0.133)	0.275a (0.154)	0.810a (0.270)	0.560a (0.190)
6.9 to 8.7	0.605a (0.037)	0.580a (0.206)	0.163b (0.212)	0.284a (0.153)	0.256a (0.167)	0.743a (0.235)	0.540a (0.199)
11 to 14	0.608a (0.031)	0.573a (0.215)	0.212b (0.231)	0.239a (0.134)	0.253a (0.149)	0.794a (0.295)	0.492a (0.197)

* Letters indicate Duncan's multiple range test group at the 0.01 significance level.

** Values in parenthesis are standard deviations.

Table 3. Hit accuracy by speed level.

Speed Level (km/h)	Number of Targets Not Hit	Number of Targets Hit	Total Number of Targets	Accuracy (%)
3.2 to 3.9	2	48	50	96
6.9 to 8.7	5	45	50	90
11 to 14	7	43	50	86
Totals	14	136	150	91

The distance from the center of the target to the position where the spray pattern started – the aft distance – was distributed with a mean of 0.235 m (9.27 in.) and a standard deviation of 0.227 m (8.95 in.). The distance from the center of the target to the position where the spray pattern stopped – fore distance – followed a similar distribution with a mean of 0.5435 m (21.4 in.) and a standard deviation of 0.225 m (8.84 in.). The large standard deviation was expected as the target could occur anywhere within the 0.610 m (2 ft) control zone row length and trigger the controller to spray for that control zone. The fore distance was larger than the aft distance as the spray pattern tended to move forward in the direction of travel relative to the target at the higher speed levels. There were statistical differences in the aft distance based on the results of the analysis of variance F-test ($P = 0.0006$) over speed levels. Similarly, the fore distance was significantly different across speed levels ($P = 0.0423$).

The results from running the main computer in the test mode showed that distance was being measured accurately. Therefore, the observed delay in where the spray was applied relative to the target was introduced by some mechanical lag in the system. The most likely source of this delay was the time required to pressurize the hose drops and the time for the spray to travel from the nozzle to the ground surface. The distances from the center of the target to the left and right edges of the spray patterns were both distributed with means of 0.270 m (10.6 in.) and 0.261 m (10.3 in.) and standard

deviations of 0.141 m (5.56 in.) and 0.156 m (6.13 in.) respectively. There was no statistical evidence to reject the hypothesis that these two distance measurements were independent of speed.

Each spray pattern length was calculated by summing the measurements of the aft and fore distances. The distribution of length was bimodal with one mode centered at approximately 0.60 m (24 in.) and the other around 1.2 m (48 in.). Similarly, when the left and right distances from the target center to the pattern edges were summed as a measure of the pattern width, a bimodal distribution resulted with one mode center at approximately 0.425 m (17 in.) and the other at 0.85 m (33 in.). These distributions were expected because when the target was on the boundary of two or three control zones and more than 100 pixels were segmented as object within any of these control zones, the main computer would signal the controller to spray in each of those control zones. Thus the length and width of the spray pattern could correspond to that of one or two control zones. In a few cases, the spray pattern was observed to cover three control zones by sensing one target. There was no statistical evidence of the pattern width and length being dependent on the speed level.

Based on the weed detection from the images in this randomly sampled data set, the weed distributions were best approximated by the negative binomial, which were coincident with some other weed distribution researches (Cardina, et al., 1997). Figure 4 depicted the weed density frequency in the experiment field. In the experiment field, more than 80 percent of the control zones had less than 20 percent weed coverage.

This work showed that selective and variable-rate herbicide application methods had advantages over uniform application method. The variable rate method had greater advantages when the weed density variation was high. In Table 4, proposed variable application rate is listed. Potential herbicide savings from comparing on/off and variable rate applications with uniform application are illustrated in Table 5, where single (economical) threshold for on/off application was set at weed density of 1% and variable rate was set to four levels as in Table 4.

