Autonomous Inter-Row Hoeing using GPS-based side-shift Control

H. W. Griepentrog, M. Noerremark, J. Nielsen, and J. S. Ibarra

Copenhagen University, Faculty of Life Sciences, Dept. of Agricultural Sciences,
Hojbakkegaard Alle 9, DK - 2630 Taastrup, Denmark.

E-mail: hwg@life.ku.dk

ABSTRACT

Several developments and investigations have been done to automate the lateral control of hoes with the aim to achieve higher weeding efficiency and decreased labor costs. The aim of this project was to investigate the accuracy and limitations for a computer controlled hoeing operation based on a GPS system. A conventional hoe and an electro-hydraulic side shift frame was used and attached to a small automatic tractor. The main task of the controller systems was to minimize the lateral deviations between current GPS positions of the hoe related to a predefined route. The range of the cross track errors (standard deviations) altered between 0.009 m and 0.028 m for the hoe (ground measurements). The hoe system enables hoeing up to 83% of a field surface area with a speed of 2 km/h and up to 79% by driving with 4 km/h. The GPS based system showed its potential to be used for high accurate crop row guidance e.g. with an inter-row hoe. Further research should be carried out to investigate sensor fusion systems consisting of GPS and other sensors e.g. based on computer vision.

Keywords: Automation, autonomous tractor, GPS, hoeing, weed control

1. INTRODUCTION

In order to reduce herbicide input or completely substitute chemical inputs and minimize labor costs mechanical weed control operations are an increasingly important option. Hoeing is one of oldest, highly matured and most common non-chemical weeding operation. Its weed control principle can be defined as (Laber, 1999):

- Operational: Soil engaged treatment (tillage) between crop rows.
- Physical: Soil coverage of weeds, weed root / stem cutting and uprooting of weeds (whole plant or partly).
- Physiological: Reduction of photosynthesis and reduction of water transpiration.

Hoeing is at least 120 years old and still a standard weed control operation today. The first hoes were horse pulled and the ones today are tractor mounted or still tractor pulled. Currently often a second operator is controlling the hoe laterally by hand and based on operator's vision. Tines or rotating discs (rotary hoes) are fixed to a frame and penetrate the upper crust of the soil. The treatment is effective on dry, compact soil and a stable working depth is maintained by ground wheels.

As for most mechanical weeding operations crop plant losses always occur. Especially if high weed control efficiencies are aimed at. Crop losses result from soil coverage, crop leaf damage, root damage and disturbance. The standard hoe setting for the untreated crop row strips is 10 cm which gives approximately a maximum of 80% area treatment e.g. in sugar beet. This row band width is measured as a row clearance between the hoe unit tools e.g. shares. Most crop losses are due to soil disturbance close to crop plants. A conflict of aims appears between i) maximizing treated area to increase weeding efficiency and ii) minimizing crop losses by keeping a sufficient distance to crop rows. Therefore the adjustment of the hoe unit working width becomes an important factor for achieving an acceptable cultivation result.

Several developments and investigations have been done to automate the lateral control of hoes (Tillett, 1991; Home, 2003). Today the most promising automation principles are based on GPS (Van Zuydam et al., 1995; Dijksterhuis et al., 1998) and computer vision (Tillett et al., 2002; Soegaard and Olsen, 2003; Astrand and Bearveldt, 2005). A fusion of both is seen today as the most promising strategy, because advantages and disadvantages of absolute and relative referencing principles compensate each other (Pilarski, 2002; Downey et al., 2003).

The aim of this project was to investigate the accuracy and limitations for a computer controlled hoeing operation based on an RTKGPS system. The objectives were i) to design and optimize a side-shift system for lateral control of a conventional inter-row hoe, ii) to quantify the accuracy of the performance (cross track errors) and iii) to determine an optimum hoe unit working width (Ibarra, 2005). For all field tests an unmanned and fully automatic tractor was used to provide mechanical, hydraulic and electric power. The tractor's navigation controller was also based on RTKGPS.

