BIOSYSTEMS ENGINEERING 110 (2011) 247–252

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Design and testing of an intra-row mechanical weeding machine for corn

C. Cordill [a], T.E. Grift [b,*]

[a] FL Smidth, Spokane, WA, USA

[b] Department of Agricultural and Biological Engineering, University of Illinois, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 10 December 2010
Received in revised form
17 July 2011
Accepted 20 July 2011
Published online 8 September 2011

As an alternative to chemical weed control, mechanical weed control between crop rows can be achieved using standard tools such as field cultivators. This paper addresses the related problem of achieving mechanical intra-row weed control in maize. The object was to non-specifically remove weed plants within the row by enabling dual tine carriers to engage the soil whilst circumventing the maize stalks. The maize stalks were distinguished from the weeds and maize leaves by utilising 1) the typical vertical quasi-cylindrical stalk of the maize plant, 2) the limited range of maize stalk diameters, and 3) by assuming constant plant spacing.

To assess the performance of the machine, a video was taken during field plot experiments. This allowed determination of the number of plants that were "fatally damaged" after inadvertently being pushed over by the implement. This was assumed to cause the plant to die, or "minimally damaged" where the implement merely touched the plant, when the plant was assumed to survive. Experiments were carried out using three arrangements being 1) three rows without weeds, 2) three rows with broadleaf weeds (simulated by planting soybean) and 3) three rows with grassy weeds. The percentage of plants that were fatally damaged was 8.8%, 23.7%, and 23.7% in cases 1, 2, 3 respectively. In addition, the percentage of plants that were minimally damaged was 17.6%, 20%, and 25.9% in cases 1, 2,3 respectively.

1. Introduction

Two recent trends in agriculture have encouraged the development of alternative weed control mechanisms to chemical application: Firstly, several weed species have shown resistance to glyphosate. Despite previous claims that target-site resistance to glyphosate will not occur (Bradshaw, Padgette, Kimball, & Wells, 1997), biotypes of goosegrass (*Eleusineindica*) (Baerson et al., 2002; Lee & Ngim, 2000) and horseweed (*Conyzacanadensis*) (VanGessel, 2001) have been reported with target-site resistance to glyphosate. Rigid ryegrass (*Loliumrigidum*) and Italian ryegrass (*L. multiflorum*) biotypes also have been identified with glyphosate resistance, although in these cases resistance occurred by unknown mechanisms (Powles, Lorraine-Colwill, Dellow & Preston, 1998; Heap, 2011). Also, Palmer amaranth (*Amaranthuspalmeri*) biotypes in Georgia have been identified that demonstrate resistance to glyphosate (Culpepper et al. 2006). As a close relative of waterhemp, Palmer amaranth is considered the most aggressive and competitive member of the pigweed complex. The term glyphosate-resistant now also has been attached to waterhemp.

The second trend is the growth of organic farming. In the US state of Wisconsin, for instance, organic farming has increased more than 90% over the past five years (NASS, 2007).

* Corresponding author.
E-mail addresses: crcordill@gmail.com (C. Cordill), grift@illinois.edu (T.E. Grift).
1537-5110/$ – see front matter
doi:10.1016/j.biosystemseng.2011.07.007

It is therefore important to develop techniques and practices to increase its productivity. In particular, the availability and cost of labour for weed control are limiting its progress, and therefore the development of suitable mechanised weeding methods is an imperative.

In earlier research, Wisserodt et al., (1999) developed a 'cycloid hoe' which consists of rotary disc-mounted tines that could be extended and retracted resulting in a combined cycloidal motion. This ingenious mechanism did however require precise lateral placement of the implement above the row, which was later addressed in research by Nørremark, Griepentrog, Nielsen, and Søgaard (2008). Earlier research by Bontsema, Grift, and Pleijsier (1991) used infrared sensors to identify the location of weeds within a row in sugar beet. One of the challenges in this research was that the weed and sugar beet plants had similar morphological features. In maize the problem is simpler. Maize has a vertically oriented cylindrical stalk of considerable size that can be more easily distinguished from common broadleaf and grassy weeds that grow nearby since they typically do not exhibit this feature. The method, as developed here, is non-weed specific. It is based on determining the location of the maize stalks, whilst considering every other plant in the row as a weed. The challenge now lies in producing a machine that can mechanically remove the weeds between standing plants in the row, whilst causing minimal damage to the crop.

