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Research Paper

Tractor-based Real-time Kinematic-Global Positioning System (RTK-GPS) guidance system for geospatial mapping of row crop transplant

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An automatic, centimetre-level accuracy mapping system was developed and evaluated for precision real-time geospatial mapping of transplanted tomato plants. The system utilised a single Real-time Kinematic-Global Positioning System (RTK-GPS) system mounted on the tractor for Global Positioning System (GPS) location mapping of planting events occurring on the tractor-drawn transplanter. The mechanical hitch interface between the tractor and the transplanter was instrumented with orientation sensors to allow computation of the GPS crop plant location without the need for an independent RTK-GPS system located on the transplanter thereby reducing the equipment cost of the system. A ruggedised, real-time, embedded controller was used for sensor monitoring and logging of GPS location, planting events and transplanter odometry data. The system was capable of producing highly accurate maps of crop plant location for subsequent precision plant care tasks conducted at the centimetre scale.

The benefit of the tractor-based RTK-GPS system for geospatial mapping of transplants such as tomato demonstrated in this work is that it enables farmers with existing RTK-GPS tractor-mounted auto guidance systems to better utilise their existing GPS technology by allowing them to automatically create centimetre-accuracy plant maps for subsequent precision plant specific treatment systems. Such systems could provide substantial savings in agro-chemicals with associated environmental and economic advantages for sustainable agricultural production systems.

1. Introduction

Over the last two decades, the opportunities for precise management of agricultural field operations have increased due to the availability of new geospatial and information technologies (Global Positioning System (GPS), Geographic Information System (GIS), sensors, electronics, agricultural machinery controllers and high resolution remote sensing). The development of new types of automated agricultural machinery that can increase sustainability and competitiveness in agricultural production have been studied by several researchers (e.g., Bakker, Van, Bontsema, Muller, & Van, 2010; Griepentrog et al., 2004; Slaughter, Giles, & Downey, 2008). The rapid adoption of these technologies in agriculture, especially for crop yield mapping and automated tractor steering systems, is motivated by a number of factors. These include; 1)

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minimising environmental contamination from excessive fertiliser applications by adopting site-specific GPS application techniques that tailor the localised application rate to the localised need; 2) increasing yields by optimising site-specific input application levels tailored to crop demand at each site within a field; 3) decreasing availability of skilled farm labourers to perform agricultural tasks such as hand hoeing. The availability of precision mapping technologies for crop plants enables a new opportunity for plant specific treatment systems where the resources for plant care are tailored to the needs of individual plants rather than providing the same level or resources to all plants in the field irrespective of need or potential for utilisation (Chancellor, 1981; Chancellor & Goronea, 1993). Such systems could, for example, provide substantial savings in agro-chemicals if Real-time Kinematic-Global Positioning System (RTK-GPS) auto steering allowed between-row cultivation tools to operate closer to the crop rows, leaving fewer weeds. As a result, pre-plant herbicide bands could be narrowed, reducing herbicide application rates and hand-weeding requirements, with the associated environmental and economic advantages (Blackmore, Stout, Wang, & Runov, 2005; Fennimore, Tourte, Rachuy, Smith, & George, 2010; Griepentrog et al., 2004).

Currently, RTK-GPS technology offers the possibility of transitioning site-specific techniques from sub-metre level precision to centimetre-level precision. As the resolution at which the geoposition (i.e., the geodetic position with latitude and longitude or easting and northing) can be accurately determined improves, it increases the number of types of plant-specific management tasks suited for automation. An automated geospatial mapping system for individual crop plants would facilitate the adoption of automatically controlled field operations such as:

- automated tractor navigation moving beyond straight-line travel paths to custom as planted paths;
- precise implement or tool position control to allow intra-row weed control without crop damage or deep tillage operations without damage to buried drip irrigation tape;
- precise application of chemical inputs to individual crop plants, and;
- measurement of plant vigour, growth status and yield estimation of individual crop plants (Abidine, Heidman, Upadhyaya, & Hills, 2004; Ehsani, Upadhyaya, & Mattson, 2004; Griepentrog, Nørremark, Nielsen, & Blackmore, 2005; Sun et al., 2010).

