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AUTOMATIC WEED CONTROL SYSTEM FOR PROCESSING TOMATOES

D.C. SLAUGHTER¹, M. PÉREZ², C. GLIEVER¹, S.K. UPADHYAYA¹,
H. SUN¹

¹ D.C. Slaughter, Department of Biological and Agricultural Engineering, University of California, Davis, United States, dcslaughter@ucdavis.edu

¹ C. Gliever, cjgliever@ucdavis.edu

¹ S.K. Upadhyaya, skupadhyaya@ucdavis.edu

¹ H. Sun, haosun@ucdavis.edu

² M. Pérez, Dpto. de Ingeniería Aeroespacial y Mecánica de Fluidos, Universidad de Sevilla. Área de Ingeniería Agroforestal

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ABSTRACT This study describes a fully automatic system developed at UC Davis for intra-row mechanical weed control for processing tomatoes in California. We developed a novel weed control system using a real-time kinematics (RTK) global positioning system (GPS) to automatically control the path of a pair of weed knives based upon an automatically generated GPS plant map. The system was capable of precisely guiding mechanical weed knives within the seedline of the crop row and around the crop plants as the system was pulled along the row. In this study, processing tomato plants were transplanted using a GPS-enabled transplanter, which developed a precision plant map documenting the geo-spatial location of each tomato plant. At the time of first cultivation, a few weeks after planting, the GPS-controlled weed knives were operated in seven tomato rows. The weed knives were set to "open" 6 cm prior to reaching, and "close" 6 cm after passing each tomato plant, killing weeds between tomato plants when the knives were in the closed position. Results show that the average distance between knife opening and closing events was 12.4 cm with a standard deviation of 1.4 cm. The standard deviation of the opening and closing positions (relative to the crop plant) was 2.08 and 2.11 cm, respectively. These results demonstrate the feasibility of using RTK-GPS to automatically control a mechanical weed control system for sustainable production of row crops.

Keywords: Weed Control, Automation, Precision Agriculture, GPS.

INTRODUCTION Weed control, specifically the development of an automatic machine for the non-chemical control of weed plants within the crop row, remains one of the biggest challenges to agricultural row crop production today. There continues to be an ever increasing interest in the use of mechanical intra-row weeding machines because of concerns over environmental degradation associated with pesticides and a growing demand for organically produced food (Tillett et al, 2008; Norremark et al, 2008; Kurstjens 2007; Dedousis et al, 2007; Astrand and Baereldt, 2001).

Nowadays, mechanical weeding is mostly used for traditional inter-row cultivation. In relation to the crop, three weeding zones are identified: inter-row, intra-row and close-to-crop (Blackmore, 2004). While hand weeding can be substantially reduced through the use of inter-row cultivation, but weeds growing intra-row are uncontrolled by this method as are the highly competitive weeds in the close-to-crop zone (Melander, 1997; Tillett et al, 2002). Much research effort is being put into the development of intra-row weeding to remove or destroy the weeds within the row without causing excessive crop damage (Gobor and Schulze, 2007; Tillett et al, 2008). However, for the majority of farms, the close-to-crop zone, i.e. within 3 to 4 cm of the crop, is presently handled by manual weeding (Griepentrog and Sogaard, 2003).

Several researchers have been working to develop automatic systems to detect separated plants from the background and to determine different weed species for optimizing and simplifying agricultural work, or for creating weed maps (Pedersen 2001; Søggaard 2005). Guidance and weed detection systems have been developed mainly to make more effective use of pesticides, either for band spraying along a crop row or detecting individual weed or crop plants for treatment (Marchant et al., 1997; Miller et al., 1997; Thompson et al., 1991; Kouwenhoven, 1997; Tillett et al., 1998; Tian et al., 1997).