2. MATERIALS AND METHODS

2.1 Inter-row Hoe

A conventional inter-row hoe was used (Baertschi-Fobro, Switzerland) consisting of five units to treat four crop rows. The hoe units including toolbar are light to be operational for a small automatic tractor. Each unit had a parallelogram for height compensation and a ground wheel for controlling the working depth. Three hoe units had each three standard A-blade cultivators as the outer ones had only two.

For determining an optimal hoe unit working width an untreated band or safety band for the crop rows had to be defined. Furthermore a failure tolerance for hoeing into the safety band around crop rows (5%) and the standard deviations of lateral errors from the field experiments were used. According to figure 1 the unit working width X_{unit} was determined and set by using the following equation:

$$X_{unit} = X_{rw} - (X_{un} + 4\,s) \qquad (1)$$

Where

X_{rw}: Row width

X_{un}: Untreated band width (safety band)

s: Standard deviation of lateral errors

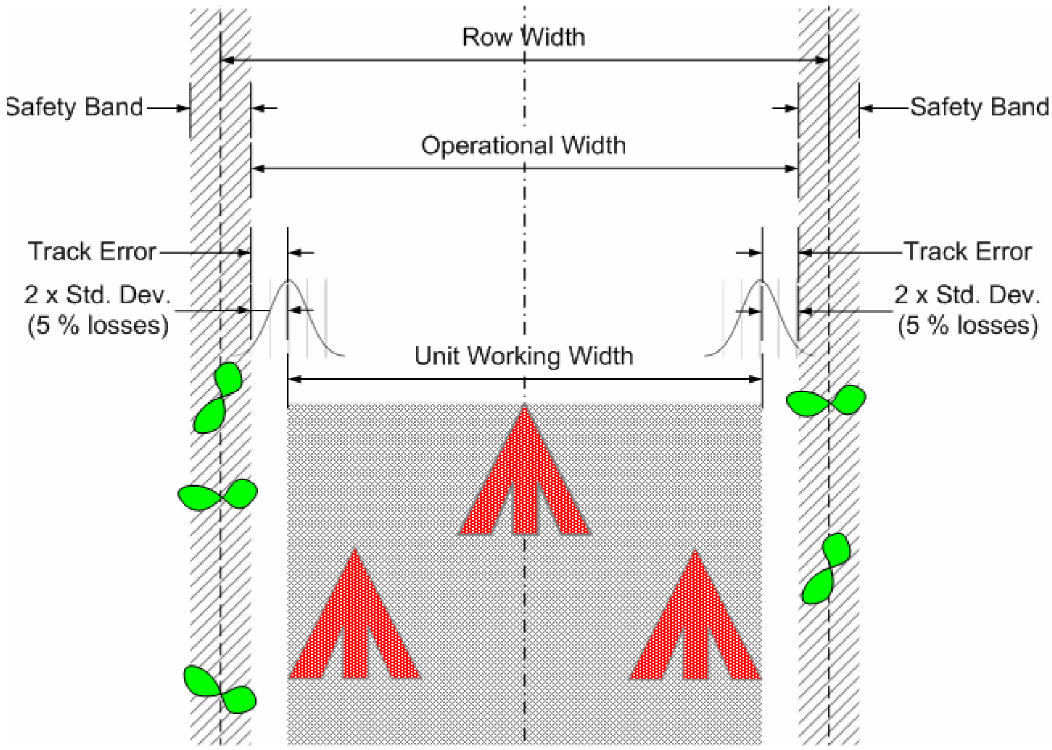

Figure 1. Unit working width setting by considering cross track errors, crop losses and an untreated band (safety band).

2.2 Side-shift Toolbar System

The aim of the side-shift system as displayed in figure 2 was to center the hoe units between the rows and parallel to the crop rows with a minimum of lateral deviations (cross track error). Furthermore, the idea was to keep the side-shift somehow independent from the motion behavior of the pulling tractor.