The objective of this research was therefore to develop a system for identifying maize stalk locations, allowing a soil engaging tool to mechanically remove weeds in the row, whilst circumventing the maize plants.

2. Materials and methods

The mechanical weeding machine as developed consisted of three subsystems: stalk sensing, a control algorithm and a mechanical weeding mechanism. These three segments will be discussed along with the experimental methodology.

2.1. *Maize stalk sensing*

The purpose of the sensing arrangement was to determine the location of the maize stalks in the row such that the mechanical weeding mechanism could circumvent them, whilst treating the remaining space between the stalks. The transmitters in the sensing arrangement consisted of four low-cost visible red (640 nm wavelength) laser beams with a diameter of 3.5 mm. They were mounted in a housing made of aluminium at a vertical spacing of 38 mm (Fig. 1). To avoid breaking the optical connection between transmitters and receivers, caused by vibrations, plano-convex lenses with a diameter of 23.5 mm and a focal length (F.L.) of 32 mm (AX76611, Anchor Optics, Barrington, NJ, USA) were fitted. The dimensions of the lenses dictated the spacings between the laser beams and limited the number of laser beams per housing to four. The receivers consisted of low-cost phototransistors (LPT2023, Ligitek Electro, Tucheng City, Taipei Hsien, Taiwan). The outputs of the phototransistors were pulled high with 100 kΩ resistors, which resulted in an active-low sensing arrangement. The signals were conditioned using Schmitt-Triggers.

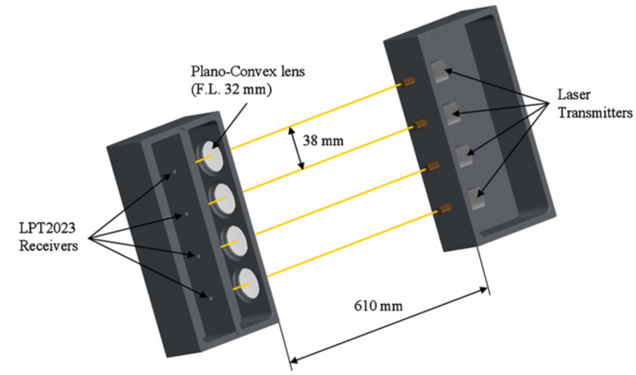

Fig. 1 – Laser transmitter-receiver pair, with four 3.5 mm laser beam transmitters and four LPT2023 receivers. The lenses keep the laser beams optically aligned to the receivers under vibration.

The laser transmitter housing was placed at a distance of 610 mm from the receiver housing to prevent leaves from touching the housings. Both the transmitter and receiver housings were attached to steel tubes allowing extension of the housings up to a height of 450 mm above the soil surface and rotating them through 360° about their vertical axes. To avoid contact, the bottom of the housing was kept at an approximate height of 50 mm above the soil surface, placing the lower laser beam at an approximate height of 70 mm above the soil surface.

To illustrate the initial method of distinguishing maize stalks from other interrupting objects such as leaves and weeds, Fig. 2 shows the interruption of the four laser beams by four maize plants. In the figure, the signals originating from the four sensors are summed at the bottom. It is clear that only in the case of the sensor passing a maize stalk, are all four

