Development of a Precision 3-row Synchronized Transplanter

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Abstract.

Commercial vegetable crop transplanters currently use several unsynchronized planting units mounted to a common transport frame. The objective of this work was to assess the performance of a new transplanting technology to improve the plant placement accuracy and spatiotemporal planting synchronization across adjacent rows, thus producing a grid-like planting pattern using adjacent vegetable crop transplanters. The feasibility of synchronization of adjacent transplanting units for vegetable crops was demonstrated using tomato as the target crop. A colour, digital, high-speed computer vision analysis of the motion and dynamics of the plant trajectories of transplanted tomatoes was conducted. The high-speed video analysis led to the design and testing of an improved plant support mechanism to enhance the control and precision of the transplanting of vegetable crops. The absolute deviation values of the final location in the soil were reduced by approximately 25% for both the right planter and left planter compared to those in previous years. These results serve as the fundamental basis for a mechatronic system that

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can precisely transplant vegetable crops in a grid-like pattern across rows as a critical first step in a systematic approach to fully automated individual plant care.

Key words. Precision agriculture; High-speed video; Transplanter; Computer vision

1. Introduction

Precision agriculture implies accuracy in the distribution of plants and seeds over fields. Optimal distributions are defined by the size and shape of the area that provides nutrients, water and light to plants to obtain the maximum possible yield. These factors are controlled by the spacing between crop rows and the spacing between plants/seeds in a row (Klenin, Popov, Sakun, 1985; Barbieri et al.~~,~~ 2012). The relationship between crop yield and plant spacing has been well documented (Nielsen, 1991; Doerge, Hall, Gardner, 2002). For many crops, the row crop spacing is determined as much by the physical characteristics of agricultural machinery used as by the specific biological spacing requirements of the crop (Blas, Barreireo, Hernández, Dias, Griepentrog, 2013~~, 201~~). In addition, a key aspect to the accurate planting of a precision transplanter/seeder for a typical square grid pattern requires equipment calibration checks ~~equipment calibration~~ before planting in both the longitudinal and transverse crop directions (Perez-Ruiz, Slaughter, Gliever, Upadhyaya, 2012).

The importance of precision planting is a well-established concept. In addition to its impact on optimizing overall yield, it affects the uniformity of crop emergence and in specialty crops like head lettuce it impacts labour costs associated with the management and harvest of the crop (Harriott, 1970). Nielsen~~ et al.~~ (2006) indicated that irregular plant spacing within rows decreased maize~~corn~~ grain yield at rates of up to 125.5 kg ha^{-1} for every 0.25 m increase in the standard deviation of plant-to-plant spacing within a range of plant spacing variability from ~0.05 to ~0.36 m. Another reason to improve the uniformity of plant distribution in the field is to ensure a rapid crop emergence and ~~(~~uniform crop canopy closure~~)~~ and hence achieving soil cover at the same time that crop’s development, thereby avoiding patches of the field that are exposed due to poor plant spacing (Upadhyaya & Blackshaw, 2007; Heege, 2013). If tomato transplants are positioned in a predetermined~~regular grid~~ patterns, resource utilization (nutrients, water, light and space) can~~will~~ be optimized. The use of a rectangular grid can improve ~~, thereby improving~~ the ability~~ of the crop to suppress weeds and making it easier~~ to utilize automated mechanical ~~or physical~~ weeding treatments.

For agronomic reasons (e.g., earlier harvesting, better crop establishment in challenging farming conditions, and better development of root systems), transplants are utilized for some crops; these plants are usually grown in transplant cell trays to reduce plant stress at the time of transplant~~at~~ing and because plants of uniform size are needed for the transplanter (Parish, 2005). In 2017, it was estimated that 70% of the 113000 hectares of canning tomato were transplanted in the USA (Miyao, Aegerter, Sumner, Stewart, 2017); according to technicians and tomato growers today, this percentage may now be 10-20% higher.

The plant~~n~~ing of most~~Most~~ vegetable crops is currently done using ~~use~~ a mechanical transplanter (carousel or pocket-type transplanter), despite its dependence on a~~the requirement for~~ significant amount of manual labour to feed and operate the machine. At this point, it is possible to find commercial automatic transplanting machines for greenhouse production (Visser Group, Holland, 2014). However, semi-automatic (Zhang, Cao, Wang, Zhang, 2013) and automatic feeding mechanisms are gradually being developed and are beginning to reach the market for vegetable plug seedling (Han, Kumi, Mao, Hu, 2019; Pearson Autoplanter, 2020). A pocket-type planting unit has a number of spring-loaded plant pockets arranged at equal intervals on a drum. The drum is driven from ground-contacting wheels through a gear (Rotty, 1960) or chain drive. When the drum rotates, a plant pocket opens as it approaches the top of the cycle, receives the transplant, closes, carries the transplant downwards, and releases the transplant in the furrow. The current designs of commercial vegetable crop transplanters utilize several unsynchronized (i.e., the units operate independently in terms of their drive mechanism) planting units mounted to a common transport frame. These systems use suboptimal open-loop methods that neglect the dynamic and kinematic effects of the mobile transport frame and the plant motion relative to the frame and the soil. The current designs also neglect to employ complete mechanical control of the transplant during the planting process, thus producing an error in the final planting position due to the increased uncertainty of plant location in the soil, which is related to natural variations in the plant size, plant mass, and soil traction and compaction characteristics (Prasanna Kumar & Raheman, 2008). Due to plant/field variations and transplanter operation conditions, the desired synchronization can't possibly occur if there is no linkage between the planting units. The in-field operation is based on the rotation of a shaft which is controlled by the travel speed of the transplanting unit~~machine~~ through the field and is often powered by separate ground-driven wheels that are affected by localized slip conditions between each transplanting unit's wheel and the adjacent soil in each row. While these~~.~~ ~~These~~ transplanters may seem to be designed to maintain a uniform distance between plants, row-to-row variability in soil conditions causes plant spacing variability and because there is no linkage between adjacent planting modules there is no synchronization in plant placement between rows.~~according to manufactures, this synchronization does exist~~

With the objective of simultaneously reducing the drudgery of menial labour associated with vegetable production and the need to reduce the negative environmental impact of pesticides, the scientific community is working on the development of new solutions for individualized plant care. One such approach is to create a plant map using real-time kinematic (RTK) global positioning systems (GPSs) by monitoring the seeds (Ehsani, Upadhyaya, Mattson, 2004) or transplants (Sun et al., 2010) while they are being planted. Studies conducted at UC Davis have shown differences between RTK-GPS-based expected seed locations versus actual plant positions. The difference in actual vs. expected position ranged from 3~~.~~0 to 3~~.~~8 m~~c~~m~~, and~~ for seeds, and for tomato transplants, the root mean square error (RMSE) was 2~~.~~6.7 m~~c~~m in the along-track direction. Taking into account the error due to the accuracy of RTK-GPS and other factors that influence the seed placement and seed dynamics (Ehsani, Upadhyaya, Mattson, 2004), these results show good performance.~~.~~ Nakarmi & Tang (2012) used a platform for~~of~~ image acquisition after planting operations to estimate the inter-plant distance along crop rows. This system was able to measure inter-plant distance with overall mean RMSE of 1~~.~~7 m~~c~~m and mean plant misidentification ratio of 2.2%. Similarly, Zong, Liu and Zhao ~~Zong et al.~~ (2020) investigated ~~a~~ real-time plant location using a machine vision system which the purpose of individual plant fertilization~~propose of fertilization for individual plant~~, under weedy condition on sunny days, has a minimum recognition rate of 88% for maize.