A seed map or crop map may be a good alternative to use in removing the intra-row weed (Griepentrog et al. 2003). Ehsani et al. (2004) retrofitted a Salvo 650 four-row vacuum planter with a centimeter-accuracy GPS unit and mapped seeds were within average 3.4 cm of a germinated plant. Griepentrog et al. (2007) devised a continuously rotating ring of rigid steel tines that are moved individually to avoid crop plant. This experimental machine relied on RTK (real-time kinetics) GPS to locate the prerecorded position of individual plants and to guide the mechanism. Auto-guidance systems can be used to cultivate or spray very close to the plant line (about 5 cm) at very high ground speed (up to 11 kph) and chisel or subsoil a field very close to buried drip tapes without damaging them (Abidine et al., 2002). The use of GPS for weeding operations require a separate positioning control system operating independently from tractor's autoguidance system. Due to the asynchronous nature of the different tasks the automated weeder and the tractor need to be positioned independently (Griepentrog et al, 2004). The aim of this project was to investigate the accuracy and limitations for an automated knife-based weeding system with knife control based on an RTK-GPS geoposition system and GPS map for individual crop plants.

MATERIALS & METHODS An automatic intra-row weeding machine was developed using a mechanical weed knife system similar to that developed by Eversman (Kepner et al., 1978) but modified for precision intra-row weed control and RTK GPS actuation. The system consisted of a pair of pneumatically actuated weed knives that could be positioned at the row centerline in a "closed" side-by-side configuration where all weeds in the central 10 cm intra-row region were cut. As the knives approached each close-to-crop zone, the knives were propelled apart, at a high velocity in the direction transverse to the crop row, to an "open" position that prevented damage to the crop plant. Once past the close-to-crop zone, the knives were returned to the closed position to continue intra-row weed control. Knife actuation was achieved using a pair of pneumatic cylinders attached between the cultivation sled and the knife arms. Knife motion was controlled by

an electronically actuated solenoid valve that provided air pressure (0.7 MPa) to the pneumatic cylinders. The weed knife system was mounted in a tractor-drawn cultivation sled (SWEMEC Woodland, CA).

A real-time kinematics global positioning system (RTK GPS) was used to control weed knife actuation based upon a GPS planting map. The RTK-GPS system used was similar to that described in Sun et al. (2010) and consisted of a rover RTK GPS with the GPS antenna mounted 3 m above soil surface to maximize access to high quality satellite geometries and minimize GPS multipath error. A dual-axis inclinometer was mounted below the GPS antenna to provide ground level offset correction of GPS data due to tilting of the cultivation sled. The GPS rover communicated with a local GPS base station to acquire the GPS correction signal required for RTK Fixed quality location information. A GPS clock reference pulse (called PPS for pulse per second), was produced by the GPS receiver for precise synchronization of the RTK Fixed quality geoposition data with weed knife actuation events. The GPS was programmed to output the “NMEA-0183 PTNL, PJK” string containing the UTM coordinates (Easting and Northing) at 1 Hz via an RS-232 serial connection. GPS location was augmented with ground-wheel odometry using an incremental optical shaft encoder interfaced to an unpowered ground wheel.

A ruggedized, real-time, embedded controller (cRIO-9004, National Instruments, Austin, TX, USA) was used for weed knife control. The controller was interfaced to a field programmable gate array (FPGA; cRIO-9104, National Instruments, Austin, TX, USA) with 3 million reconfigurable logic gates. FPGA I/O modules for high-speed pulse detection/counting, TTL digital and RS-232 serial data were utilized for odometry, solenoid control, and GPS data transfer, respectively. The optical encoder signal for odometry was input to a real-time counter in the FPGA. This real-time odometry localization information, was needed for inter-GPS interpolation needed between the 1 HZ GPS data location updates for real-time asynchronous knife actuation that was based upon the GPS planting map. All software for the embedded controller was written in LabVIEW™ (National Instruments, Austin, TX, USA). At run time, the graphical LabVIEW code was automatically translated into text-based VHDL code, which was then compiled into a hardware circuit realization and used to reconfigure the FPGA logic.