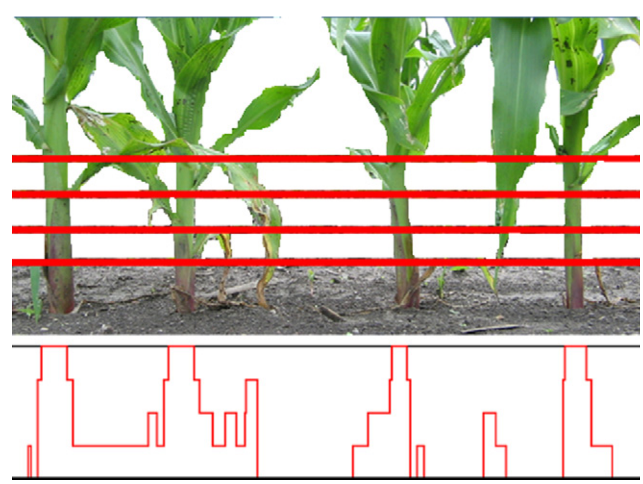

Fig. 2 – Four laser beams as they are interrupted by maize stalks and leaves, generating binary pulses. Shown below are the cumulative pulses. Cumulative pulses reaching level four represent the maize stalks, elucidating a logical AND function being able to distinguish corn stalks from other objects.

laser beams interrupted simultaneously (signals adding up to four), and therefore, a simple logical AND function provided the initial stalk identification mechanism. Therefore, the AND function output that was used to control the weeding arms consisted of binary pulses (logical high where the pulse heights add up to four in Fig. 2, and logical low otherwise) of varying widths, occurring at varying positions along the row.

2.2. Control algorithm

The physical distance between the sensing arrangement and the weeding tines was 600 mm, or four plant spacings. The speed of the machine was limited to 0.1 ms^{-1}, which yielded sufficient time (6 s) for the control algorithm to process the data. Therefore, in this prototype, processing time was not a limiting factor. The control algorithm that determined the location of the corn stalks from the AND filtered signals was implemented in a microcontroller (Propeller, Parallax Inc., Rocklin, CA, USA). The stalk diameters, as well as the spacings among the stalks, were measured using a relative encoder that yielded a resolution of 0.2 mm.

To determine whether a pulse in the signal represented a corn stalk, in addition to the logical AND filter, a WIDTH filter and a DISTANCE filter were applied. The WIDTH filter evaluated whether the pulse widths in the AND filter output signal (expressed in a number of encoder steps), were within pre-set limits. To determine these limits, the machine was operated with 1) maize stalks only, 2) maize stalks with weeds and 3) weeds only. Fig. 3 shows a histogram of the pulse widths (in encoder steps) in these three cases. The histogram of case 1), (maize stalks only, in blue) was Gaussian distributed with a mean of 100 encoder pulses (20 mm). The histogram of case 2, (maize stalks with weeds in red), was Gaussian with an elongated upper-tail. This tail was caused by the weeds (case 3, in green) which had a quasi-Gamma distribution because of the smaller size of their leaves compared to the maize stalks and its leaves.

The DISTANCE filter was used to add another measure to the AND and WIDTH filters, exploiting the fact that maize is planted at relatively constant (150 mm) spacings. Tests on maize-only revealed that the interplant spacings were normally distributed (not shown). The decision whether a pulse represented a maize stalk and if so, what the location of this maize stalk was, was made based on the WIDTH filter that used cut-off points obtained from the distributions shown in Fig. 3 as well as the weighing factor from the DISTANCE filter. The locations of the positively identified maize stalks were passed on to an algorithm that varied the speeds of two electric DC motors that generated sinusoidal motions through a crank mechanism, enabling the weeding tines to circumvent the maize stalks.

2.3. Mechanical weeding mechanism

A typical US Mid-Western Corn Belt in-row maize spacing is 150 mm (6 inches) and this narrow spacing complicates the removal of weeds. To prevent the weeding tines from damaging the maize roots, it was decided that the mechanism should leave a 50 mm diameter circle surrounding the maize stalk base termed the “no-step” zone. This left approximately 100 mm of potentially weed infested area to be treated between the subsequent maize stalks. Since row cultivators can be used effectively to remove weeds in the area between the rows, the tillage area was defined as reaching 50 mm at either side of the row centreline. Since the weeding implement must be pulled parallel to the rows for the sensing mechanism to work, a motion perpendicular to the row was considered to be the most efficient. A crank mechanism, which changes a rotational motion into a quasi-sinusoidal motion, was used for this purpose. Fig. 4 shows the theoretical path of the implements in an ideal situation, with maize plants spaced 150 mm apart. The red circles represent the no-step zones around the plants and, as shown in Fig. 4, by overlapping two quasi-sinusoidal motions, weeding took place while excluding the no-step zones. However, creating the paths as shown required both lateral and longitudinal position control of the tines, since firstly, the spacing among the plants