Today, one of the challenges associated with agricultural row crop production in industrialized countries is the non-chemical control of intra-row weed plants (i.e., within a crop row). A number of researchers have documented the negative impacts of weeds on crop productivity: Fennimore & Umeda (2003) found that 4 weeks of weed competition reduced lettuce yields by 11 to 23%, Wicks, Johnston, Nuland and Kinbacher (1973) found that onions infested with annual weeds for 8 weeks reduced yields by 65%, Ngouajio, McGiffen and Hembree (2001) found that ~~1.~~5 velvetleaf weeds per meter~~foot~~ of row caused yield losses of up to 80% in tomato. Several researchers (e.g., Bell 1995; Haar & Fennimore, 2003) have documented that weeds in vegetable crops also cause contamination of the harvested crop and can be a host of disease. The complete elimination of weeds within the seedline with mechanical methods is very attractive for organic growers, and such methods involve mechanical knives and rotating hoes that are suited for use with robotic weed control actuators (Perez-Ruiz, Slaughter, Fathallah, Gliever, Miller, 2014; Lati, Siemens, Rachuy, Fennimore, 2015). However, the performance of mechanical weed removal is constrained by plant spacing, the closeness of the weed to the plant, the plant height and the actuation time between plants.

In the past decade, several research groups have worked diligently on precision intra-row weed control (~~Jørgensen et al., 2007; ~~Nørremark, Griepentrog, Nielsen, Søgaard, ~~Nørremark et al.,~~ 2008; ~~Ulloa~~Ulloa, Datta, Knezevic~~ et al.~~, 2010; Van Evert et al., 2011; Forcella, 2012; Perez-Ruiz et al.~~,~~ 2012; Raja et al., 2019). These systems have demonstrated the importance of highly accurate plant placement to facilitate the use of mechatronic or robotic technology in weed control tasks. The precise planting of vegetable crop transplants in an orchard-like grid planting pattern is a critical step in a systematic approach to automated individual plant care methods, such as automatic mechanical or grit-abrasion weeding, precision spraying for pest control, fertilization, and irrigation.

The goal of this work was to develop and analyse the performance of a precision plant placement technology to improve the plant position accuracy and synchronize the planting pattern between adjacent rows planted in the same planting pass. The specific objectives were as follows:

1. To design and evaluate the performance of a three-row synchronized transplanter using tomatoes as the target crop;
2. To evaluate the plant kinematics of tomato plants during transplanting; and
3. To evaluate the effect of seedling support during transplanting on the precision of transplanting performance.

2. Materials and methods

2.1. Synchronized three-row transplanter design

The purpose of the 3-row synchronized system is to consistently space tomatoes along a row and align the plants across three rows in a grid-like rectangular planting pattern. Since California processing tomatoes were the target crop, the planters used in this study were spaced 1.5 m apart. Three finger-type, positive-placement, vegetable transplanters (model 1600, Holland Transplanter Co., Holland, MI, USA) were mounted on a transplanting sled (SWEMEC Woodland, CA) that was designed for synchronized operation. This modified transplanter design used three precision planting wheels custom manufactured for synchronized operation and allowed a simple telescoping mechanical linkage to connect and synchronize the angular rotation of adjacent planting wheels (Figure 1). Mechanical synchronization was achieved by using splined power take-off (PTO) drive shafts on the planting wheels and two ~1.5 m matching PTO splined linkages to connect the adjacent planting wheels. A torque-limiting hub was mounted in the centre of each planting wheel to allow both overload protection (in the event of an object getting jammed in the planter) and a splined drive shaft.

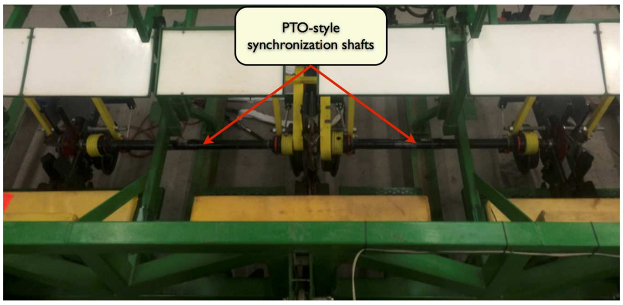


Figure 1. Photograph showing the PTO-style synchronization shafts (black with yellow safety end covers) connecting the three precision planting wheels.

In addition to the main frame and 3-planting wheels, this transplanter included soil preparation equipment that opened three planting furrows in the planting beds ahead of the positions where the tomato plants were placed. The transplanter also included three furrow-closing devices that closed the planting furrows and pressed the soil around the plant root balls to provide the necessary growing conditions and support after plants were released by the machine. In a traditional, unsynchronized transplanter, a set of two steel ground wheels (560 m~~c~~m diameter and

7~~.~~6 m~~c~~m width, with two ground wheels per planter) serve as both the source of mechanical power to rotate the planting wheels and as the furrow-closing device. Due to the location of the PTO synchronization shafts, custom furrow-closing steel wheels (30~~.~~5 m~~c~~m diameter, 80 m~~c~~m width) were required that would fit below the synchronization shaft on both sides of the centre planter and inside the two outside planters.

2.2. Synchronization system

The first prototype of the synchronized 3-row transplanter used custom steel ground-driven wheels (Figure 3) to provide mechanical power to drive the planting wheel rotation (Figure 2). However, planting inconsistencies were observed in the year-1 field trials due to differences in ground wheel slip between the two ground wheels shown in Figure 3 and the elasticity in the long drive shaft that connects the three planting modules. To improve both the accuracy of the plant spacing along a row and the accuracy and precision of the planting pattern synchronization, a hydraulic power system was designed in year-2 to drive the planting wheel.