Guidance systems (mechanical or electronic) allow precision cultivation at greater speeds with reduced risk of crop damage associated with operator steering errors. RTK-GPS provides row positioning accuracy comparable to machine vision guidance systems, but without the need for visual guidance landmarks in the field. This is particularly advantageous when visual cues may not be available because the crop has not emerged or it is too small, etc. In addition, since GPS does not rely on visual feedback it is not adversely affected by poor illumination, windblown foliage, weed pressure, missing crop plants or other conditions that degrade the performance of machine vision guidance systems. When RTK-GPS tractor auto guidance is used to form the planting beds and to plant the crop, steering accuracies within 25 mm of the desired path in subsequent passes through the field are possible (Leer & Lowenberg-DeBoer, 2004). This level of accuracy in row crops can enhance the precision of chemical placement in narrow bands or cultivating close to the plant line (Abidine et al., 2004). One disadvantage of RTK-GPS solutions is the requirement that a base station be located within 10 km at all times and this requires high capital cost. GPS service companies and government institutions are working in mitigate this challenge by developing a network of base stations, which provide access to the RTK correction signal over a wide geographic region via cellular or radio modem (Mesas & Torrecillas, 2007). In the future this network may provide coverage to all farmers with GPS-RTK receivers, eliminating the need for multiple base stations on each farm.

A significant advantage of RTK-GPS mapping technology over plant sensing methods (remote or ground-based) is that accuracy and precision is that performance is independent of any variation in biological morphology, or visual occlusion, which can be substantial for agricultural crop plants at the juvenile stage. For example, by adding an appropriate interface to precision seed planters, it is feasible to develop a RTK-GPS enabled seed planter that can create a map the geoposition (i.e., latitude and longitude) of each crop seed as they are released by the planter (e.g., Ehsani et al., 2004; Griepentrog et al., 2005; Nørremark, Griepentrog, Nielsen, & Blackmore, 2003). In addition, mapping of individual crop plants could incorporate planning steps that include task sequencing and route planning for further optimisation. Both techniques are currently under study for optimising highly complex operations for agricultural robots (Bochtis et al., 2011).

Despite the significant financial investment, RTK-GPS quality guidance systems are increasingly being used by commercial farming operations for automatic guidance of tractors and other types of field equipment. Among the motivations for this trend are opportunities for savings due to more efficient use of farm equipment and the ability to better utilise less skilled equipment operators when GPS automatic guidance is available (Lindores, 2007). Increases of as great as 15% in tractor speed and field capacity may justify the added cost of the RTK-GPS auto guidance systems, providing that the purchasers are able to offset the initial expense with improved productivity across a wide range of farming operations and can utilise the systems at frequently during the year (Pedersen, Fountas, Have, & Blackmore, 2006). The full benefit of RTK-GPS technology will probably only be fully realised when all field operations, from initial tillage to harvest, are conducted with GPS guided systems.

The feasibility of RTK-GPS enabled seed planters or transplanters that can map the geoposition of crop seeds or transplants as they are released by the planter has been demonstrated (e.g., Ehsani et al., 2004; Griepentrog et al., 2005; Nørremark, Søgaard, Griepentrog, & Nielsen, 2007; Sun et al., 2010). However, these systems utilised an RTK-GPS system dedicated to the planter, in addition to any RTK-GPS auto guidance systems present on the tractor, greatly increasing the capital cost of the crop mapping operation. The aim of this project was to develop a centimetre-level

accuracy geoposition plant mapping system for transplanted row crops which utilised a single RTK-GPS auto guidance system mounted on the tractor, and not the planter, thereby reducing the capital cost of the system. The specific objectives were:

1. Develop a real-time, transplant geoposition data-logging system which could record, at the moment each transplant is placed into the soil, the relative position of the planting shoe of the transplanter with respect to the RTK-GPS system mounted on the tractor via a tractor-planter hitch position sensor and roll and pitch inclination sensors on the transplanter.
2. Produce geospatial transplant maps, containing the true geoposition of each transplant, using the real-time GPS coordinates from the tractor-mounted RTK-GPS auto guidance system, transplanter odometry, and the relative position and orientation of the transplanter relative to the tractor during planting.
3. Compare the accuracy of the automatically generated transplant geoposition map with surveyed transplant locations under standard conditions (straight rows on level ground with recommended hitch settings) and more challenging conditions (curved row planting patterns, and loose hitch settings).

