2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Development of an RTK GPS plant mapping system for transplanted vegetable crops.

H. Sun[1], D.C. Slaughter[1], M. Pérez Ruiz[2], C Gliever[1], S.K. Upadhyaya[1] and R. Smith[1]

1. University of California, Davis
2. Universidad de Sevilla. Área de Ingeniería Agroforestal
   Dpto. de Ingeniería Aeroespacial y Mecánica de Fluidos.

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***Abstract*.**

This study investigated the feasibility of using real-time kinematics (RTK) GPS to automatically map the locations of tomato transplants in the field as they are planted using a vegetable crop transplanter retrofitted with an RTK GPS receiver, and an on board real-time controller. Two detection methods were evaluated for sensing plant location during planting. One method used an infrared light beam sensor to detect the stem location of each plant immediately after planting. The second method used an absolute shaft encoder mounted on the planting wheel to sense the location that each plant was placed in the soil. Odometry was used to determine the actual Easting and Northing GPS coordinates of each plant by interpolation from the original RTK GPS data stream. A field test was conducted to compare the accuracy of this transplant map with actual plant location. The average absolute differences between the automatically generated transplant map and the plant location determined by GPS survey was 0.8 to 2.1 cm in the Northing direction and 1.6 to 3.8 cm in the Easting direction, which was also the travel direction. Results suggest the feasibility of creating an accurate plant map using an RTK GPS equipped transplanter.

Keywords. RTK GPS, transplanter, plant map, tomato, precision agriculture.

Introduction

Automated technologies for agricultural field operations have been made possible in part by recent advances in sensors, electronics and computational processing power (Bak and Jacobsen, 2004; Griepentrog et al., 2004; Kise et al., 2005; Lee et al., 1999; Slaughter 2008). The need for advanced technologies in agriculture, especially the ability to accurately map plant locations, is motivated by a number of factors including, an increased consumer demand for organic produce, consumer and regulatory demand for a reduction in the environmental footprint due to pesticide and fertilizer usage, and a decrease in the availability of farm laborers willing to perform manual agricultural tasks such as hand weeding. A study conducted by Melander and Rasmussen (2001) showed that hand weeding usually requires 100-300 h/ha. Chandler and Cooke (1992) reported that in-row hand hoeing is over 5 times more expensive than between-row cultivation of cotton. Despite capital costs of new machinery, Sorensen et al. (2005) determined that an increase of 72-85% in profitability was seen on the assumption that sufficient weed control was provided by new technologies.

The availability of precision mapping technologies for crop plants would facilitate the development of automated individual plant treatment systems, which could translate into significant savings in chemical usage with environmental and economic advantages (Blackmore et al., 2005; Griepentrog et al., 2003). An accurate map of individual crop plants would open the door to several automatically controlled field operations such as (Ehsani et al., 2004; Griepentrog et al., 2005):

- Guidance of implements or tools (e.g. intra-row weed control)
- Application of insecticides, fungicides or fertilizers to individual crop plants
- Measuring vigor, growth status and yield estimation of individual plants

Geo-spatial mapping of crop plants requires both a crop plant sensor and a global positioning system (GPS). For agricultural tasks like mechanical intra-row weed control or thinning of crop plants, a high level of geo-position accuracy and precision is required. High-accuracy (~1 cm range) geo-positioning accuracy and precision is available using real-time kinematic (RTK) GPS. For example, Abidine et al. (2004) demonstrated the application of RTK GPS autoguidance technology for precision inter-row cultivation and deep tillage operations in close proximity to buried drip-irrigation tubing (5 cm target distance between crop row or drip-tape and cultivation or tillage tools) without damage to crop plants or the drip-tape. Commercial RTK GPS autoguidance systems are generally described as being capable of steering with precision errors of 25mm or less from pass to pass in crop rows where the RTK GPS autoguidance system was used to form the beds (e.g., Leer and Lowenberg-DeBoer, 2004). To achieve this level of accuracy in practice, RTK GPS requires that a GPS base station be located close (~10 km) to the mobile GPS used to control the tractor steering, radio frequency interference and GPS multipath errors must be minimal, and a minimum of four GPS satellites with good sky distribution are available (Gan-Mor and Clark, 2001).