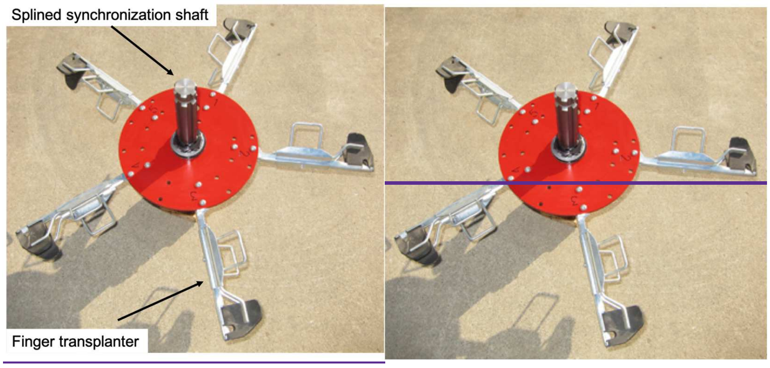


Figure 2. A planting wheel with the splined, PTO-style, index shaft used for synchronization

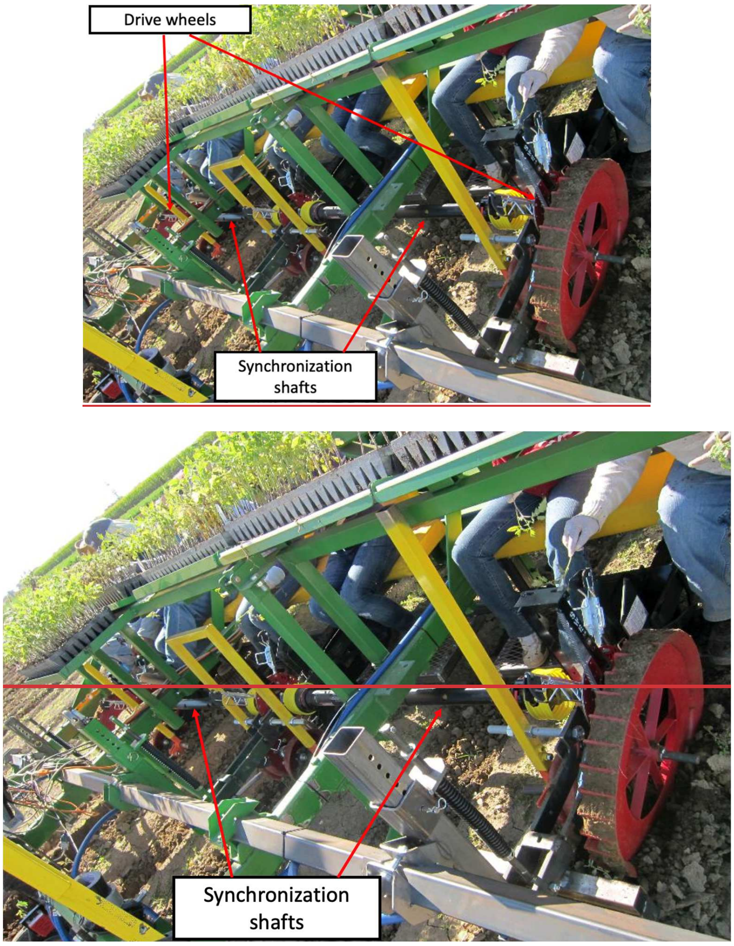
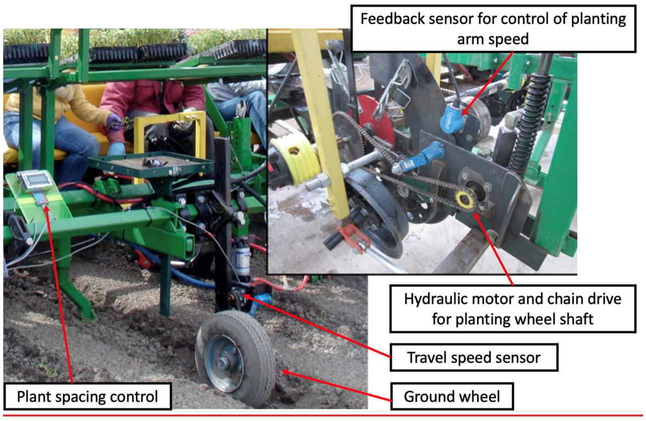


Figure 3. View inside the year 1 synchronized transplanter showing the splined PTO-style connecting shafts used to synchronized the rotation of the planting wheels. The red outer ground wheels supplied power.

For the second-generation transplanter, the synchronization system was composed of an unpowered gauge wheel equipped with an optical shaft position encoder (model 0622 Grayhill, Inc., IL, USA); a 2-way electrohydraulic, proportional, directional control valve (model

D1FXE01HCNCK00, Paker Hanninfin Corporation, OH, USA); a 12-bit absolute shaft encoder (model ARS 20 Sick Stegmann, Inc., OH, USA); and a microcontroller (model ATmega1280, Arduino, Duemilanove, Italy). The standard non-powered agricultural gauge wheel was used as the odometry sensor (Figure 4). A compact hydraulic gear motor (model Char-Lynn 101-1008-009, 0.37 L•revolution^{-1}, 5 kW power at 1260 L•h^{-1} flow, Eaton Corporation Inc., Cleveland, OH, USA) was used with a chain drive system to rotate the planting wheel, as shown in the inset photograph in Figure 4. Hydraulic power was transmitted from the tractor's hydraulic quick plug to the hydraulic gear motor of the transplanter. The absolute encoder was connected via a mechanical linkage to the planting wheel shaft. The microcontroller provided closed-loop control of the angular velocity of the planting wheel by comparing the output of the two shaft rotation sensors and adjusting the hydraulic oil flow through an electrohydraulic, proportional, directional control valve that was connected to the hydraulic motor.

Three pairs of light-beam sensors (Mini-Beam models SM31EL/RL, Banner Engineering, Corp., Minneapolis, MN, USA), one for each row, were configured to output a TTL pulse when the infrared beam was blocked by the passage of the plant stem during the transplanting process. All three light-beam signals were monitored simultaneously in real time with a very-high-speed embedded control system.



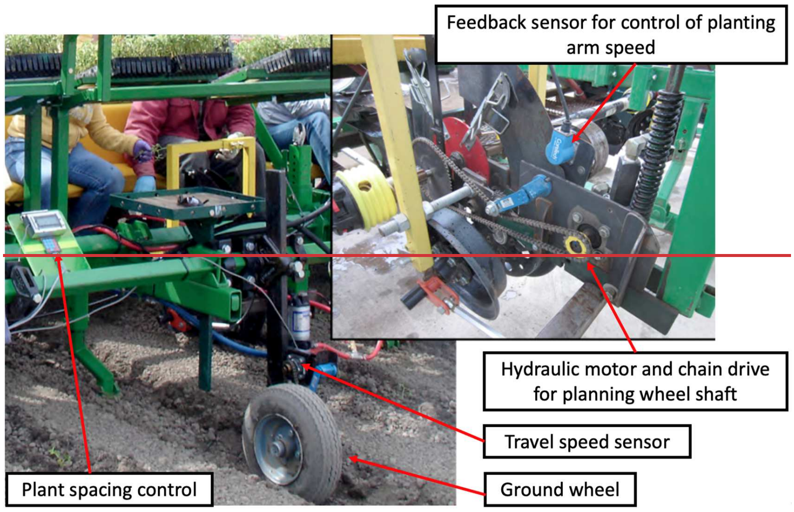


Figure 4. (a) The PTO-style synchronization shafts connecting the three planting wheels and (b) the ground –wheels speed sensor and feedback control system for maintaining the desired plant spacing.