2. Materials and methods

2.1. Global positioning system

RTK systems are the most accurate solution for GNSS (Global Navigation Satellite System) applications (2 cm accuracy). An RTK system requires two receivers, a radio link, and embedded navigation controller that integrates rover sensors and GPS data to compute the final position of the rover receiver (Misra & Enge, 2006). In this study, an RTK-GPS automatic guidance system (AgGPS Autopilot, Trimble Navigation Ltd., Sunnyvale, CA, USA) was used to pilot the tractor (John Deere model 6430 with category 2, 3-point hitch) for all field trials and seedbed preparation operations. The GPS system included:

- A rover RTK-GPS receiver (Trimble EZ Guide 500) with the GPS antenna mounted on top of the tractor's cabin (~3 m above the soil surface).
- A user interface capable of displaying cross-track error information and receiving user input, such as the desired pass spacing and the location of the first guidance line.
- Path-planning algorithms capable of calculating cross-track error relative to the desired guidance path.
- Vehicle steering actuators.
- Manual override sensors.
- Steering angle sensors.
- Controller calculating steering correction algorithms.
- Terrain compensation sensing (i.e. pitch, roll and yaw)

The system utilised an RTK-GPS correction signal from a local (located ~1 km from the test site) GPS base station (Trimble Model 4700) to obtain RTK Fixed quality accuracy. An 8 μs clock reference PPS (pulse per second) signal, was produced by the autopilot receiver to synchronise the geoposition data with external events. The autopilot receiver was set to output the "NMEA-0183 GPGGA" string containing the geographic coordinates (Latitude and Longitude) at 1 Hz rate via an RS-232 serial connection.

2.2. Transplanter design

A vegetable row-crop transplanter (model 1600, Holland Transplanter Co., Holland MI, USA) was retrofitted as described by Sun et al. (2010) with sensors and instrumentation required for creating crop plant maps as shown in Fig. 1. Briefly, the position of the transplanting wheel was monitored in real-time using an absolute shaft encoder (12-bit Grey code,

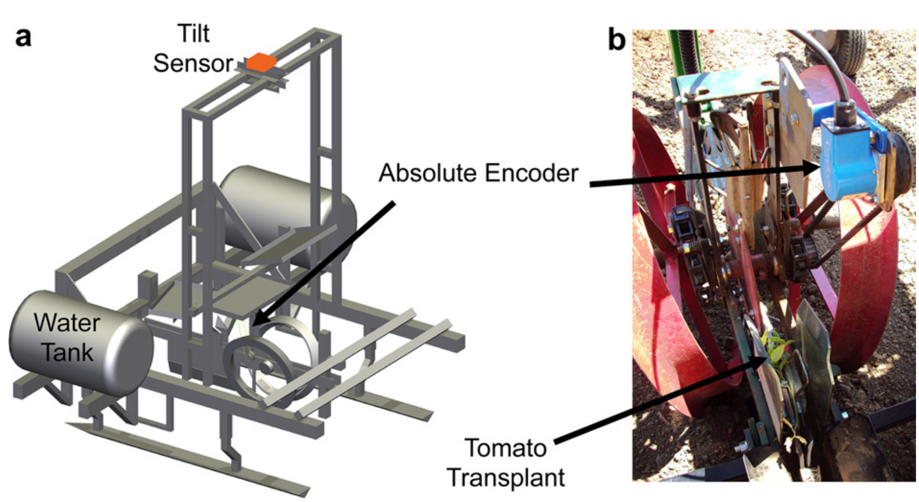

Fig. 1 – Vegetable crop transplanter, setup for geospatial mapping of crop plants. (a) Schematic diagram showing the plant wheel encoder, (b) photograph of the transplanter showing the absolute shaft encoder used to monitor the placement of each transplant as it is placed into the soil.