A large body of research has been conducted in an attempt to develop crop plant sensors for both automated implement guidance in row crops and for species identification of individual plants in agricultural fields (e.g., Slaughter et al., 2008; Brown and Noble, 2005; Scotford and Miller, 2005). Most of the recent crop plant sensing research has focused on machine vision techniques because it is a non-contact method and has good potential for real-time applications. Despite commercial success in implement guidance applications, machine vision techniques have not been commercialized for precision (~1 cm range) mapping in agricultural applications. Common environmental factors such as leaf occlusion, leaf damage, missing plant structures and leaves twisting in the wind present significant challenges to precision machine vision applications at this demanding level of performance. Even though newer and more robust machine vision methods are being developed, a major drawback to the majority of machine vision methods developed to date is that they must be developed adapted or trained to distinguish each weed-crop pair.

A significant advantage of RTK GPS mapping technology over machine vision-based methods is that the accuracy and precision of the method are independent of any variation in biological morphology for agricultural row crop fields with plants at the juvenile stage (this may not be true of orchard or forest crops, however). For example, by adding appropriate sensors and instrumentation to precision seed planters, it is feasible to develop a RTK GPS enabled seed planter that can map the location of crop seeds as they are released by the planter (e.g., Griepentrog et al., 2005; Norremark et al., 2003; Ehsani et al., 2004).

The basic concept used in these seed-mapping systems is that a standard serial-type CPU is used to create a timestamp record each time a seed is dropped from the seed singulation chamber of a precision planter, where the seed drop event was sensed optically as the seed falls. A separate (asynchronous with the seed drop events) timestamp record is created at the 1 Hz GPS data rate recording the GPS time and corresponding UTM coordinates. A time-based interpolation technique is then used off-line to estimate the GPS location of the planter at the time of seed drop events.

In previous seed-mapping designs, the GPS antenna was mounted in close proximity to the planter (~1.2 m above ground) in an attempt to eliminate the need for planter/GPS antenna tilt correction (Ehsani et al., 2004). However, Griepentrog et al. (2005) concluded that the desired accuracy of this application required real-time roll and pitch tilt sensing to correct for non-uniform inclination of the GPS antenna pole during planting. Disadvantages of mounting the GPS antenna in close proximity to the planter are a decreased accuracy due to GPS-multipath error and the potential for the tractor to adversely affect the quality of the satellite geometry by blocking access to the full sky.

Another constraint of previous GPS seed-mapping systems has been the use of planters that drop the seed onto the soil. In these designs, the GPS map is based upon the planter location at the time the seed is dropped, not the location of the seed once it becomes stationary with respect to the soil. To minimize potential errors associated with seed bounce, or other factors that can result in a displacement between the location where the seed is dropped and where it germinates, planter designs that attempt to drop the seed with a zero horizontal velocity component relative to the ground were utilized. Griepentrog et al. (2005) note that a zero horizontal velocity component is typically only achieved at one operational setting of the planter. They also noted that soil texture and the quality of the seed bed preparation can also be factors.

During planting, basic sensor data were first recorded and later referenced with a 1 Hz GPS data to estimate the plant location in the field. The overall aim of the project was to create a map from which decisions could be automatically made to physically weed or apply chemicals around the plant.

The objective of this research was to develop a centimeter-level accuracy geo-position plant mapping system for transplanted row crops. The specific objectives were:

1. To instrument a positive-placement row-crop transplanter with the sensors needed to simultaneously monitor the placement of each transplant into the soil, the roll and pitch inclination of the transplanter, transplanter odometry, and transplanter geo-position from a RTK-GPS.
2. To develop a real-time, transplant geo-position data-logging system using a ruggedized industrial data acquisition system based on field programmable gate array technology for truly parallel, odometry registered sensor monitoring, without the need for timestamp synchronization.
3. To compare the accuracy of the automatically generated transplant location map with actual transplant locations.