2.3. High-speed plant kinematic assessment

The successful operation of the transplanter was dependent upon its ability to securely grasp and hold a considerable variety of seedlings without injuring the seedlings or requiring a high degree of manual attention when feeding the plants into the machine. In a finger-type transplanter, the final planting depth of the root ball is regulated by the distance the root bulb extends past the end of the pocket of the planting arm. Individual variation between plants characteristics, such as root bulb weight, stem strength and age, is a complicating factor that affects the oscillatory motion of the plant when released by the worker.

A high-speed machine vision analysis of the plant root ball kinematics during transplanting was conducted. Under laboratory conditions, a high-speed digital camera (model Powershot ELPH 300HS, 120 frames per second, 640 x 480 pixel resolution, Canon, Tokyo, Japan) was used to record the motion of tomato plants from the time the operator placed the plant into the planting arm hand holder until the plant was released and dropped to the ground. -The planting wheel was operated at angular velocities equivalent to two planting travel speeds: 0.8 km h^{-1} and 1.6 km h^{-1}. The transplanter was stationary for this laboratory study, and the planting wheel speed was controlled using a function generator (model 33220A Agilent, Santa Clara, CA) to simulate forward travel. Two different sizes of tomato plants were used in this laboratory test: a typical transplant size (~~0.~~2.5 m~~c~~m mean stem diameter and 18~~.~~6 m~~c~~m mean height) and a large size (~~0.~~3.1 m~~c~~m mean stem diameter and 26~~.~~1 m~~c~~m mean height). The two-dimensional trajectory (i.e., in the plane of the planting wheel) was determined by an automatic tracking process using digital video motion analysis software (Kinovea version 0.8.7, www.kinovea.org) to obtain the actual position of the centroid of the plant root bulbs over time. The tangential speed and corresponding tangential acceleration in each video frame were calculated during the travel path as the planting wheel rotated from the plant feeding location to the plant release location.

To measure the variation in the radial distance from the root ball to the centre of the planting wheel shaft, the following expression for the 2D image plane coordinates (x,y) related to the distance between two points (X_{root}, Y_{root}) and X_{wheel}, Y_{wheel}) was utilized.

$$\Delta r = ((X_{root} - X_{wheel})^2 + (Y_{root} - Y_{wheel})^2)^{1/2} \qquad \text{Eq. 1}$$

2.4. Improved planting precision system

In California, the centroid of the root ball of the tomato transplant is typically planted 7~~.~~5 m~~c~~m below the soil surface. To achieve this planting depth, the centroid of the root ball was cantilevered 7~~.~~5 m~~c~~m past the end of the rubber fingers on the transplanting wheel. As a result, a bending moment is applied to the root ball at the time the plant is placed in the fingers of the transplanter. Depending on the strength of the plant stem, this bending moment can result in the erratic motion of the root ball as the planting wheel rotates the seedling from the loading position to the release position.

To avoid this erratic motion and improve the precision with which the tomato plants were placed in the soil, a hemicylindrical metal channel support was mounted on the end of each of the five planting arms. This support was mechanically fastened to ~~located on~~ the back of each~~the~~ planting finger and created an extension of the plant holder to avoid random motion between the time the plant was placed in the fingers and when it was released into the soil (Figure 5). In addition, the length of this support was adjustable and designed to facilitate precise root ball placement, in the radial direction along the planting finger, by the worker. During operation, the worker simply placed the top edge of the root ball against the tip of the metal support when loading the planting finger. This additional feature was designed to improve the precision of the depth of root ball placement below the soil level.

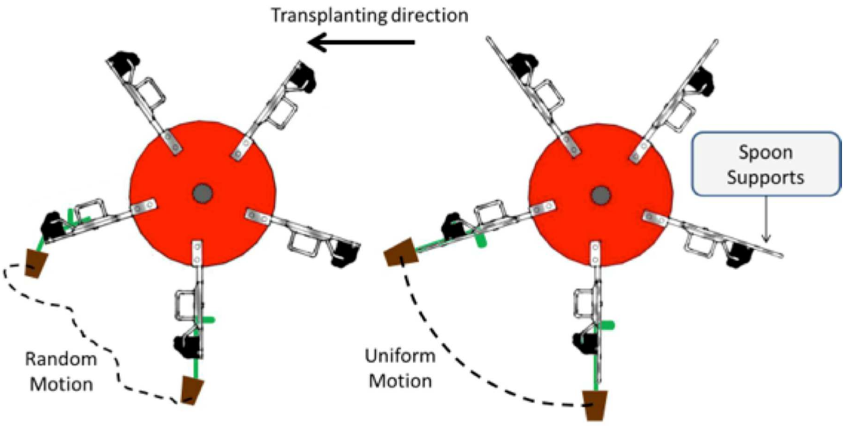


Figure 5. (a) Conventional 5-arm planting wheel designed to allow mechanical linkage to connect adjacent planters and (b) Experimental 5-arm planting wheel with the metal spoon supports mounted.

2.5. Field experiments

Three years of field tests were conducted to evaluate the performance of the 3-row synchronized transplanter. In year-1, field tests were carried out in a 53-ha ~~(130 acre)~~ commercial organic tomato field in northern California (latitude: 38.372129ºN, longitude: 121.712159ºW). In year-2 and 3 field tests were conducted at the Western Center for Agricultural Equipment (WCAE) at the University of California, Davis campus farm (latitude: 38.53894946°N~~—~~, longitude: 121.7751468°W). All pre-planting soil tillage and seedbed preparation operations were completed as part of the normal farming operations in the field where the test plot was located. In each year, a team of six experienced farm workers (two individuals working as a paired team for each planter) assisted with the synchronized transplanting operation by manually placing tomato seedlings in the fingers (Figure 6). The forward travel speed was set to 1.6 km h^{-1} during each planting trial and the target plant spacing along the row was 380 m~~c~~m. In year-2, each test block was divided into two equal-sized subplots, one planted with the metal supports integrated in the plant holder to increase planting position precision, and the other a control treatment planted using the traditional method without the metal supports.

The prototype 3-row synchronized vegetable crop transplanter was attached via a 3-point hitch to a tractor (model 6430, John Deere, Moline, IL) equipped with two 378-L water tanks for irrigation during transplanting according to standard farming practice. Figure 6 contains a photograph taken during operation, in which the position of the planting fingers of the right planter and centre planter are shown to be at nearly the same position relative to the finger closing guides on the sled, demonstrating synchronization.

To evaluate the performance of the 3-row synchronized transplanter, a large 3.66 m by 3.05 m three-row, rectangular, metal measuring frame was constructed with one longitudinal element per row. ~~The measuring frame contained three longitudinal braces that were 3.66 m in length, one for each row of tomato plants. Additional bracing was utilized to maintain the rigidity and rectangular shape of the frame. Along each of the three longitudinal braces of the frame, a 3.66-m measuring tape was secured.~~ In the field, the longitudinal braces of the frame were placed adjacent to each of the three rows of tomato plants within a 3-bed planting set. For each plant location (27 plants per length, and 81 plants per frame) ~~along each of the three measuring tape brace sections,~~ the plant location was evaluated visually and recorded. The precision and accuracy of the synchronization of plant placement were analysed using statistical software (SAS/STAT, version 9.3, SAS Institute Inc., Cary, NC, USA).