ARS 20 Sick Stegmann, Inc., OH, USA) to provide an angular resolution of 0.00154 radians, which corresponded to about 0.45 mm of travel along the row. This allowed the embedded controller (described below) to determine the exact moment the stem of the transplant was released and the plant transferred to the soil. Transplanter odometry, required for geoposition interpolation between 1 Hz GPS data points, was monitored using an incremental optical shaft encoder (model 0622 Grayhill, Inc., IL, USA.) mounted upon an unpowered ground wheel and provided a resolution of 0.6 mm in the direction of travel. A dual-axis inclinometer (Accustar II/DAS 20 Measurement Specialities Inc., Hampton VA, USA) was installed on the transplanter, directly above the planting wheel to monitor implement pitch and roll. The sensor was capable of measuring pitch and roll relative to level with a resolution of 0.00017 radians (corresponding to a 0.5 mm resolution parallel and perpendicular to the direction of travel at the ground level) and was used to provide ground level offset correction of location due to implement tilt. To measure the relative yaw between the tractor and the transplanter, a linear position transducer (model TD590 Transducers Direct, LLC, OH, USA.) was rigidly mounted to the end of a custom steel beam that was attached to the tractor frame (Fig. 2). The measurement arm of this position transducer was spring loaded to maintain physical contact with the hitch frame of the transplanter at all times. The hitch yaw sensor was capable of measuring deviations in the transverse direction between the respective centrelines of the tractor and the transplanter with a resolution of 0.003 mm. All sensor outputs were automatically recorded by the embedded controller (described below) at each planting event.

2.3. Data acquisition hardware

A ruggedised, real-time (1 kHz control loop execution rate), embedded controller (cRIO-9004, National Instruments, Austin, TX, USA) with a low-power CPU (195 MHz Pentium, Intel,

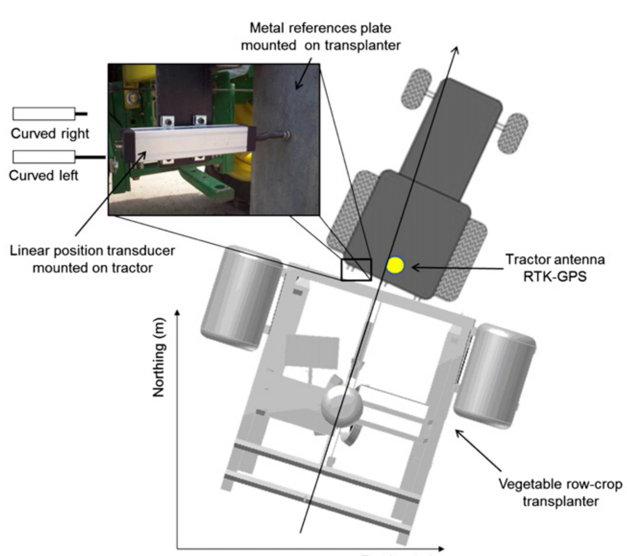

Fig. 2 – Hitch position sensor used to determine the relative heading between the tractor-implement system.

Santa Clara, CA, USA) and 512 MB of nonvolatile flash memory storage was used for GPS and sensor data-logging tasks. System status and logged data were accessed via a LAN using an on-board FTP server. A field programmable gate array module (FPGA with 3M logic gates; cRIO-9104, National Instruments, Austin, TX, USA), integrated to the controller, provided real-time, parallel, sensor monitoring with a 25 ns temporal resolution. FPGA data input/output (I/O) modules for analogue sensor inputs, high speed pulse detection; TTL digital I/O and RS-232 serial data I/O (NI 9201, NI 9411, NI 9403 and NI 9870, respectively, National Instruments, Austin, TX, USA) were utilised.