Field tests were conducted at the Western Center for Agricultural Equipment (WCAE), on the University of California, Davis campus (Latitude: 38.53894946 N, Longitude: 121.7751468 W) using processing tomato transplants as the target row crop. In this study, seven rows were planted (single crop row/bed, 1.5 m bed spacing) with the GPS mapping transplanter described by Sun et al. (2010). The field layout was such that the rows were predominantly in the East-West direction. All the rows were planted at a constant travel speed of 1.6 km/h. All seedbed preparation operations, planting and automatic intra-row weeding trials were conducted with a tractor steered by RTK GPS autoguidance using a common set of GPS AB line coordinates for all tillage, planting and cultivation operations.

At the start of the automatic intra-row weeding trial, the GPS crop plant localization map was uploaded into the memory of the embedded controller. At the beginning of each row, the digital GPS plant map was accessed and searched to find the closest plant. The direction of heading was then determined based on comparing the first and last plants in

the map of the row containing this plant to the current GPS location of the implement. If the current GPS location of the implement was determined to be closer to the last plant location in the array, then the map array would be reversed so that the map sequence matched the weeding operational travel plan. An FPGA program was set up to monitor the GPS PPS pulse and read the subsequent PJK string.

During automatic intra-row weeding operations, a real-time control loop in the FPGA logic was used to compare the implement's odometry localization value (i.e., the instantaneous implement location in the local coordinate system of the current row) to the "open knives" command localization value for the closest upcoming plant in the row. The "open knives" localization value would be determined by subtracting the distance in meters selected by the human operator corresponding to the desired radius (in meters) of the close-to-crop zone from the planting map location for the upcoming plant. Similarly the "close knives" localization value would be calculated by adding the desired radius to the plant's map location. The close-to-crop zone is a region in which no automatic intra-row weed control is conducted due to concerns about damage to the crop plant's root system. The size of the close-to-crop radius value was affected by the error in the RTK GPS geoposition (nominally a standard deviation of 2.5 cm). In addition to the nearest upcoming plant's knife "open" and "close" locations, the "open" and "close" values of the next two adjacent crop plants are also made available in the control loop. This look-ahead feature was utilized when intra-row weeding was needed between multiple crop plants in less than the 1 Hz GPS update frequency. The three sets of open and close values would be updated each time a new GPS string arrives.

During automatic intra-row weeding, the FPGA continuously compares the current odometry localization (i.e., the instantaneous implement location in the local coordinate system of the current row) to the "open knives" and "close knives" localization values. When the open value is reached, the FPGA would signal the pneumatic valve to open the knives. Once the closed value is reached, the FPGA would close the pneumatic knives. Upon closing, the current plant number corresponding to the set of open and close values would increment and the program would know that the knives just passed a plant and the next plant in the plant map should be examined.

A digital video camera was mounted directly above the weeding knives to record the entire set of open and close sequences for each row during each intra-row trial. At the beginning of each row, a standard scale was placed on the soil surface to give a length reference for calibration. This video sequence was used to determine how far before the plant the knives opened and how far after the plant the knives closed. Video software (Premier, Adobe Inc., San Jose, CA) was used to view the sequence of frames captured by the video camera. The frame at the instance the knives opened and the frame at the instance the knives closed would be exported into digital image files. The distance between the knives and the plant at the time the knives opened and the distance between the plant and the knives at the time the knives closed were determined using image analysis software (ImageJ, NIH. 2009).

RESULTS An automatic intra-row weeding machine which utilized GPS crop plant map to determine the geospatial position of each tomato plant in the field was successfully developed and operated in a processing tomato field in California. The system was specifically designed to control intra-row weeds, i.e. those in the center of the row, but

outside of the close-to-crop zones where mechanical weed control in close proximity to the crop plant may cause root damage to the crop (Blackmore, 2004). Figure 1 shows an illustration of the three weed control zones: region A is the inter-row zone, region B is the intra-row zone, and region C is the close-to-crop zone. In our design, a pair of weed knives is used to control weeds in the intra-row zone. On the left side of figure 1, the weed knives are shown in the “closed” position with the two knives side-by-side in the intra-row zone. As the knives approach the tomato plant in the center, they separate, following the purple dashed lines in the ideal case. This leaves the close-to-crop zone C unweeded. As the knives pass the tomato plant, they again follow the purple dashed lines, in the ideal case until they meet in the center of the row. This process is repeated for each tomato plant.