Figure 6. Photograph showing the position of the root ball relative to the fingers of the transplanter. The root ball (held inside the person's hand in the foreground) is typically cantilevered 7~~.~~5 m~~c~~m past the end of the finger.

Improvements to the 3-row synchronized transplanter for the on-campus field test in year-3 included: change to automobile drive shafts, reduced the play in the driveline, added the metal supports and changed the rubber in the fingers. Thirty rows of tomatoes were planted (single crop row/bed with 1.5-m bed spacing), and all rows were planted at a travel speed of 1.6 km h^{-1}. In this year, seventy-two sets of conditions for the metal support treatment and sixty-nine sets for the control treatment of tomato plants were measured along the 3-row planting sets. These measurements were analysed to determine the accuracy of the synchronization across each 3-row planting set as well as the plant spacing consistency along each row in the direction of travel.

3. Results and Discussion

~~A synchronized, 3-bed precision transplanter was developed for the precision planting of vegetable seedlings in a three-row, grid-like planting pattern. The field results demonstrate that the system was effective at synchronously placing seedlings plants were precisely placed at the same grid location in the direction of travel along three adjacent rows. This system was specifically designed to achieve a high level of synchronization for the rotational positions of adjacent 5-finger-type tomato transplanters.~~

3.1. Three-row transplant position and synchronization

A summary of the final plant placement of tomato plants along the row is shown in Table 1 for the trials conducted in three years. In year-1, the planting wheels of the transplanter were powered by a traditional chain drive that linked the shaft of the planting wheel to the 560-m~~c~~m-diameter steel (red) soil packing wheels shown in Figure 3. The target plant spacing along the row was 380 m~~c~~m. ~~The best matching mechanical gear ratio was selected from those provided by the transplanter manufacturer to achieve this target spacing.~~ The mean, as-planted, spacing was fairly close to the goal, with a mean error of ~9 mm and a standard deviation of ~30 m~~c~~m.

In the year-2 trial, the power required to rotate the three planting wheels was supplied by a hydraulic gear motor rather than the soil packing wheels. Thus, the mechanical coupling between the packing wheel and the planting wheel was replaced by a digital control virtual~~data~~ coupling between an unpowered ground wheel speed sensor and a feedback control circuit for the hydraulic motor speed controlling the planting wheel rotation. A closed-loop feedback control system was used to control the angular velocity of the planting wheel, where the planting wheel velocity setpoint was determined by sensing the angular velocity of the unpowered ground wheel using an optical shaft rotation encoder. The mean, as-planted, spacing was closer to the target

(380 m~~c~~m) using the hydraulic power system and unpowered ground wheel sensor. The improvements in the design form year 1 to 2 showed that the mean plant spacing error decreased from ~9mm in year-1 to ~3mm in year-2, and the improvement in the plant spacing accuracy was statistically significant at α = 0.01. In contrast to the improvement in the plant spacing accuracy, the plant spacing precision was not significantly (p-values > 0.15) improved for two of three planters (left and centre), while a significant (α = 0.01) improvement was observed in the precision of the right-side planter. In addition to the planting performance improvements, ~~Because~~ the use of a~~of the~~ digital interface for the feedback control system in year 2, allowed the operator to easily make~~,~~ changes to the desired plant spacing ~~could be implemented~~ by keypad entry, rather than by mechanically changing drive sprockets, as was required in year-1, which represents a significant improvement in ease of use.

Table 1. Summary of the Plant Spacing ~~Accuracy and Precision~~Performance

				Plant Spacing* (m~~c~~m)	
Year	Power Source	Obs.	Planter	Mean	Std. Dev.
1	Ground Wheel	288	Left	37~~.~~1.60a	2~~.~~6.40a
2	Hydraulic Motor	90	Left	38~~.~~0.50b	2~~.~~6.90a
1	Ground Wheel	288	Centre	37~~.~~0.80a	2~~.~~8.20a
2	Hydraulic Motor	90	Centre	38~~.~~2.30b	2~~.~~2.09a
1	Ground Wheel	288	Right	37~~.~~0.30a	3~~.~~0.00a
2	Hydraulic Motor	90	Right	38~~.~~3.30b	2~~.~~0.30b

*Treatments with different grouping letters are significant at the alpha = 0.01 level.

Con formato: Izquierda, Posición: Horizontal: Centro, Con relación a: Columna, Vertical: 0 cm, Con relación a: Párrafo, Horizontal: 0,25 cm, Ajuste automático

Tabla con formato

The distribution of the relative plant alignment between the three synchronized planters in the year-1 trial is shown in the upper two histograms in Figure 7, and a summary of the mean and standard deviation values is shown in Table 2. The tomato plants planted by the transplanter on the left lagged behind the centre plants by 1~~.~~3.2 m~~c~~m on average, with 90% of the tomato plants planted by the left planter being within -5~~.~~1 to 2~~.~~5 m~~c~~m of the corresponding centre plant, where a zero value indicates perfect alignment. Similarly, the tomato plants planted by the transplanter on the right were planted 1~~.~~4.7 m~~c~~m ahead of the centre plants on average, with 90% of the tomato plants planted by the right planter being within -3~~.~~8~~1~~ to 70~~6.99~~ m~~c~~m of the corresponding centre plant. In general, the plants planted by the centre and left planters were better aligned than those for the centre and right planters. The misalignment between the plants planted by the left and right planters was the most severe, with the left side lagging the right side by 2~~.~~7.9 m~~c~~m on average. Visual observation during the year-1 trial suggested that a differential in the wheel slip of the packing wheels due to irregularities in planting bed height, soil moisture and compressibility ~~may~~ and the elasticity in the long shaft that connects them may have been~~be~~ responsible for the reduction in ~~lack of~~ synchronization. In the year-1 design, the two packing wheels used to power the rotation of the planning wheel shaft were on the two extreme sides of the 3-row set, making them 2~~.~~7.9 m~~c~~m apart. ~~This large span may also be a source of the misalignment problem observed in year 1.~~ The year-1 results motivated the design change in year-2 to eliminate the powered ground wheels and mechanically decouple the ground wheel from the planting wheels.

In figure 7 the top two histograms are from the on-campus trial of the year-1 prototype. The bottom two histograms are from the year-2 trail in a commercial tomato field using the improved system.