2.4. Data acquisition software

All data collection software was written the G programming language (LabVIEW™ version 8.5, National Instruments, Austin, TX, USA). The FPGA graphical code was automatically translated into text-based VHDL code and then compiled (ISE Design Suite, Xilinx Inc. San Jose, CA, USA) into a hardware circuit realisation bit file. The FPGA was programmed to continuously run four parallel data monitoring tasks at a loop rate of 100 kHz. Data logging simultaneously stored; tractor-transplanter odometry, tractor-transplanter hitch yaw and transplanter roll and pitch inclination, transplanting wheel position, and the tractor auto guidance RTK-GPS output string. To analyse the data, analytical geometry was used to transform the geographic coordinates to UTM projected coordinates (easting and northing). The transformation was performed offline with an application specific computer program (SAS Institute Inc., 2008).

A linear regression technique as described by Sun et al. (2010), based upon tractor-transplanter odometry and 1 Hz GPS geoposition data (corrected for hitch yaw and transplanter roll and tilt), was used to estimate the geospatial location of each transplant. This step was required because planting events and GPS signals were asynchronous. The instantaneous heading angle and geospatial location values for each planting event were determined using the closest set of three consecutive RTK-GPS positions and their corresponding odometry values. The geospatial location values of all crop plants were determined offline semi-automatically using this method.

2.5. Field experiments

Field tests were conducted using processing tomato transplants as the target row crop. The field site was located near the Western Centre for Agriculture Equipment (WCAE), on the University of California, Davis campus (Latitude: 38.53894946 N, Longitude: 121.7751468 W). In this test, twelve rows were planted (single crop row/bed, 1.5 m bed spacing, and 43 cm crop plant spacing) with the transplanter and GPS autoguided tractor. The field layout was such that the rows were in a predominantly North–South direction. All bed preparation operations were conducted using a common set of GPS bed centreline ("AB") coordinates for all tillage and planting operations. All rows were planted at a travel speed of 1.6 km h^{-1}.

Planting wheel events were automatically logged in 2 different bed configurations in this study: "straight" (6 rows created with an AB straight-line) and "curved" (6 rows created with an AB curved line). The "straight" bed configuration is the one normally used by large commercial farms in California, where field levelling is performed to allow straight row furrow irrigation. The layout of the straight row test was designed to use the GPS transplant mapping system under ordinary planting conditions. To provide a robust test of the system a "curved" row bed configuration was created. The curved rows were designed to provide a curved planting path which would be a severe test of the tractor-transplanter hitch instrumentation system. The layout of the curved row test is shown in Fig. 3. Two hitch setting treatments were imposed on the curved row tests, in a split-plot design, to allow evaluation of system performance under the recommended 3-point hitch configuration with sway blocks fitted to minimise sideways relative motion and allow the planter to closely follow the path and heading of the tractor (Deere & Co, 2010) versus a "loose" hitch configuration that may occur when a lack of proper training or carelessness results in a loose, dynamic coupling between the tractor and planter that allows uncontrolled transverse motion between the tractor and the planter. Hitch setting was the main factor and bed curvature was the sub factor in the design, with two levels of the main factor (standard hitch, and loose hitch), and three levels of the sub factor (curved right, straight, or curved left). Planting wheel events, GPS location, tractor-transplanter hitch yaw, transplanter inclination and odometry were automatically logged in real-time by the embedded controller during planting trials. The absolute encoder identification values corresponding to the planting positions of the planting wheel were determined by using a subset of 15 plants as a calibration set and these offset values were subsequently applied to the remaining plants in the study.

After planting, the actual geospatial location of each transplant was determined by RTK-GPS using a handheld surveying system (Trimble model TCS1) interfaced to a rover RTK-GPS (Trimble model 4700). The GPS coordinate for each plant was obtained by placing the bottom tip of the 2m GPS antenna survey pole against the plant stem at the soil surface and holding the pole vertically with the aid of a bubble level (shown as the "real" plant location in Fig. 4). The WGS 84 Datum was used during and after planting for all RTK-GPS measurements.