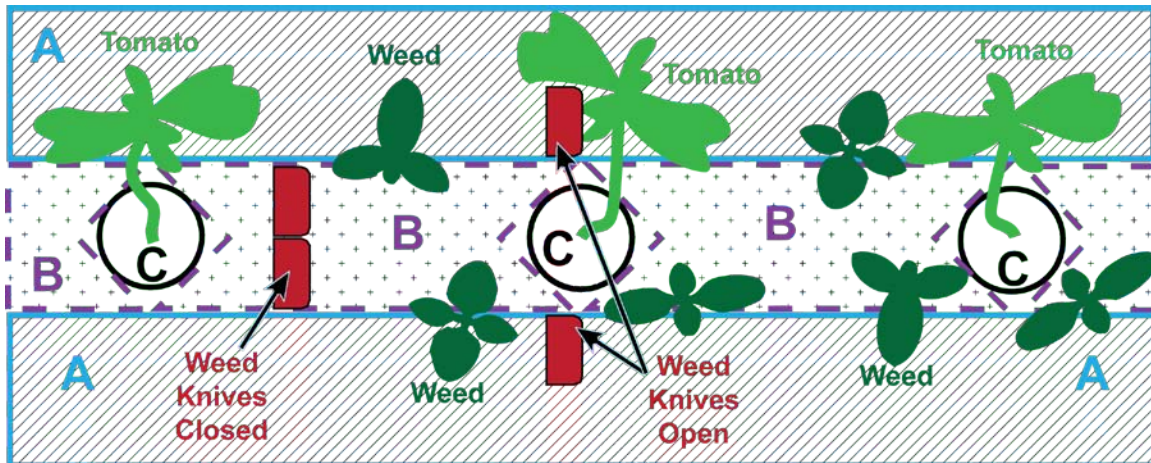


Figure 1. Illustration showing the three weeding zones: A=inter-row (blue with gray diagonal hatching), B=intra-row (purple dashes with + symbols), and C=close-to-crop (black circles) and the ideal path of the weed knives (red rectangles).

The results of the field trial, where the automatic intra-row system was operated in seven crop rows, are shown in Table 1. The total size of the close-to-crop zone was 12.39 cm on average for the seven rows. Ideally this would represent the diameter of the circles labeled C in figure 1. However, with the on/off style solenoid valve used in this design, the knives follow a straight-line path (assuming constant knife opening and tractor velocities) represented by the purple dashed lines in figure 1. In order to achieve a circular close-to-crop zone, a more complex closed-loop knife position control system would be required. The difference in uncultivated area between the current diamond shaped zone and the ideal circularly shaped zone may not justify the increased complexity of the design. The standard deviation for the total size of the close-to-crop zone was 1.35 cm on average or about 11% of the mean. These results show that the precision of the system in maintaining a consistent close-to-crop zone size was quite good. The size of the close to crop zone is mainly a function of the odometry system since the GPS geoposition data is only used to initiate the knife opening and the closing event is dictated by odometry. The precision of the ground-driven pneumatic encoder wheel-based odometry observed in this study is consistent with the precision observed by Lee et al. (1999) for odometry in a precision spray application that was similar in scale and was also conducted in a processing tomato field.

Table 1. Precision and Accuracy for Automatic Intra-Row Weed Control.

Row	Average Knife Distances			Standard Deviation		
	Open (cm)	Close (cm)	Total (cm)	Open (cm)	Close (cm)	Total (cm)
1	6.14	5.09	12.05	1.84	1.90	1.21
2	4.85	5.97	10.82	2.87	2.47	1.84
3	4.68	7.98	12.67	2.08	1.87	1.04
4	3.80	8.97	12.78	2.09	2.08	1.10
5	3.73	9.07	12.80	1.94	1.72	0.96
6	3.99	9.45	13.44	1.64	1.77	1.09
7	3.33	8.83	12.16	2.09	2.93	2.23
All	4.36	7.91	12.39	2.08	2.11	1.35