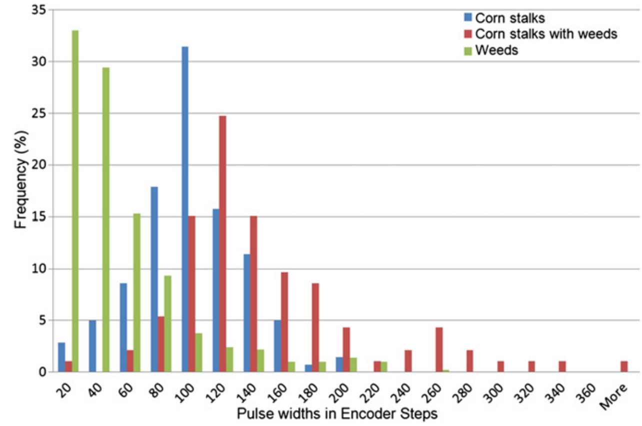

Fig. 3 – Histogram of the widths of pulses in encoder steps, where each step represents 0.2 mm. The blue distribution represents only maize stalks which have a Gaussian distribution with a mean of 100 pulses (20 mm). The weed distribution in green resembles a Gamma distribution. The combination of maize stalks and weeds (in red) resulted in a Gaussian distribution with an elongated upper-tail.

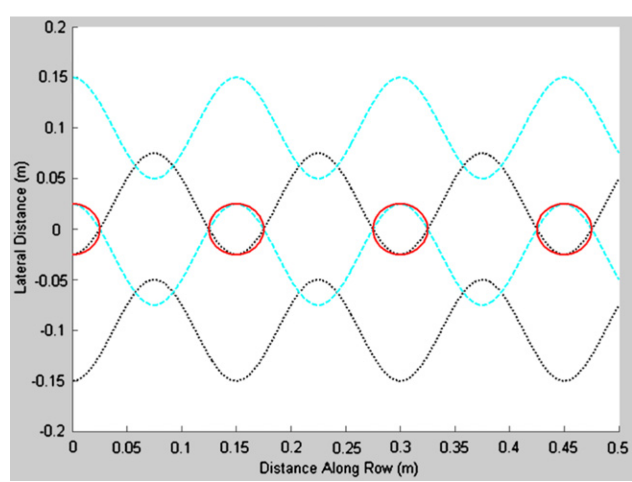

Fig. 4 – Design path of weeding mechanism when all maize plants are equally spaced at 150 mm. The red circles represent the “no step” region, while the sine waves represent the paths of the two end effectors.