The side-shift controller was configured to keep the GPS antenna of the hoe on the same planned route as the automatic tractor was using for its navigation. This setup enables a somehow independency of the implement from the pulling tractor.

A double toolbar side-shift system carried five hoe units to cover four crop rows. The system was attached to the tractor using the rear three point linkage. The tractor only pulled the hoe system via loose linkages as the hoe had two carrying ground wheels. A soil engaging disc (diameter 0.47 m) was mounted in the center of the first toolbar which was connected to the tractor. The disc functioned as a counterpart to compensate for lateral reaction forces resulting from the side-shift's lateral movements (2nd toolbar).

The lateral position of the 2nd toolbar was altered by controlling the oil flow rate to a double acting hydraulic cylinder with a stroke length of 0.2 m. A 2-way solenoid valve allowed a left / right switching and a proportional valve regulated the oil flow rate to vary the piston velocity. The different flow rates to ensure the same piston speeds for left and right directions were achieved by using individual calibration settings.

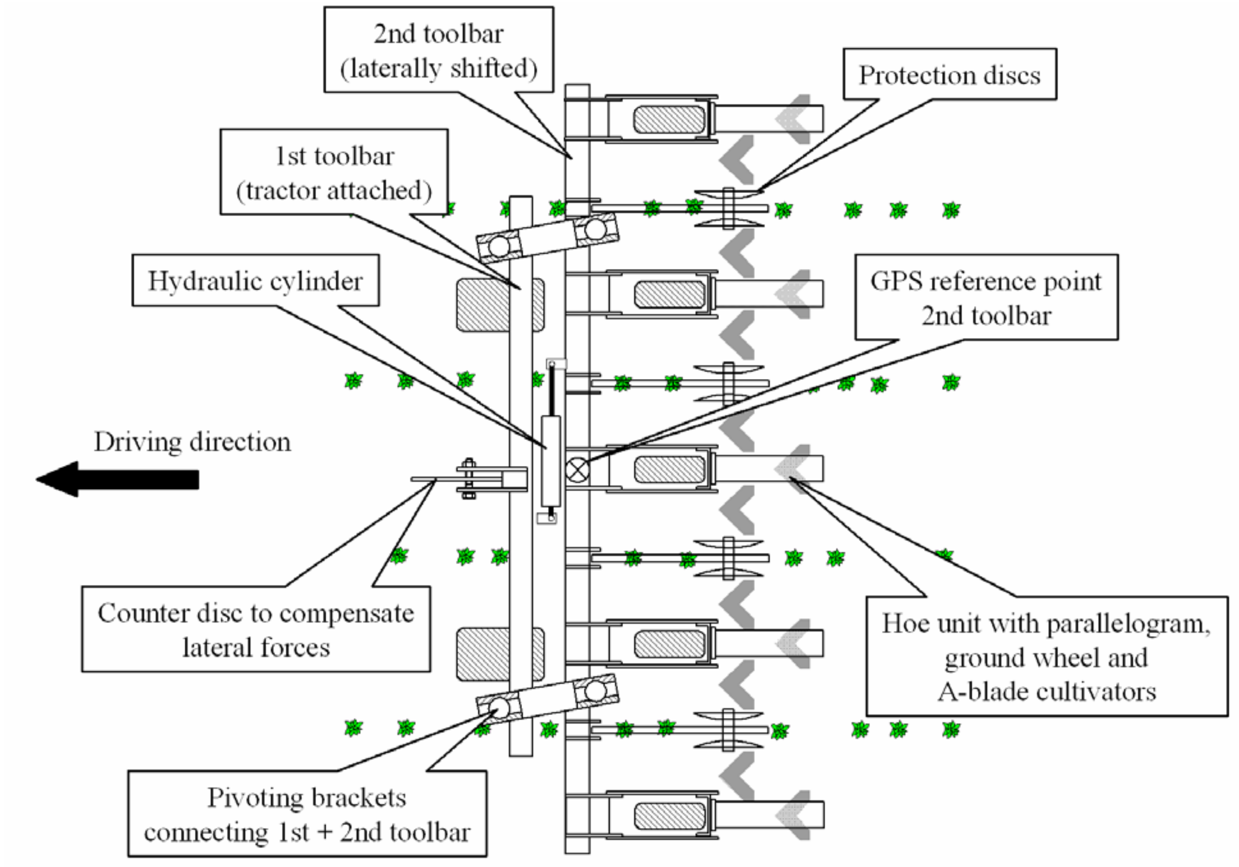

Figure 2. Conventional inter-row hoe and the toolbar side-shift system.

2.3 Controller Hardware

The lateral control of the inter-row hoe was based on an RTKGPS (Trimble MS750) and a dual axis tilt sensor (Applied Geomechanics, MD900). The GPS was connected to a local reference station via an FM radio modem (Satel 3ASd). The GPS antenna was mounted at a height of 1.3 m in the middle of the 2nd toolbar and functioned as a closed-loop feedback for keeping the hoe on the planned route.