The performance of the GPS transplant mapping system was evaluated by calculating the geometric distances in the easting and northing directions between the transplanter mapped plant positions, $Q(x_i, y_i)$, and the surveyed plant positions, $P(x_i, y_i)$. For each successfully planted transplant, the Euclidean distance, e_{QP}, from surveyed point P and the estimated at location Q was determined. The mean error, root mean square error (RMS), and standard deviation of error (SD) were calculated for each planting treatment in the trial.

$$e_{QP} = \sqrt{(Q(x_i) - P(x_i))^2 + (Q(y_i) - P(y_i))^2} \quad (1)$$

3. Results and discussion

Within this study a total of 1193 planting wheel events were automatically logged in the two experiments. The first experiment consisted of 607 tomato plants divided into six straight rows and the second experimental trial had 586 tomato plants also divided into six rows with two curves per row. The two main effects (standard and loose hitch settings) occurred within the second experiment. The division of tomato plants into these main effects was as follows: 314 planted with the standard hitch setting, and 272 planted with

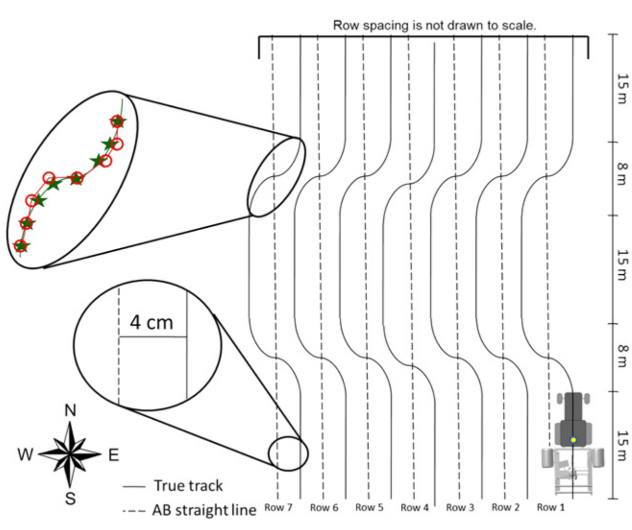

Fig. 3 – True track and straight AB line for the curved planting path treatment. The red circles represent the actual geospatial location of each transplant and the green starts the desired geospatial location.

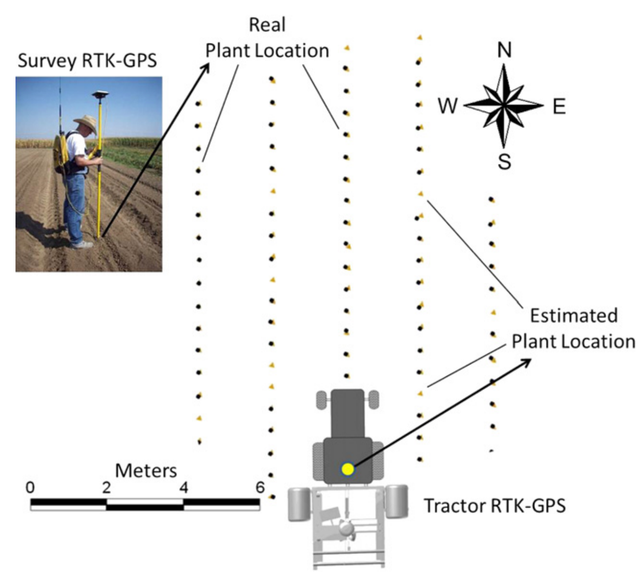

Fig. 4 – Automatically generated crop geoposition map. The map shows the crop plant locations determined by the automatic GPS mapping transplanter during planting (orange triangles). The inset photo shows the manual RTK-GPS survey measurement of the plant location ground truth. The ground truth points (black circles) were overlaid on the automatically generated map for comparison.

the loose hitch setting, respectively. For the sub factor of row curvature the division of tomato plants was 348 tomato plants within the straight sections of the six rows and 238 tomato plants within the curved sections of the six rows.