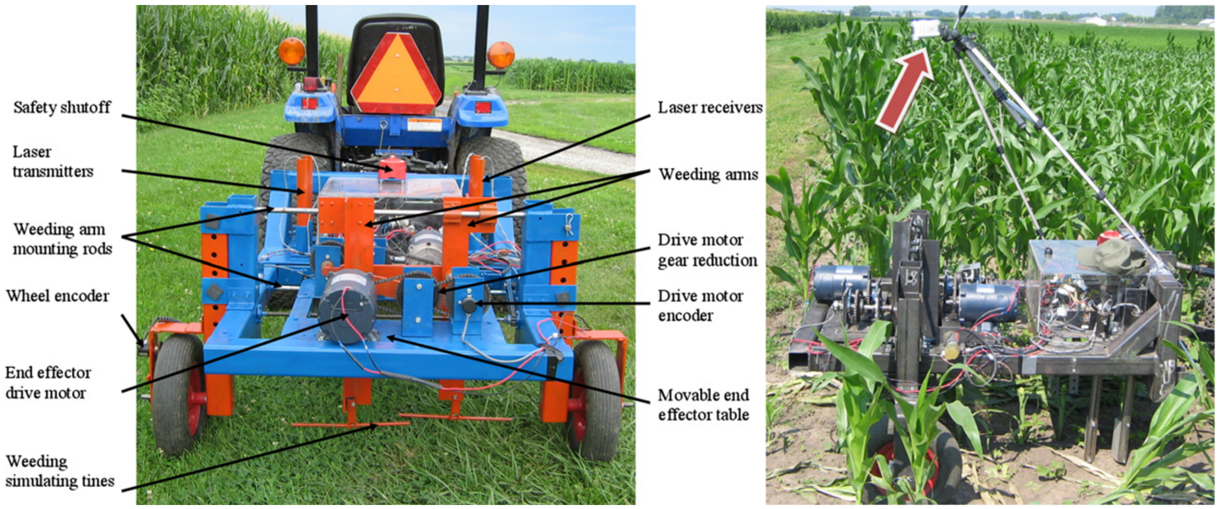

Fig. 5 – (left). Photo of the rear of the mechanical weeding machine. (right). Side view of the weeding machine, showing the mounting of a downward looking camera that was used to evaluate the performance of the machine.

may have varied in the longitudinal direction, and secondly, the machine needed to be centred exactly above the row which may not always be the case. To ensure proper alignment above the row, a second identical set of laser interruption sensors was added, that is not perpendicular to the row, but at an angle of 15°. The signals from the two sensor sets were in phase when the machine was above the centreline of the row, and out of phase, during misalignment. The phase difference between the two sensor sets was used to control a table on which the end-effector motors were mounted, which was moved laterally, to keep the centre of the end-effectors above the maize row centreline.

Fig. 5 shows a rear view of the complete mechanical weeding machine. The left photo shows how the weeding arms were both mounted on a table that enabled moving the machine above the centre of the row. At the front of the machine, the housings of the laser transmitters and receivers were attached. Between them, two batteries were placed, along with motor driver boards and ancillary hardware. An acrylic cover was placed over all electronic power and control parts. The right side photo in Fig. 5 shows the mounting of a camera (annotated by the arrow) that looked downward to assess the functioning of the machine.

2.4. *Experimental procedure*

Experiments were performed in late June and early July at the Agricultural Engineering Farm in Urbana, IL, USA. Glyphosate resistant maize was planted in late May on a 0.2 ha field that had been out of production for several years. No herbicide or fertiliser treatments were applied and weed and corn plants were allowed to grow *ad libitum*. Because the majority of weeds during a preceding fallow period were grasses, glyphosate resistant soybeans were planted with a hand planter, directly into several corn rows to simulate a broadleaf weed infestation. Heavy rain in June caused the field to be inundated for two weeks, resulting in stunted plant growth. Also, late rain caused the fields to be inaccessible for several weeks. This allowed the maize to reach a growth stage where the plants were bent underneath the tractor as it passed over the row. To conduct tests, the tops of the maize plants were cut off at 250 mm height to allow undisturbed passage underneath the tractor. This practice was justified, as the sensor only aimed laser beams at the bottom 150 mm of the plants and no leaves growing from higher than 250 mm reached below 150 mm above the ground.

As the maize plants reached 300 mm–900 mm in height, the field was separated into 9 plots, each of which contained 45 consecutive plants. Three plots were manually weeded and weeds higher than 50 mm were removed. Another three plots were established in areas of high broadleaf infestation and the final three plots were made in an area of high grassy weed infestation.

Table 1 – Portion of damaged maize plants in rows without weeds.

Plot	Weed type	Number of Maize plants	Number of plants with fatal damage	Number of plants with minimal damage
1	None	45	7	3
2	None	46	0	5
3	None	45	5	16
	Total	136	12	24

2.4.1. *Implement testing*

Full implement testing was conducted to observe how well the implement was able to distinguish corn stalks and circumvent them. To quantify the extent of weed infestation, the number and species of weeds were counted in 10, 0.2 m^2 areas for each plot. A metal frame with measurements of 100 mm by 200 mm was used as a guide and was placed centred on two corn plants on the row centreline. All plants within this frame were counted.