Materials and methods

Transplanter Design

A positive-placement row-crop transplanter (model 1600, Holland Transplanter Co., Holland MI, USA) was mounted in a transplanting sled (SWEMEC Woodland, CA) that was modified for RTK GPS capability, figure 1. The planting wheel was fitted with four planting arms and configured to plant each transplant approximately 18 inches apart along the row. The position of the planting wheel was monitored using an absolute shaft encoder (12-bit Gray code, ARS 20 Sick Stegmann, Inc., OH, USA) to provide an angular resolution of 0.00154 radians or about 0.45 mm of travel along the row. This encoder provided a unique 12-bit ‘identification’ value for each of the four planting arms when the arm was in the correct position to place a transplant into the soil. Transplanter odometry was monitored using an optical shaft encoder (model 0622 Grayhill, Inc., IL, USA.) interfaced to an unpowered ground wheel to provide a resolution of 0.6 mm in the direction of travel.

A second plant monitoring system, based upon an infrared (880 nm), opposed-mode, optical light beam-based sensor (Mini-Beam models SM31E/SM31R Banner Engineering Corp., Minneapolis, MN, USA) was also evaluated, figure 1. This sensor was configured to output a TTL pulse when the infrared beam was blocked by the passage of the plant stem and was mounted about 6 cm above the soil surface and positioned 1.035 m behind the GPS antenna to allow the motion of the transplant to stabilize before it passed between the sensor’s emitter/detector pair. Two rollers were installed between the optical sensor and the transplanter to flatten the soil on either side of the seedline to minimize false detection of soil clods.

Global Positioning System

A real-time kinematic global positioning system (RTK GPS) was used to monitor transplanter location. The system consisted of a rover RTK GPS (model MS750, Trimble Navigation Ltd., Sunnyvale, CA, USA) with the GPS antenna mounted 3 m above the planting wheel, figure 1. In contrast to previous GPS seed planter designs, which mounted the GPS antenna about 1 m above ground, this mounting position provided a clear view of the entire sky, unobstructed by the tractor or the transplanter, to maximize the potential for utilizing high quality satellite geometries. In addition, the 3 m antenna height also minimized the potential for GPS multipath error. A dual-axis inclinometer (Accustar II/DAS 20 Schaevitz Sensors) was installed below the GPS antenna 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 GPS data due to implement tilt. The system communicated with a local GPS base station (Trimble model 4700) to acquire the GPS correction signal required for RTK Fixed quality location information. An 8 µs duration GPS clock reference pulse (called PPS for pulse per second), was produced by the GPS receiver for precise synchronization of the RTK Fixed quality geo-position data with external events. The GPS was programmed to output the "NMEA-0183 PTNL, PJK" string containing the UTM coordinates (Easting and Northing) once a second via an RS-232 serial connection.

After planting, the actual location of each transplant was determined by RTK GPS using a handheld control unit (Trimble model TCS1) interfaced to a rover RTK GPS (Trimble model 4700) and configured for surveying with the GPS antenna mounted on a 2 m range pole. The location of each plant was determined by placing the lower tip of the range pole against the transplant stem at the soil surface with the pole held vertical by aid of a bubble level. The NAD 83 (Conus) Datum was used during and after planting for all RTK GPS measurements.

Data Acquisition Hardware

A ruggedized, real-time, embedded controller (cRIO-9004, National Instruments, Austin, TX, USA) with a low-power CPU (195 MHz Pentium, Intel, Santa Clara, CA, USA) and 512 MB of nonvolatile flash memory storage was used for GPS and sensor data-logging tasks. The embedded controller was capable of executing deterministic control loops at update rates exceeding 1 kHz. System status information and access to logged data (via an on-board FTP server) were provided via Ethernet. The embedded controller was interfaced (via a local PCI bus) to a field programmable gate array (FPGA; cRIO-9104, National Instruments, Austin, TX, USA) which provided truly parallel sensor monitoring capability in real-time (25 ns resolution). The FPGA contained a matrix of 3 million reconfigurable logic gates for parallel processing applications. Analog sensor input data was digitized at a 12-bit resolution with a real-time rate of 500 k-samples/s using an input module (NI 9201, National Instruments, Austin, TX, USA) interfaced directly to the FPGA. FPGA i/o modules for high-speed pulse detection/counting, TTL digital and RS-232 serial data (NI 9411, NI 9403 and NI 9870, respectively, National Instruments, Austin, TX, USA) were also utilized.