The average knife opening and closing distances shown in Table 1 represent the performance of the system in its ability to center the actual unweeded zone, represented by the purple dashed diamond-shaped regions in figure 1, about the tomato plant. Ideally, the actual close-to-crop zone C would be centered inside the true unweeded diamond-shaped zone. In practice, this condition was best achieved in crop row 1 of the weeding trial, where the center of the unweeded zone was shifted, on average, 1.05 cm from the soil entry point of the tomato main stem and in the opposite direction from the direction of travel. However, in subsequent crop rows, a systematic shift of about 2 cm on average in the knife opening location in the direction of travel, relative to the position in row 1 was observed. This shift was believed to have occurred due to an overcompensation by the operator during the trial in an attempt to correct the offset observed in row 1. The small declining trend in knife opening distance shown in rows 2 through 7 was believed to have occurred due to the use of a static odometry encoder count to meters conversion factor used in the calculation of the encoder count for the knife opening event. Changes in the compressibility of the soil from row to row due to differences in soil moisture can lead to changes in the number of encoder counts per meter in the odometry value from the unpowered ground wheel. This trend is consistent with the sprinkle irrigation method used in the trial, which resulted in a soil moisture gradient from rows 1 to 7. Overall, the mean offset error in centering the unweeded zone about the tomato plant stem was superior to the results (3 to 3.8 cm error) obtained by Ehsani et al. (2004) in RTK GPS mapping of direct-seeded corn.

The precision of the knife opening and knife closing locations within each row are represented by the standard deviation values shown in Table 1. These results show that the system was quite precise and that the level of precision was fairly uniform across all rows in its ability to open and close the knives about the ideal locations selected by the operator. On average the standard deviations in the knife opening positions and knife closing positions were similar, at about 2 cm. A 2 cm standard deviation in dynamic GPS-based position control is consistent with the expected level of precision for dynamic RTK-GPS measurements and control for a mobile platform, where averaging of GPS measurements is not feasible. It is important to remember that these knife actuation control points are based upon two GPS measurement events, the first one occurred at planting, and the second at weeding. Nørremark et al. (2003) reported a 24-h RTK GPS static trial RMS error of 0.95 cm. The precision of the system was similar in magnitude to that observed by Sun et al. (2010), Nørremark et al. (2007) in GPS transplant and seed

mapping trials, indicating confirming that the performance is consistent with the current level of mobile RTK-GPS system accuracy.

CONCLUSION An automatic intra-row weeding machine, which utilized a GPS crop plant map to determine the geospatial position of each tomato plant in the field, was successfully developed and operated in a processing tomato field in California. The system was specifically designed to control intra-row weeds, i.e. those in the center of the row, but outside of the close-to-crop zones where mechanical weed control in close proximity to the crop plant may cause root damage to the crop. Weed control was achieved through the pneumatic actuation of a pair of mechanical weed knives that could be positioned in the center of the crop row, in between crop plants, for intra-row weed control in real-time. An automatic weed knife control system was developed that monitored the crop plant geospatial locations as the mobile weed control system traversed along the crop row. As the knives approached a crop plant, a pneumatic actuation event was triggered to propel the knives away from the crop row centerline and preventing any damage to the crop plant or the crop roots in the close-to-crop zone.

A weeding trial was conducted in a processing tomato field on the UC Davis campus farm. In this trial, processing tomato plants were transplanted using a GPS-enabled transplanter, which developed a precision plant map documenting the geospatial location of each tomato plant. At the time of first cultivation, a few weeks after planting, the GPS-controlled weed knives were operated in seven tomato rows. The weed knives were set to "open" 6 cm prior to reaching, and "close" 6 cm after passing each tomato plant, killing weeds between tomato plants when the knives were in the closed position. Results show that the average distance between knife opening and closing events was 12.4 cm with a standard deviation of 1.4 cm. The standard deviation of the opening and closing positions (relative to the crop plant) was 2.08 and 2.11 cm, respectively. These results demonstrate the feasibility of using RTK-GPS to automatically control a mechanical weed control system for sustainable production of row crops.

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