The implement was drawn through the field whilst sensing corn plants and moving the mechanism along its intended path. The video from the downward looking camera was used

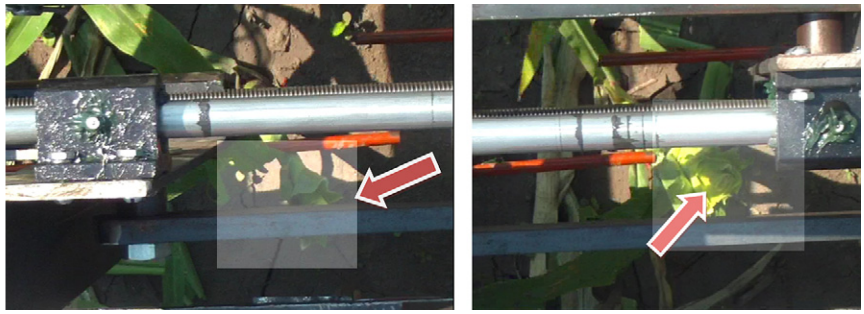

Fig. 6 – (left). Fatal damage to a plant that is being pushed over by a weeding tine. (right) Minimal damage to a maize plant caused by the tine merely touching the plant, but not pushing it over.

to evaluate the potential damage of the weeding tines to the maize stalks.

Supplementary video related to this article can be found at doi:10.1016/j.biosystemseng.2011.07.007

3. Results and discussion

How effective the implement was in weeding could not be judged, since the tines did not contact the soil. Instead, the accuracy of the implement in circumventing the maize stalks under various weed cover scenarios was assessed. A video of the end effector movement around the plants showed that the path through which the end effectors moved was close to the theoretical path as shown in Fig. 4.

Two criteria for determining the effectiveness of the weeding system were set. Firstly, when the end effector tine extended beyond the centre of a corn stalk, the weeding tine pushed the plant over; this was assumed to have killed it. Therefore, this case was considered as "fatal damage" (Fig. 6, left photo). Fatal damage occurred when a maize plant was falsely regarded as a weed, or when the algorithm did not properly locate the maize plant. Secondly, if the end effector tine merely touched a maize stalk, but did not overrun it, it was deemed to be "minimally damaged" (Fig. 6, right photo). This situation occurred when the tine extended beyond a stalk perimeter, but not its centre. Minimal damage would most likely not kill the maize plant, but could cause yield loss. This type of damage occurred either when the sensor predicted stalk location was slightly different from the true location or if the error in the lateral tine position control was large.

3.1. *Results in plots without weeds*

The implement was used in three plots with no weeds taller than 50 mm. In this way, the effectiveness of the weeding implement in the absence of weeds could be judged. The results of this experiment can be found in Table 1. In the three plots combined, among 136 plants, 12 were fatally damaged (8.8%), and in addition, minimal damage was caused to 24 plants (17.6%).

3.2. *Results in plots with weeds*

Weeds that were present in the other six plots were giant foxtail (*Setariafaberi*), common lambsquarters (*Chenopedium album*), redroot pigweed (*Amaranthusretroflexus*), and hairy crabgrass (*Digitariasanguinalis*). Weed population densities were measured in the intra-row region. Table 2 shows the populations of weeds in each of the plots.

The weeding implement was employed in the same manner as in the plots without weeds and the results of the experiment are shown in Table 3. In the combined three rows with broadleaf weeds, out of 135 plants, 32 (23.7%) were fatally damaged and 27 (20%) were minimally damaged. In the combined three rows with grassy weeds, out of 135 plants, 32 (23.7%) were fatally damaged and 35 (25.9%) were minimally damaged.

Based on these data, it can be concluded that the weeding implement was more effective at locating maize stalks and

Table 2 – Weed populations in broadleaf and grassy weed rows.

Plot	Number of broadleaf weeds per m^2	Number of grassy weeds per m^2	Total number of weeds per m^2
4	160	75	235
5	265	285	550
6	155	700	855
7	140	630	770
8	95	715	810
9	555	215	770

Table 3 – Portion of damaged corn plants in broadleaf and grassy weed rows.