Table 4. Proposed variable application rate (VAR)

Weed density (%)	0-1	1-2	2-10	>10
Application rate (%)	10	33	66	100

Table 5. Herbicide saving over uniform application method.

	High weed density plot (STD*=0.18)	Low weed density plot (STD=0.05)
Single threshold method	6%	52%
Variable rate method	18%	71%
Ratio of VR/ST	3	1.36

* Standard deviation of weed density

Figure 5 showed the chemical application map which is also the weed infestation area distribution map. Figure 6 showed an example of the correlation between weed maps and processed aerial image data. Figure 7 is the color near infrared image of the treated field. The correlation between the aerial image and the weed map generated with smart sprayer showed that this sensor-based real-time system can also be used for high-accuracy field variability mapping.

5. SUMMARY AND CONCLUSIONS

An automatic sprayer controlled by a real-time machine-vision system was developed and tested. The prototype system was designed with an optimization strategy of balancing the practical need for accuracy in field operations and the requirement for a real-time system. A low-cost microcontroller in conjunction with a PC running on a multitasking operating system were combined

together for selectively spraying objects which were sensed in real-time. The PC provided a standard interface between a video camera and a digital computer; a high-level programming environment while the microcontroller provided an interface with the system to respond to real-time events.

This type of hybrid system provides a low-cost alternative for the development of real-time machine vision applications without the development overhead of a customized real-time system. This approach could be used for a variety of precision farming applications where system events need to be synchronized with the location of stationary objects in acquired images relative to a moving sensing and control platform. Machine vision-guided cultivation and harvesting are two examples of such applications in addition to the application of herbicide as discussed here.

Instead of using high spatial resolution images and individual plant recognition, low-resolution (large view area) images were used. Real-time image processing algorithms, the coverage density employed to detect weed infestation zones. The zone size was designed to match the prevailing post-emergence sprayer boom standard.

General specifications for when system events should occur based on the physical configuration of the system were developed and could provide easy adaptation of these techniques to other applications and system configurations. The test results demonstrated that the system operated with a 91% overall accuracy. A system time lag was discovered through field tests which were most noticeable at higher travel speeds.

The precision chemical application embraces the concept of creating a balanced crop-weed ecosystem in the field with lowest cost and minimum environmental impact. With the availability of such a precision sprayer, new questions are generated which require an interdisciplinary effort to find answers. Further research and experimentation are needed to determine the optimal chemical input amount for different crop/weed coverage, control zone size, and timing combinations. The knowledge of agricultural engineers, agricultural economists, weed scientists, and agrochemical experts must be brought together in order to develop the high performance expert system required for a precision sprayer. When fully developed and available, the precision sprayer will be a great benefit in increasing agricultural profitability and to society by reducing environmental damage.

6. ACKNOWLEDGEMENTS

This research has been supported by the Illinois Council of Food and Agricultural Research (C-FAR), Project Number 97I-124-3; and the Research Board of the University of Illinois.

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Fig. 1- the Smart sprayer concept

Fig. 2- Smart sprayer prototype system set up. Camera 1 is for vision system calibration, camera 2 and 3 are the cameras for real-time applications.

Fig. 3a – System set up (top view)

Fig 4 – Example of weed density distribution in the field

Fig. 5 – Positions of camera field of view related to the sprayer boom and individual control zones. This relative position set up decided the system control event sequence in the time domain.

Figure 5- High resolution weed map (400 mm/pixel) generated with ground truth machine (dark points represent high weed density) overlaid on top of soil type map.

Figure 6- Weed density predicted from RS image (Fig 4) using Artificial Neural Network vs. actual ground truth weed density (Fig 1).

Figure 7a- Example original color near-infrared image of a test plot at a resolution of 1 meter per pixel (Soybean field, 7-23-1998).

Figure 7b- Image taken on the same day with higher spatial resolution aerial imaging system (300 mm/pixel).