Data Acquisition Software

All data collection software was written the G programming language (LabVIEW™ version 8.5, National Instruments, Austin, TX, USA). At run time, the graphical code was automatically translated into text-based VHDL code. The VHDL code is then compiled (ISE Design Suite, Xilinx Inc. San Jose, CA, USA) into a hardware circuit realization and used to reconfigure the FPGA gate array logic. The FPGA was configured to continuously run five simultaneous (i.e. truly parallel) data monitoring tasks in real-time (100 kHz) to store instantaneous transplanter odometry and inclination, planter wheel position, and GPS PPS and optical sensor (i.e., plant presence) events. Three events, planter wheel in the planting position, presence of a GPS PPS, or plant presence at the optical sensor, would trigger a data archival event where transplanter odometry and pertinent sensor data was written to the nonvolatile flash memory, as illustrated in figure 2.

A linear regression technique, based upon transplanter odometry, was used to estimate the geo-spatial location of each transplant. This step is required because planting events and GPS signals are asynchronous, which for mobile applications results in the plant and GPS data not being co-located, as shown in figure 2. In this analysis, (X_i^a, Y_i^a) were defined to be a RTK GPS (Fixed quality) antenna position and Δ_I to be the corresponding transplanter odometry value. The heading angle, ϕ, was determined by linear regression between X_i^a and Y_i^a for a set of consecutive positions. Once ϕ was known, the offset in Easting and Northing at the ground surface due to roll and pitch of the transplanter at position i were determined and used to provide an inclination corrected position (X_i,Y_i). Utilizing three consecutive inclination corrected positions, i, j, and k, and their corresponding odometry values, linear regression models can be written:

$$x_m = a\delta_m \tag{1}$$

$$y_m = b\delta_m \tag{2}$$

where x_m , y_m and δ_m are the mean centered values the three positions. Using the sum of squared errors minimization technique of Ehsani's et al. (2004), modified for odometry, the regression parameters a and b were determined by:

$$a = \frac{\sum_m x_m \delta_m}{\sum_m \delta_m^2} \tag{3}$$

$$b = \frac{\sum_m y_m \delta_m}{\sum_m \delta_m^2} \tag{4}$$

The geo-spatial location values were determined off-line semi-automatically using a program (written in Visual Basic and implemented in Excel, Microsoft Corp., Redmond, WA) designed to search the plant event database to find the three position values bounding a planter wheel or optical (light beam) sensor event, determine the associated regression coefficients using equations 3 and 4 and calculate the predicted geo-spatial position using equations 1 and 2.

Field Experiments

Field tests were conducted during the summer of 2008 using processing tomato transplants as the target crop. The field site was located at the Western Center for Agriculture Equipment (WCAE), on the University of California, Davis campus (Latitude: 38.53894946 N , Longitude: 121.7751468 W). In this test, seven rows were planted (single crop row/bed, 1.5 m bed spacing) with the GPS Transplanter to evaluate the performance of the transplant mapping system. The field layout was such that the rows were predominantly in the East-West direction. All the rows were planted at a travel speed of 1.6 km/h. The transplanter sled was pulled behind a tractor steered by an RTK GPS autoguidance system (model EZ-Guide 500, Trimble Navigation Ltd., Sunnyvale, CA, USA). All seedbed preparation operations were also conducted with a tractor steered by GPS autoguidance using a common set of GPS AB line coordinates for all tillage and planting operations.

After planting, the actual geo-spatial location of each transplant in a 350 m^2 section of the field was estimated using a RTK GPS surveying system (shown as the 'real' plant location in figure 2). For each plant, the bottom tip of the GPS antenna range pole was placed against the plant stem at the soil surface and the pole held vertical using the aid of a bubble level. The absolute encoder identification values corresponding to the planting positions of the planting wheel were determined by using a subset of 15 plants in rows 1 and 5 as calibration set and these offset values were applied to the remaining plants in the study. The performance of the GPS transplant mapping system was evaluated by calculating the geometric distances (Easting and Northing) between the transplanter mapped plant positions and the surveyed plant positions. Data were analyzed using standard statistical methods for mean and standard deviation.