An example of the transplant maps, geo-referenced to the world coordinate system, showing the estimated plant locations automatically generated from the plant wheel sensor data and the surveyed plant locations is shown in Fig. 3. The GPS antenna mounting location on the tractor and the open nature of a processing tomato field enabled an unobstructed view of the sky during the entire trial. This allowed for optimal signal reception regardless of satellite geometry, and RTK-GPS fixed quality was obtained for the recording of all planting events during this experiment.

The data in Table 1 show the mean, standard deviation, and RMS displacement values recorded using the tractor-mounted GPS during transplanting of the six straight row experiment with the recommended standard hitch setup. This table characterises the northing and easting displacement between the surveyed plant positions and the plant position estimates automatically generated from GPS data. A mean total error in plant location accuracy of 3.2 cm was obtained by the system. These results are comparable to the 3–3.8 cm total accuracy obtained by Ehsani et al. in the RTK-GPS mapping of direct-seeded corn, where the RTK-GPS system was mounted on the planter. Results obtained by Nørremark et al. (2007) in direct-seeded sugar beet and Sun et al. (2010) with the RTK-GPS antenna attached to the planter's toolbar, showed a mean accuracy in the direction of travel ranging from 0.07 to 3.98 cm, and 0.12–3.36 cm, respectively, which is comparable to the 0.04–3.47 cm range in accuracy in the direction of travel obtained in this study.

These results demonstrate that by using a hitch sensor, a single RTK-GPS system mounted on the tractor can perform as well as systems where a separate RTK-GPS system was mounted on the planter. The tomato plant RMS location accuracy in the direction transverse (East/West) to the direction of travel was slightly lower (10%, which was significantly different from zero at $\alpha = 0.05$ according to the ANOVA) than the RMS accuracy longitudinal (North/South) to the driving direction. This is in contrast to the results by, Ehsani et al. (2004), Nørremark et al. (2007), and Sun et al. (2010) where increased error in the along-track direction was observed and attributed to due to dynamic effects during planting. This difference may be partially due to error in the hitch sensor measurements since the geometry of the relative motion between the tractor and the transplanter causes hitch position errors to have a substantially greater impact on transverse-track errors when compare to the effect on along-track errors. This issue is discussed in greater detail when the results of the second experiment are discussed, where the heading deviations between the tractor and transplanter were more severe.

Table 2 shows a summary of performance for the plant position map generated from the data recorded using the tractor-mounted GPS during transplanting in the curved row experiment. The mean and RMS deviations in plant positions between the estimated geospatial locations using the automated system from the manually surveyed map locations for the curved rows with the recommended standard hitch setup are shown at the top of Table 2, while the results for the mapping conducted with the loose hitch setting are shown at the bottom of the table. These results are for mapped points after yaw, pitch and roll correction using transplanter tilt and hitch position sensor data were applied to the GPS position data from the tractor.

The performance of the hitch yaw sensor was quite good and allowed the estimated plant map accuracy in the curved sections of the rows to be comparable to the straight sections of the trial. Since the heading of the rows in the experiment was primarily due North, errors in easting values (i.e., the transverse-track direction) were sensitive to yaw deviations particularly in the curved sections of the trial, while yaw deviations would have a minor effect on errors in northing values (i.e., the travel direction) due to the large distance between the tractor GPS and the planting wheel of the transplanter relative to the magnitude of the row offset (4 cm) in the curved sections of the trial. Comparing the mapping performance from trial tow with the data in Table 1 shows that the mean RMS easting displacement errors for the curved portions of the beds were similar to those obtained in the straight sections. Results from the ANOVA showed that there was no significant ($\alpha = 0.05$) difference in mean easting values between bed shape treatments and that the variance about the mean was also not significantly different between bed shapes. Furthermore, no trend was observed in the displacement errors associated with curve direction (right vs. left). Similarly, when the displacement errors in the Northing

Table 1 – Geospatial mapping performance with the tractor's RTK-GPS auto guidance system and real-time 3-point hitch yaw sensing for the straight row trial.