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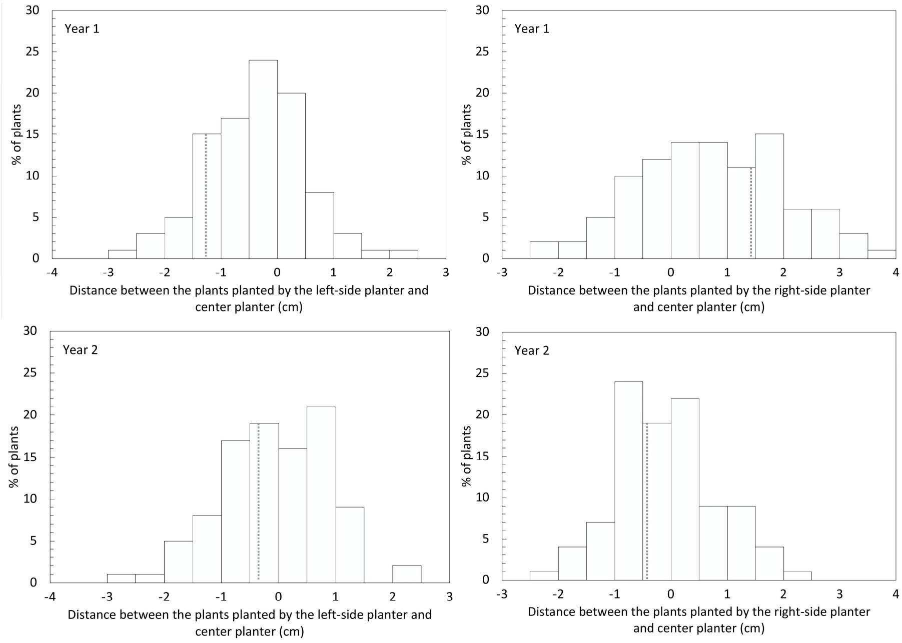
Year 1
% of plants
Distance between the plants planted by the left-side planter and center planter (cm)
Year 1
% of plants
Distance between the plants planted by the right-side planter and center planter (cm)
Year 2
% of plants
Distance between the plants planted by the left-side planter and center planter (cm)
Year 2
% of plants
Distance between the plants planted by the right-side planter and center planter (cm)
0
5
10
15
20
25
30
-4
-3
-2
-1
0
1
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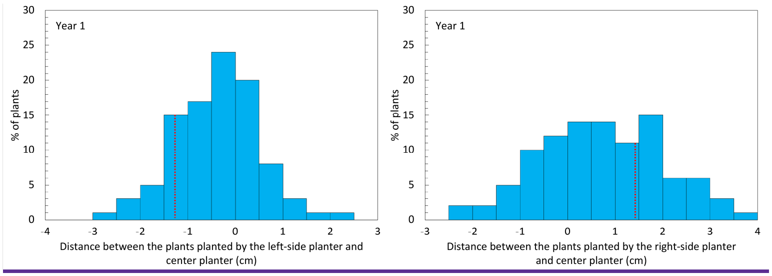
Year 1
% of plants
30
25
20
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-4
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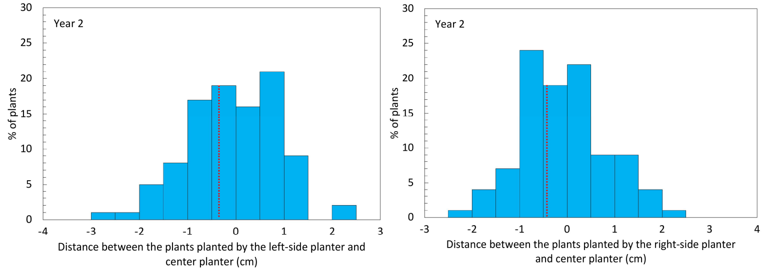
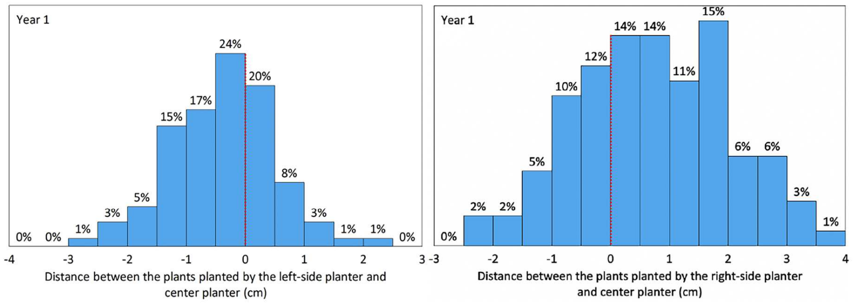
3
Distance between the plants planted by the left-side planter and center planter (cm)
Year 1
% of plants
-3
-2
-1
0
1
2
3
4
Distance between the plants planted by the right-side planter and center planter (cm)


Year 2
% of plants
30
25
20
15
10
5
0
-4
-3
-2
-1
0
1
2
3
Distance between the plants planted by the left-side planter and center planter (cm)
Year 2
% of plants
-3
-2
-1
0
1
2
3
4
Distance between the plants planted by the right-side planter and center planter (cm)


Year 1
0%
0%
1%
3%
5%
15%
17%
24%
20%
8%
3%
1%
1%
0%
-4
-3
-2
-1
0
1
2
3
Distance between the plants planted by the left-side planter and center planter (cm)
Year 1
0%
2%
2%
5%
10%
12%
14%
14%
11%
15%
6%
6%
3%
1%
-3
-2
-1
0
1
2
3
4
Distance between the plants planted by the right-side planter and center planter (cm)

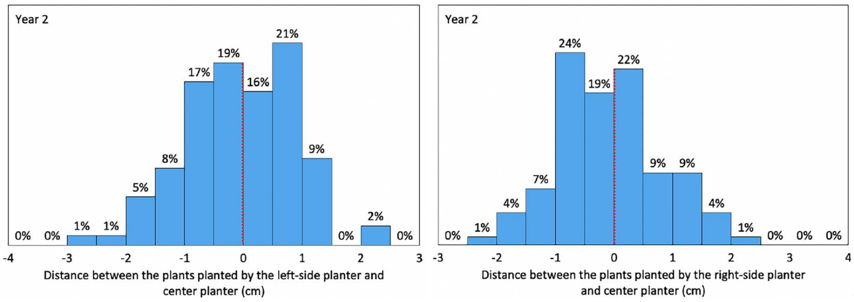

Year 2
0%
0%
1%
1%
5%
8%
17%
19%
16%
21%
9%
0%
2%
0%
-4
-3
-2
-1
0
1
2
3
Distance between the plants planted by the left-side planter and center planter (cm)
Year 2
0%
1%
4%
7%
24%
19%
22%
9%
9%
4%
1%
0%
0%
0%
-3
-2
-1
0
1
2
3
4
Distance between the plants planted by the right-side planter and center planter (cm)

Figure 7. Histograms showing the distributions of plant alignment, comparing the plant locations of the right and left sides to the centre. ~~The top two histograms are from the on-campus trial of the year-1 prototype. The bottom two histograms are from the year-2 trail in a commercial tomato field using the improved system.~~ The ~~red~~ dotted vertical lines are placed at the origin, as a reference. Ideally all plants would be close to this line.