A PC/104-based computing platform was used. It comprised a 400 MHz Via Eden processor (Pentium class). Additional boards were connected to allow digital, analog and PWM I/O connections. The analog voltage and power to control and operate the hydraulic valves respectively was provided directly from the amplifier board via three-pole standard valve connectors.

2.4 Controller Software

The controller software was developed in the programming tool MATLAB Simulink from MathWorks. It allows modeling and simulating of system functionality prior to actual tests. The software comprised, i) a route tracking, ii) hydraulic cylinder velocity control and iii) a left / right direction switching of the hydraulic cylinder. The software used a standard PID controller to minimize the route tracking errors (cross track errors). When starting the route tracking - a route is defined by waypoints - the "next waypoint" is selected when the Euclidean distance becomes less than 0.5 m (fig. 3 and fig. 4). When following a route the hoe position is translated to the coordinate system with waypoint P2 as Origo and waypoint P1 on the negative x-axis. When the y-axis is crossed, the waypoints are shifted and the next segment between waypoints is chosen as the reference from which the cross track error is calculated.

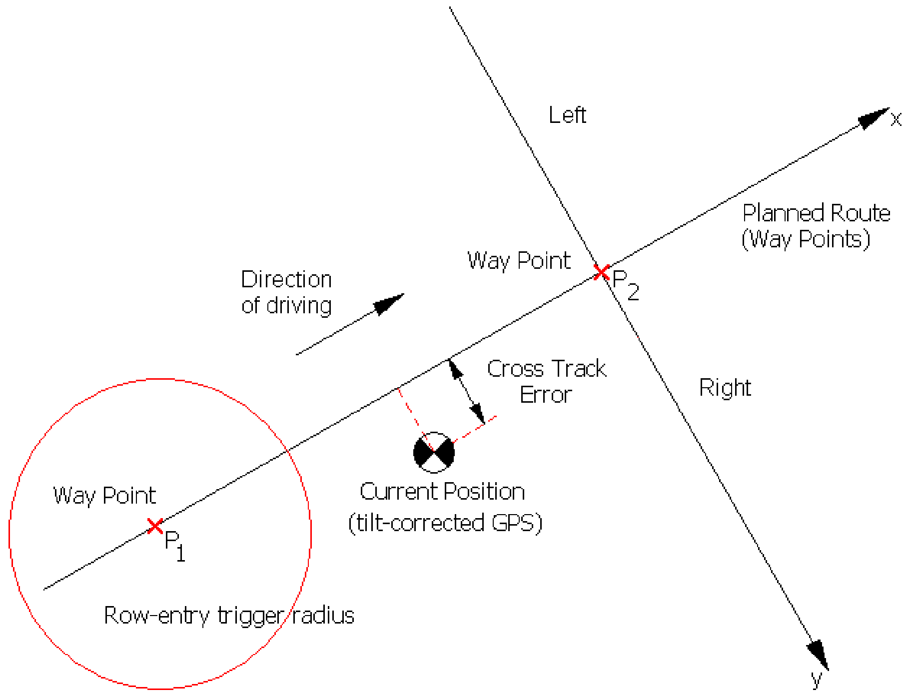

Figure 3. Determination of cross track errors from GPS positions and planned route defined by way points.