Results and Discussion

In total, 527 planting wheel events were automatically logged in 7 different rows in the study. Of which, only 512 corresponded to tomato plants that were actually planted in the test plot. The optical (light beam) sensor detected a total of 491 objects, of which 249 (51%) corresponded to the main stems of the tomato plants. The mounting location of the GPS antenna allowed good satellite geometry to be obtained during the experiment and RTK GPS Fixed quality was obtained for all antenna positions recorded during planting.

Figure 2 illustrates the four different situations that resulted in a plant event (or lack of) in the mapping database: (a) a plant was correctly detected (by plant wheel sensor, optical sensor or manual survey); (b) false detection by planting wheel sensor because the operator occasionally forgot to place a plant on one of the planting arms, (c) false detection of soil or non-stem plant structure by the optical sensor, and (d) failure to detect a plant by the optical sensor because the plant was planted at an angle or was planted too deep, causing it to pass below the sensor without breaking the light beam. The false negative error rate for the planting wheel sensor was a function of the diligence of transplanting team during planting. Elimination of this type of error would require an additional sensor to confirm that a plant was actually placed in the planting arm. False negatives could also be a function of the transplant survival rate, however this type of error did not occur in this study. The planting wheel sensor was generally reliable and had no false positive errors during this study.

The optical sensor was considerably less reliable than the planting wheel sensor, generating both false positive and false negative errors. Selecting the optimum location for the optical sensor was challenging. Depending upon the soil clod structure, the optical sensor should be place at a height sufficient to pass above the majority of soil clods. However to avoid detection of plant foliage or upper branch structures, the sensor needed to positioned close to the soil to provide reliable detection of the main stem. In this study, a good position for the optical sensor proved elusive. The optical sensor was only able to successfully detect 48.6% of the transplants planted, with undetected plants having passed beneath the sensor without blocking the light beam. Additional research is require to develop an automated technique to extract the optical sensor event that corresponds to the main stem of the transplant and to distinguish between light beam interruption events due to soil, foliage and stems..

The transplant map, 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 are shown in figure 3. The data in Table 1 shows the absolute difference between the surveyed plant positions and the plant position estimates automatically generated using the plant wheel sensor or the optical (light beam) sensor, respectively, for the 7 rows in the test plot when transplanter inclination is ignored. The absolute differences between the surveyed positions and the automatically generated position estimates after correction for transplanter inclination are shown in Table 2. Since the rows were predominantly oriented in the East/West direction, the error in Northing values is dominated by inclination and GPS errors. The data show that correction for inclination is very important when attempting to develop centimeter accuracy maps. For example, the absolute error in Northing dropped from an average of 3.0 cm to 1.2 cm for the plant wheel sensor when the GPS antenna locations were corrected for transplanter inclination. A similar improvement in performance was observed for the optical sensor Northing values. These results are in agreement with those observed by Norremark et al. (2003) demonstrate that inclination sensing is important RTK GPS level accuracy transplanter generated plant maps.

The absolute error in Easting after correction for inclination, was 3.0 cm for the plant wheel sensor and 3.7 cm for the optical sensor, Table 2. The error values in estimating Easting are considerably higher than for estimating Northing. This increase is not unexpected due to the fact that the travel direction was aligned with the Easting direction and errors associated with accurate determination of plant placement would be expected in the travel direction. The data show a small advantage in both accuracy and precision of the plant wheel sensor over the optical sensor. Coupled with the high false positive error rate (almost 50%) of the optical plant sensor, these data show that sensing planting position by using an absolute encoder on the transplanting wheel shaft is gives superior performance.

The errors for the plant wheel sensor map ranged from 0.8 to 2.1 cm in the Northing direction and 1.6 to 3.8 cm in the Easting direction, which was also the travel direction. These levels of performance are similar to those obtained by Ehsani et al. (2004), and Griepentrog et al. (2005) in their work on automatic RTK GPS mapping of seeds during planting. Given the GPS error in the reference (survey) method, these results are very good and demonstrate the feasibility of developing a RTK GPS enabled transplanter for the automatic generation of centimeter accuracy planting maps in transplanted crops.

Table 1. Geo-spatial mapping performance of plant wheel and optical plant sensors without pitch and roll correction.