A statistically significant (α = 0.01) improvement was ~~made~~ observed in the planting pattern synchronization in year-2 using a hydraulic motor to drive the motion of the planting wheels. The distribution of the plant alignment between the three synchronized planters in year-2 is shown in the lower two histograms in Figure 7, and a summary of the mean and standard deviation values are shown in Table 2. The goal is to have most of the data concentrated near the origin of each histogram, as indicated by the red vertical reference line. The mean error was -~~0.~~4.6 m~~c~~m between the plants planted by the left-side planter and the centre planter in year-2. This value is less than half the -1~~.~~3.2 m~~c~~m mean error observed in year-1. The mean error was also -~~0.~~4.6 m~~c~~m between the right and centre planters in year-2, which is approximately one-third of the +1~~.~~4.7 m~~c~~m error observed in year-1. In sharp contrast to year-1, when the error between the two outside planters was high, the two outside planters were, on average, very well synchronized, with an error of only -0.~~0~~3 m~~c~~m. The decrease in the total range of the synchronization error in year-2, represents an improvement of 24% or more. Furthermore, the distributions from year-2 were more symmetric about the origin than those in year-1, which were skewed. These results appear to show that the new hydraulic-powered drive system improved the planting synchronization~~precision~~. We hypothesize that the -~~0.~~5 m~~c~~m average lag of the right and left planters compared to the centre planter by -~~0.~~5 m~~c~~m on average, was due to a torque load on the PTO synchronization shafts. Further study is required to investigate whether a design improvement to the planter connecting linkages could further improve the level of synchronization. ~~In Italy, Mazzetto & Calcante (2011) developed a precision vineyard transplanter based on a DGNSS-hydraulic moto that was able to obtain an inter-row average distance of 2.31 m (SD 0.036~~

~~m) and an average distance between plants along the row of 0.9 m (SD 0.041 m). However, this study did not take into account the plant placement between different rows.~~

Table 2. Comparison of Plant Location Synchronization for Two Power Sources

				Synchronization Error (m~~c~~m)	
Year	Power Source	Obs.	Comparison	Mean	Std. Dev.
1	Ground Wheel	288	Centre vs. Left	-1~~.~~3.20a	2~~.~~3.90a
2	Hydraulic Motor	90	Centre vs. Left	-~~0.~~4.60b	2~~.~~4.10a
1	Ground Wheel	288	Centevs. Right	1~~.~~4.70a	3~~.~~3.30b
2	Hydraulic Motor	90	Centre vs. Right	-~~0.~~4.60b	2~~.~~2.90a
1	Ground Wheel	288	Right vs. Left	-2~~.~~7.90a	3~~.~~5.10b
2	Hydraulic Motor	90	Right vs. Left	-~~0.~~0.30b	2~~.~~6.40a

*Treatments with different grouping letters are significant at the alpha = 0.01 level.

3.2 High-speed plant kinematic results

A total of 120 root bulb trajectories were recorded for dynamic motion analysis. Half of the transplants studied corresponded to regularly sized seedlings, of which 30 used the support treatment and 30 were of the unsupported control treatment. The other half of the transplants were larger plants with the same numbers of digital videos analysed for each treatment. Figure 8 contains example digital images showing the typical dynamic path of the root ball centroid for the two treatments. Table 3 shows the velocity and acceleration of the root bulb centroid during the period of interest with planting wheel rotational speeds equivalent to forward travel speeds of 0.8 and 1.6 km h^{-1}. For both rotational speeds, the standard deviations of both the velocity and

Comentado [MPR2]: Reviewer 1: Surely the inter-row spacing is determined by either the fixed spacing between rows (if there is more t

han one row unit to a toolbar) or the accuracy of GNSS guidance of the tractor, if there is only one row per pass. How does the planting mechanism driven by the DGNSS controlled hydraulic motor influence the between row spacing?

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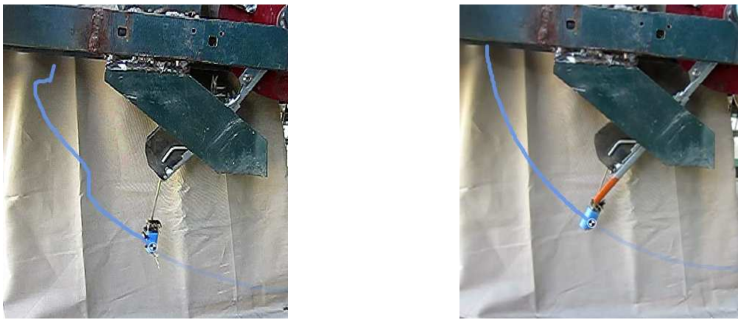
acceleration were higher for the control than for the fully supported treatment. The low variation in the velocity and acceleration for the supported plants may reduce the chance of the accidental release of tomato plants while in transit between the time they are released by the operator and the time they are released by the planter into the soil. In addition, although not quantified in this study, the metal supports facilitate the ease with which the operator places the plant upon the planting arm holder in the radial direction, potentially improving the precision of the depth of the root ball in planting.



(a) (b)

Figure 8. a) Example of root bulb trajectories from the unsupported control treatment and b) supported treatment

Analysis of variance indicated that there was a significant difference in the tangential speed ($p<0.01$) and acceleration ($p<0.01$) for large plants at both a nominal tractor speed of~~at a nominal tractor speed of~~ 0.8 km h^{-1} ~~for large plants when comparing the performance using the metal supports and the control system. A nominal tractor speed of~~and 1.6 km~~ 1.6 km~~ h^{-1} when comparing the performance using the metal supports and the control system. ~~also yielded significant differences in the tangential speed (p0.0) and acceleration (p0.0) values for the different treatments (control vs. supported).~~ In addition, the tangential speed ($p=0.0794$) and acceleration (p=0.522) showed no significant differences for regular-size plants under different treatments (control vs. supported) at a nominal speed tractor of 0.8 km h^{-1}.

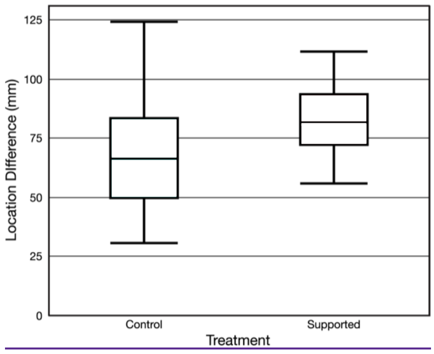
Table 3. Mean and standard deviation of both the velocity and acceleration for large and regular-size tomato plants.

	Large Plants				**Regular size Plants**			
	Tangential Velocity~~Speed~~ (m s^{-1})		**Tangential Acceleration (m s^{-2})**		**Tangential Velocity (m s^{-1})**		**Tangential Acceleration (m s^{-2})**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Control (0.8 km h^{-1})	0.069	0.035a	0.970	0.824a	0.058	0.027a	0.755	0.687a
Supported (0. 8 km h^{-1})	0.074	0.024b	0.902	0.694b	0.066	0.022a	0.822	0.652a
Control (1.6 km h^{-1})	0.136	0.058c	1.442	1.159c	0.125	0.054b	1.149	1.000b
Supported (1.6 km h^{-1})	0.150	0.035d	1.319	0.954d	0.149	0.037c	1.269	0.898b

*Within each factor level, values followed by different letters are significantly different ($p < 0.005$ for both factors).

Figure 8 shows an example of the root bulb trajectories from the control and the supported treatments obtained from the digital video analysis. In the control treatment (Figure 8a), the root bulb tended to move in a more random path compared to that in the supported treatment (Figure 8b). This random motion begins from the point that the operator releases the tomato plant in the holder and normally lasts until the plant is released into the soil.