The hoe operation had to be planned prior to the weeding cultivation. The route way points were generated from geo-referenced seed positions. The geo-referenced seed positions were determined from the seeding operation of the cultivated crop plants by logging and processing GPS and seeder attitude data (Griepentrog et al., 2005).

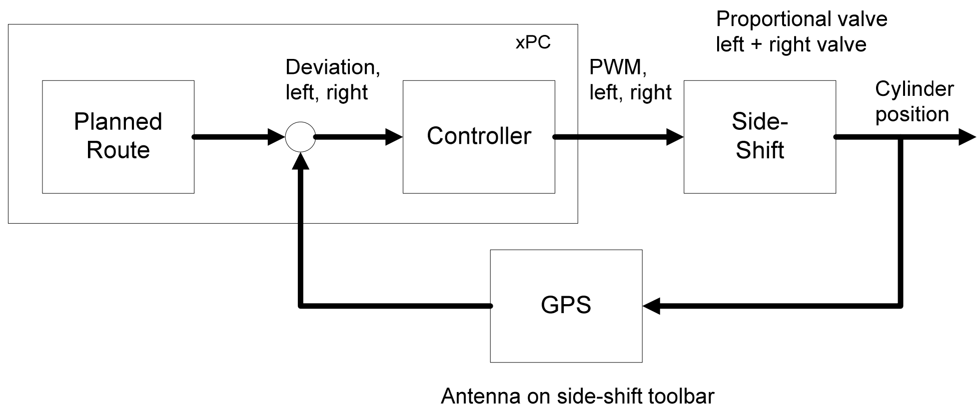

Figure 4. Lateral control system for a hoe (side-shift).

2.5 Autonomous Tractor

An automatic tractor was used to operate the hoe. This conventional 20 kW tractor (Hakotrac 3000) was retrofitted with an RTKGPS (Trimble MS750) and a controller system for navigation. The steering control, engine speed, vehicle speed, PTO and three point linkage was achieved by using an electronic controller unit (ESX). Two electro-hydraulic valves (Sauer Danfoss EHP) actuate the steering and electric linear motors (Linak) control engine rpm and continuously variable transmission (CVT). The safety interlocks and emergency shutdown was achieved by a combination of stamp computers (with PIC microcontrollers), radio links and hardwired relays. The tractor navigation controller was designed to follow a predetermined route plan accurately and repeatable e.g. across a field with planned action points for implement control (Blackmore et al., 2004).

2.6 Field Experiment

The field trial was carried out at the KVL research farm, Denmark, on 7 and 8 July 2005 (55°40.16726'N, 12°18.52900'E). The experiments included driving along eight straight trajectories. The length of each straight line trajectory was 45 m.

The field experiments were carried out by using varying forward speeds and driving directions. The system was tested with four tracks in each orientation East-West (1.1 to 1.4) and North-South (2.1 to 2.4). The testing was conducted by driving with two speeds: 2 km/h for tracks 1.1, 1.2, 2.1 and 2.2 and 4 km/h for tracks 1.3, 1.4, 2.3 and 2.4. Compared to a standard hoeing operation with a standard tractor the speeds are low. The reason is that the performance of the small automatic tractor limited the speeds.

Virtual crop plant rows were set up by using small white plastic sticks.

Two complete repetitions were made. The working depth of the hoe was set to as shallow as possible (0.010 to 0.020 m).