	Mean Absolute Deviation (cm)						Std. Dev. (cm)					
	Absolute Encoder			Light Beam Sensor			Absolute Encoder			Light Beam Sensor		
Rows Planting	Plants	Northing	Easting	Plants	Northing	Easting	Plants	Northing	Easting	Plants	Northing	Easting
1	82	4.60	5.68	40	4.63	4.00	82	1.92	2.47	40	2.21	3.01
2	83	1.65	3.91	24	5.26	3.79	83	1.11	1.87	24	1.57	3.02
3	79	1.60	5.11	38	4.66	2.26	79	1.09	2.25	38	1.61	1.58
4	73	3.24	6.26	33	5.71	2.22	73	2.06	2.51	33	3.18	1.65
5	65	2.00	1.72	31	2.37	5.17	65	1.30	1.50	31	1.32	2.61
6	72	3.10	1.73	41	5.51	6.86	72	0.48	2.82	41	1.15	2.82
7	58	4.70	2.12	27	4.97	5.92	58	1.54	1.48	27	1.55	2.82

Table 2. Geo-spatial mapping performance of plant wheel and optical plant sensors with pitch and roll correction.

	Mean Absolute (cm)						Std. Dev. (cm)					
	Absolute Encoder			Light Beam Sensor			Absolute Encoder			Light Beam Sensor		
Rows Planting	Plants	Northing	Easting	Plants	Northing	Easting	Plants	Northing	Easting	Plants	Northing	Easting
1	82	0.83	3.83	40	1.59	3.03	82	0.77	2.21	40	1.05	1.74
2	83	0.86	2.31	24	3.82	2.93	83	0.70	1.61	24	1.65	2.24
3	79	2.12	2.56	38	2.40	3.74	79	1.34	2.25	38	1.51	2.90
4	73	1.72	3.76	33	1.58	3.48	73	1.18	2.69	33	0.83	2.43
5	65	0.73	1.57	31	1.11	3.36	65	0.25	0.81	31	1.07	2.31
6	72	1.01	3.53	41	1.11	4.45	72	0.79	1.82	41	0.87	2.18
7	58	1.13	3.54	27	1.15	4.85	58	0.78	1.55	27	0.98	2.07

Conclusion

Based on this study, the following conclusions were reached:

- A vegetable crop transplanter was successfully modified to allow automatic data logging of RTK Fixed quality GPS data, and transplant odometry.
- Using an off-line interpolation method based upon linear regression, a plant map could be automatically created with centimeter-level accuracy when compared to plant positions determined manually by RTK GPS survey.
- The plant map generated by the method of plant detection using a light beam sensor towards the rear of the implement was not as accurate as the plant map generated using an absolute shaft encoder mounted on the planting wheel.

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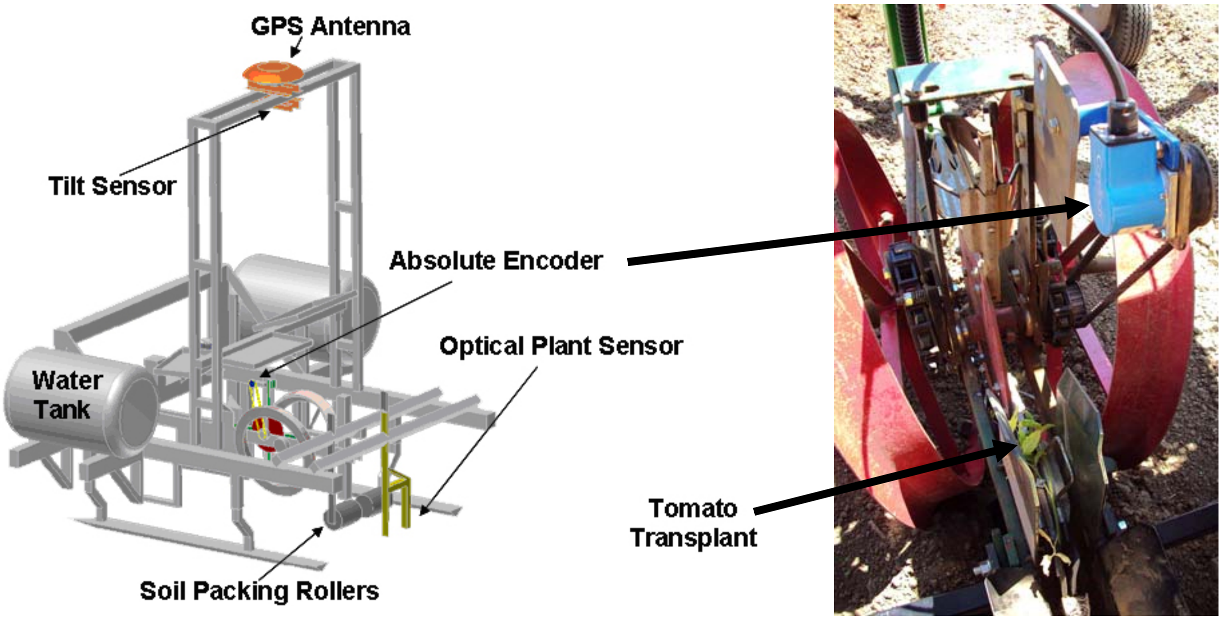
Figures