Row	Plants	Standard Hitch Settings							
		Easting Displacement (cm)			Northing Displacement (cm)			Total Error (cm)	
		Mean	S.D.	RMS	Mean	S.D.	RMS	Mean	S.D.
1	109	−0.78	2.65	2.75	0.04	2.57	2.56	3.4	1.6
2	135	1.36	2.26	2.63	3.47	2.5	2.51	3.28	1.58
3	102	0.18	1.86	1.86	0.94	2.4	2.57	2.79	1.53
4	91	−0.33	2.26	2.27	−0.44	2.94	2.96	3.32	1.7
5	87	−0.15	2.16	2.16	−1.2	2.49	2.75	3.15	1.52
6	83	0.74	2.4	2.49	−1.64	2.19	2.73	3.41	1.43
All Rows	607	0.22	2.39	2.4	−0.22	2.66	2.67	3.22	1.58

Table 2 – Geospatial mapping performance with the tractor's RTK-GPS auto guidance system and real-time 3-point hitch yaw sensing for the curved row trial.

Treatments	Plants	Easting Displacement (cm)			Northing Displacement (cm)			Total Error (cm)	
		Mean	S.D.	RMS	Mean	S.D.	RMS	Mean	S.D.
Standard Hitch Settings									
Straight beds	191	0.36	2.17	2.20	0.10	2.33	2.33	2.90	2.10
Beds curved to left	66	0.05	1.90	1.89	−0.55	1.95	2.01	2.45	1.28
Beds curved to right	57	0.00	1.85	1.83	−0.27	2.15	2.15	2.53	1.73
Loose Hitch Settings									
Straight beds	157	−0.15	1.60	1.60	0.22	2.54	2.54	2.67	1.38
Beds curved to left	58	0.11	1.85	1.84	0.01	2.41	2.39	2.72	1.31
Beds curved to right	57	0.09	1.97	1.96	0.08	1.81	1.79	2.37	1.22
All Rows	586	0.11	1.92	1.92	0.01	2.30	2.30	2.68	1.34

direction were compared, there were no significant ($\alpha = 0.05$) differences observed between the mean northing displacement errors for the different path treatments (straight vs. curved).

When the transplanter was connected to the tractor using the loose hitch setup, the extra space within the hitch allowed greater movement between the transplanter and the tractor than the recommended hitch setting. Results from the ANOVA indicated that there was no significant ($\alpha = 0.05$) difference in the easting displacement errors when comparing the performance using the loose and standard hitch settings. In addition, the northing displacement errors also showed no significant ($\alpha = 0.05$) differences in either mean or variance values for the different path treatments (straight vs. curved). These results indicate that the hitch position sensor was effective in correcting for the extra transverse-track motion of the transplanter when the loose hitch setting was used, and that the system performance did not diminish even when traversing a sharply curved path.

4. Conclusion

There exists a base of scientific research focused upon achieving accurate geospatial mapping of seeds and plants through RTK-GPS equipment mounted on the planting implement (e.g., Griepentrog et al., 2005; Nørremark et al., 2007; Sun et al., 2010), but to our knowledge a system for the geospatial mapping of crop plants using an RTK-GPS automatic guidance system mounted on the tractor without a second GPS system on the implement has not been developed. This study demonstrated the feasibility using the GPS signal from an RTK-GPS auto guidance system mounted on the tractor in the automatic mapping of crop plants during planting.

An instrumented hitch orientation sensor was developed that allowed for accurate real-time monitoring of the position of the transplanting sled in relationship to the tractor. When combined with tractor GPS coordinate data, a transplant map was automatically created during planting which had a mean RMS error of 2.67 cm in the along-track direction where 95% of the crop plants were located within a circular radius of 5.58 cm from the mapped location. These results show that it is possible to use a single RTK-GPS system mounted on the tractor for GPS location mapping of planting events occurring on the tractor-drawn transplanter without the need for an independent RTK-GPS system located on the transplanter, greatly reducing the total equipment cost of the system, without a large performance penalty.

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