2.7 Data Acquisition and Analysis

A rigid disc was attached to one hoe unit parallelogram to create a small furrow to indicate the hoe trajectory as it passed across the field. Ground distances between this furrow and the crop rows were measured by a hand ruler to describe the lateral hoe movement. Furthermore the side-shift GPS output string was also logged.

The performance of the hoe was assessed i) by analyzing data from lateral ground measurements between hoe trajectory and plant rows and ii) by analyzing tilt corrected GPS position data as they were used for the control system.

3. RESULTS AND DISCUSSION

The cross track errors can be divided up into bias (mean deviation) and variability (standard deviation). A summary of the results for all trial variants are presented graphically in figure 5 and figure 6.

The range of the mean values altered quite low between – 0.016 m to 0.011 m (fig. 5). The ground measurements (ruler) showed higher mean values than calculated from the GPS data, means the repeatability was not as high as for the GPS data.

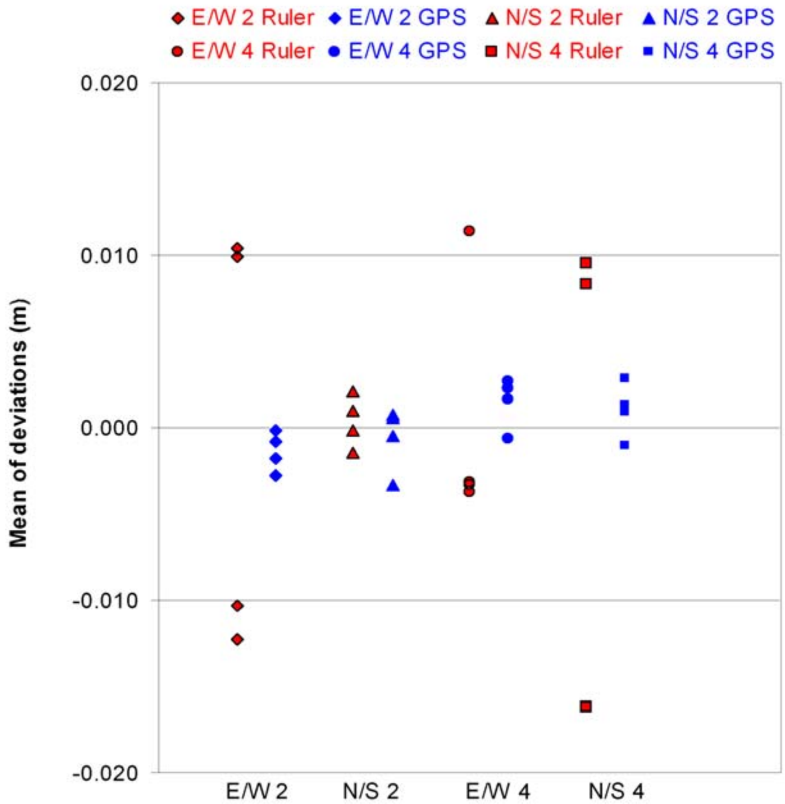

Figure 5. Mean lateral deviations versus ground measurements and GPS position logging and versus heading directions and forward speed (E/W east-west, N/S north-south, 2 and 4 km/h).

The range of the mean values from the GPS altered only ± 0.003 m. This could be due to the use of different measurement techniques or due to the controller's characteristic to minimize the lateral deviations of GPS positions from the planned route. Home (2003) analyzed the cross track errors for different row guidance systems as with a tractor driver, a second operator and a computer vision system. The investigations included no GPS system. The author observed a similar small range of the bias (– 0.017 m and 0.009 m).

The variability of the cross track error can be described by using the standard deviation (fig. 6). There are three obvious trends in the graph i) the values from the GPS logging are much higher compared to the ground measurements, ii) the values increase from lower to higher driving speeds for both observations and iii) the repeatability for the lower speeds seems higher.