(a) (b)

Figure 1. Row crop transplanter, adapted for geo-spatial mapping of crop plants. 1a) Schematic diagram showing the sensor arrangement and GPS antenna, 1b) photograph of the transplanter showing the absolute shaft encoder used to monitor the placement of each transplant as it is placed into the soil.

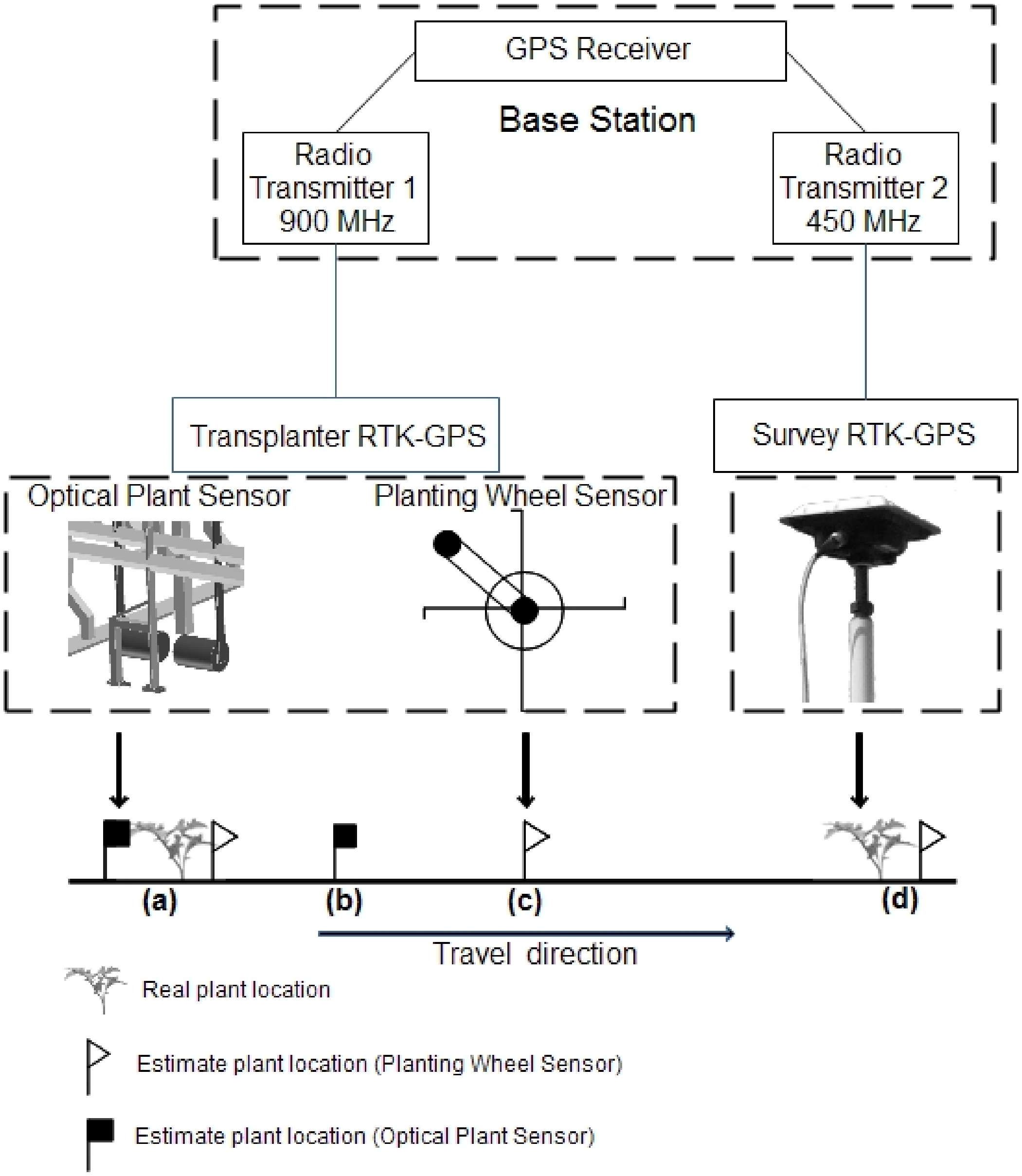
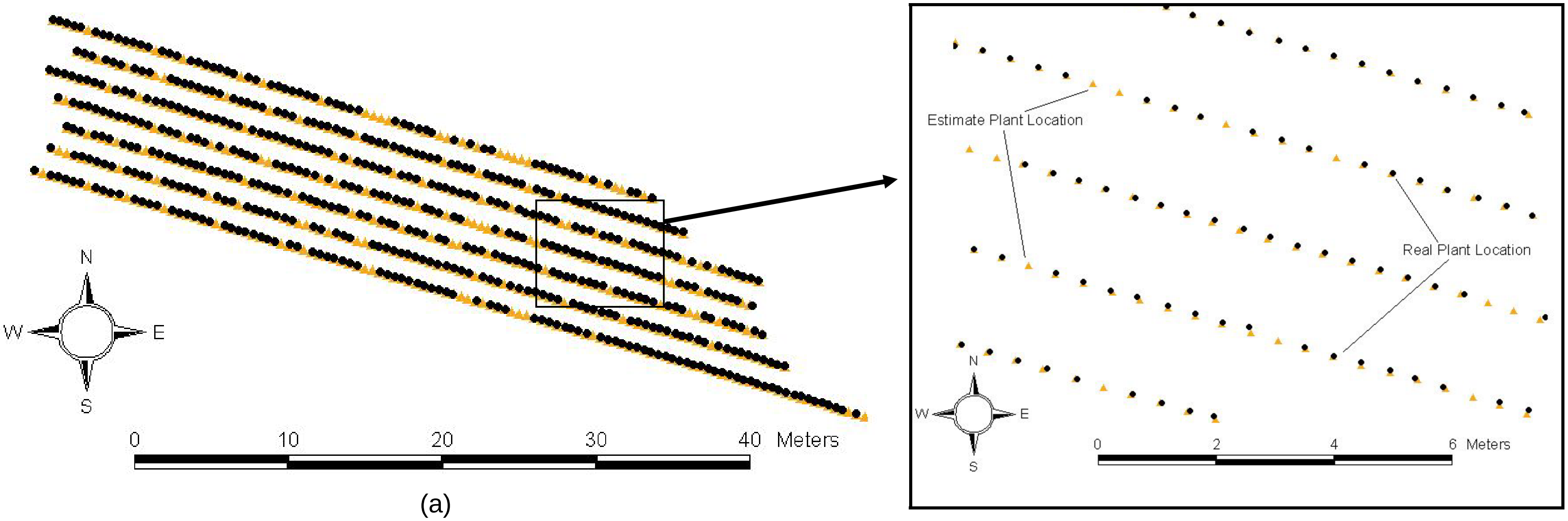


Figure 2. Schematic diagram of the GPS mapping and surveying systems illustrating the asynchronous relationship between GPS data events and plant location.



(a)

(b)

Figure 3. Example transplant location map. 3a) Plant location map for the 7 test rows using the RTK-GPS transplanter and the planting wheel sensor and 3b) view in detail of the surveyed plant location and estimated plant location using the planting wheel sensor.