Plot	Weed type	Number of Maize plants	Number of plants with fatal damage	Number of plants with minimal damage
4	Broadleaf	45	13	10
5	Broadleaf	45	4	8
6	Broadleaf	45	15	9
7	Grassy	45	10	13
8	Grassy	45	17	13
9	Grassy	45	5	9
	Total	270	64	62

moving the end effector in the broadleaf weed plots than in the grassy weed plots because fewer plants overall were damaged. However, the results showed that the same number of fatally damaged plants occurred in both types of plots. One reason for fewer maize plants being minimally damaged may be the diameter and shape of the broadleaf weed stems which are generally round and narrow, distinctively different from maize stalks and leaves. In addition, on some broadleaf plants the leaves are horizontal. Therefore, instead of the laser beams being intercepted by the wide face of the leaf, they were intercepted by the side of the leaf. This decreased the distance through which the laser was intercepted which made the task of distinguishing the maize stalks from the weeds more effective. When the plots contained grassy weeds, more interceptions occurred, resulting in more pulses. The increased number of pulses created more difficulty in locating the maize stalks and consequently the damage to the maize plants increased. More in-depth research is needed to determine whether the increase in the number of signal pulses originates from the density of the weeds, from their morphological features, or both.

4. Conclusions

A mechanical weed control machine containing a sensing arrangement, control algorithm and dual mechanical end effectors was successfully developed and tested. The overall functionality of the machine was proven, but the percentage of fatally damaged plants was 8.8% in the absence of weeds and reaching 23.7% in heavy weed infested areas with hundreds of weeds per m^2. More work is needed to identify the causes of misjudging the locations of the corn plants. In addition, for the machine to be regarded as a realistic alternative to chemical weed control, the field performance needs to be improved significantly.

REFERENCES

Baerson, S. R., Rodriguez, D. J., Tran, M., Feng, Y., Biest, N. A., & Dill, G. M. (2002). Glyphosate-resistant goosegrass. Identification of a mutation in the target enzyme 5-enolpyruvylshikimate-3-phosphate synthase. *Plant Physiology, 129*, 1265–1275.

Bontsema, J., Grift, T. E., & Pleijsier, K. (1991). Mechanical weed control in sugar beet growing: detection of a plant in a row. *IFAC/ISHS workshop*, Matsuyama, Japan, 30 Sept.–3 Oct. 1991.

Bradshaw, L. D., Padgette, S. R., Kimball, S. L., & Wells, B. H. (1997). Perspectives on glyphosate resistance. *Weed Technology, 11*, 189–198.

Culpepper, S. A., Grey, T. L., Venvill, W. K., Kichler, J. M., Webster, T. M., Brown, S. M., et al. (2006). Glyphosate-resistant Palmer amaranth (Amaranthuspalmeri) confirmed in Georgia. *Weed Science, 54*, 620–626.

Heap, I. (2011). *International Survey of Herbicide Resistant Weeds*. Available at: http://www.weedscience.com [Accessed 04.07.11].

Lee, L. J., & Ngim, J. (2000). A first report of glyphosate resistant goosegrass (Eleusineindica) in Malaysia. *Pest Management Science, 56*, 336–339.

NASS. (2007). *Wisconsin 2007 agricultural statistics: National agricultural statistics service*. Available at: http://www.nass.usda.gov/ [Accessed 04.07.11].

Nørremark, M., Griepentrog, H. W., Nielsen, J., & Søgaard, H. T. (2008). The development and assessment of the accuracy of an autonomous GPS-based system for intra-row mechanical weed control in row crops. *Biosystems Engineering, 101*, 396–410.

Powles, S. B., Lorraine-Colwill, D. F., Dellow, J. J., & Preston, C. (1998). Evolved resistance to glyphosate in rigid ryegrass (Loliumrigidum) in Australia. *Weed Science, 46*, 604–607.

VanGessel, M. J. (2001). Glyphosate-resistant horseweed from Delaware. *Weed Science, 49*, 703–705.

Wisserodt, E., Grimm, J., Kemper, M., Kielhorn, A., Klein-Hartlage, H., Nardmann, M., et al. (1999). Gesteuerte Hacke zur Beikrautregulierung innerhalb der Reihe von Pflanzenkulturen. [Controlled hoe for weeding within crop rows]. In *Tagung Landtechnik 1999/VDI-MEG* (pp. 155–160). Düsseldorf, Germany: VDI-Verlag.