The range of the standard deviations altered between 0.009 m and 0.028 m for the hoe (ground measurements) and between 0.023 m and 0.042 m for the GPS logging. The smaller lateral variations of the hoe occur probably due to the inertial forces which is system intrinsic. These forces suppress high frequency movements (low pass filter). Home (2003) published a range for the standard deviation of 0.009 m to 0.022 m for a tractor driver, a second operator and a computer vision system. The best results were obtained by using a computer vision system as a row guidance (0.009 m).

The experiments were carried out by using a small automatic tractor. Due to the tractor design the track width was much smaller than from a standard tractor. The tractor size reduced the maximum forward speed for hoeing to 4 km/h due to too dynamic vehicle performances. Due to the lower dynamic vehicle behaviors at slow speeds it seems that the repeatability was higher.

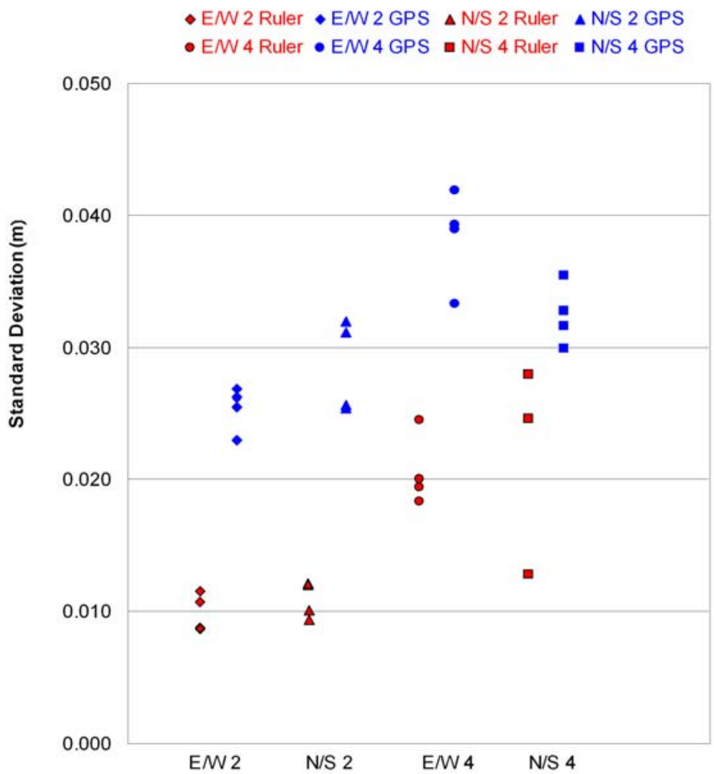

Figure 6. Mean standard deviations of lateral errors versus ground measurements and GPS position logging and versus heading directions and forward speed (E/W east-west, N/S north-south, 2 and 4 km/h).

Table 1 presents the treated or hoed surface areas based on the analysis of the cross track errors acquired from the field experiments. The setting of the optimum hoe unit working width is also displayed based on the field results. Small standard deviations of the track errors resulted in wider width of the hoeing units and in high effected field surface areas. The hoe system enables hoeing up to 83% of a field surface area with a speed of 2 km/h and up to 79% by driving with 4.3 km/h.

Table 1: Hoe unit working width and treated area versus forward speed and cross track errors (row width 0.5 m, untreated row band 0.010 m and failure tolerance 5%)

Forward speed [km/h]	Standard deviation of cross track errors [mm]	Hoe unit working width [m]	Treated area [%]
2.0	9 – 12	0.404 – 0.415	81 – 83
4.3	13 – 28	0.338 – 0.399	68 – 79

4. CONCLUSIONS

A row guidance method consisting of an electro-hydraulic side shift system for implement attachment was developed and tested. The GPS based system showed its potential to be used for high accurate crop row guidance e.g. with an inter-row hoe. The mean as well as the standard deviations of the cross track errors were comparable with other row guidance systems as traditional tractor mounted and computer vision systems. Further research should be carried out to investigate sensor fusion systems consisting of GPS and other sensors e.g. based on computer vision.

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