The final portion of the plant trajectory, after the planting arm holder releases the plant, has a crucial influence on the final soil location of plant. To synchronize the planting patterns between adjacent tomato transplanters, it is essential to minimize the variability in the horizontal distance between the release of the plant from the planting arm holder and the final root bulb position in the soil. Figure 9 shows the box plots illustrating the distribution and mean of the distance between the location at which the planting arm holder released the tomato plant and the final plant location in the soil for the two treatments. The distance between the control (6~~.~~6.7±2~~.~~6.0 m~~c~~m) and supported (8~~.~~2.8±1~~.~~4.5 m~~c~~m) treatments were~~was~~ significantly different (p=0.0098). The variances were also significantly different between treatments (p=0.0408). An additional laboratory test indicated that plant size did not significantly influence the planting location for the control or the supported treatment (ANOVA, p=0.43). Since plant size did not affect the final plant location in the soil, the new synchronized precision transplanter could have a longer time window of opportunity for optimal precision planting giving more flexibility to the grower compared to that of the traditional row crop transplanter.



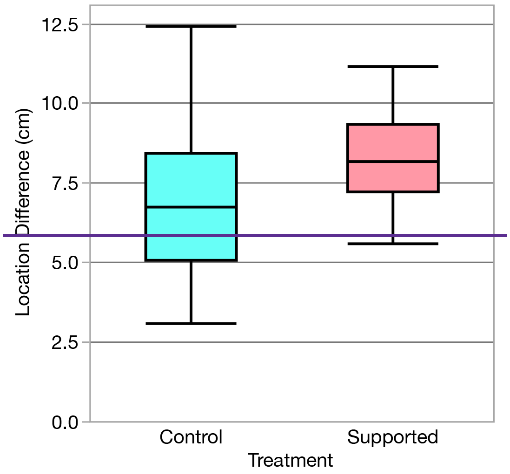


Figure 9. Box plots showing the mean and spread of the distance between the location at which the planting arm holder released the tomato plant and the final plant location in the soil for the two treatments.

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3.3 Improved precision plant placement into the soil

In year-3, the prototype synchronized transplanter was improved by incorporating the metal supports past the end of the finger, as shown in Figure 8b. Table 4 shows the standard deviation of the error for the plants planted by the left-side and right-side planters compared to those of the centre planter in~~ year-2 and~~ year-3. Average standard~~Standard~~ deviation values close to 3~~.~~8 m~~c~~m were obtained for the synchronized 3-row precision transplanter without metal supports; this value was similar to the result (4~~.~~1.0 m~~c~~m) obtained by Mazzetto and Calcante, (2011) using a single planting unit in a vineyard transplanting machine. The standard deviation error for the treatment in which the metal supports were integrated in the plant holder was 30 m~~c~~m for the left-side planter and 2~~.~~8 m~~c~~m for the right-side planter, where a zero value indicates perfect alignment. This finding indicates that increased planting position precision was achieved by the additional plant stem support.~~.~~

Table 4. Standard deviation of the left-side and right-side planters compared to the centre planter ~~and the Mahalanobis distance.~~for the control (unsupported) and supported plant treatments.

Year	Treatment	N	Variable	SD (m~~c~~m)
Year-3	**Control**	621	Centre –Left	4~~.~~0.20
	Supported	650	Centre –Left~~Right~~	2~~.~~9.20~~3.33~~
	Control~~Supported~~	621~~50~~	Centre –Right~~Left~~	~~2.92~~3~~.~~3.30~~3~~
	Supported	650	Centre –Right	2~~.~~7.80

~~In this study, the Mahalanobis distances were calculated to compare the patterns of the left and right planters with those of centre planter. This distance metric works well when there are relatively few covariates (Zhao, 2004), but is does not perform as well when the covariates are not normally~~

Comentado [MPR3]: Reviewer 1: Is 0.2% of plants a significantly different result? There is no discussion of how results of 0, 0.2 are significantly different from results of 0,0.

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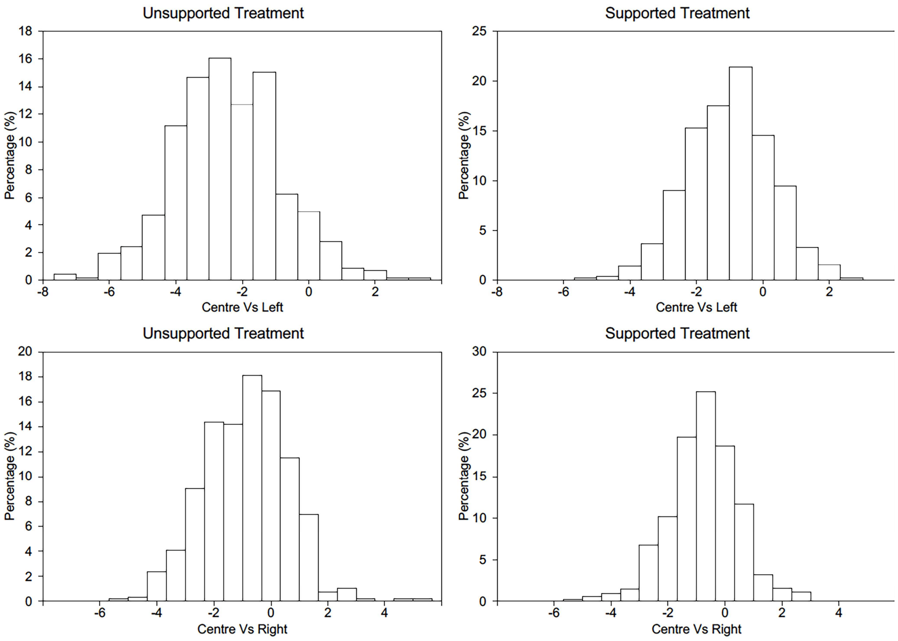
Comentado [MPR4]: Reviewer 1: Should be a reference to this, particularly if it is not a common statistical measure.

~~distributed or there are many covariates (Gu and Rosenbaum, 1993). In year-3, the supported treatment exhibited values of 0% for the proportion of plants with a Mahalanobis distances for the left and right planter units.~~

The error in plant alignment between the three synchronized planters in year-3 was plotted using histograms for the control and supported treatments (Figure 10~~9~~). In all cases, near-normal distributions were obtained. The mean level of synchronization was better than in the previous year in both treatments, and the standard deviation was smaller with the metal spoon supports than in the control treatment. The Brown-Forsythe test for homoscedasticity on the data in Table 4 shows that the variance in 3-row plant synchronization was significantly reduced (p=0.0001) when the transplanted root bulb was fully supported during planting. Additionally, the absolute deviation values of the final location in the soil were reduced by approximately 25% for both the right planter and left planter compared to those in previous years.


Unsupported Treatment
Supported Treatment
Percentage (%)
Centre Vs Left
Unsupported Treatment
Supported Treatment
Percentage (%)
Centre Vs Right
0
2
4
6
8
10
12
14
16
18
20
25
30
-8
-6
-4
-2
0
2
4

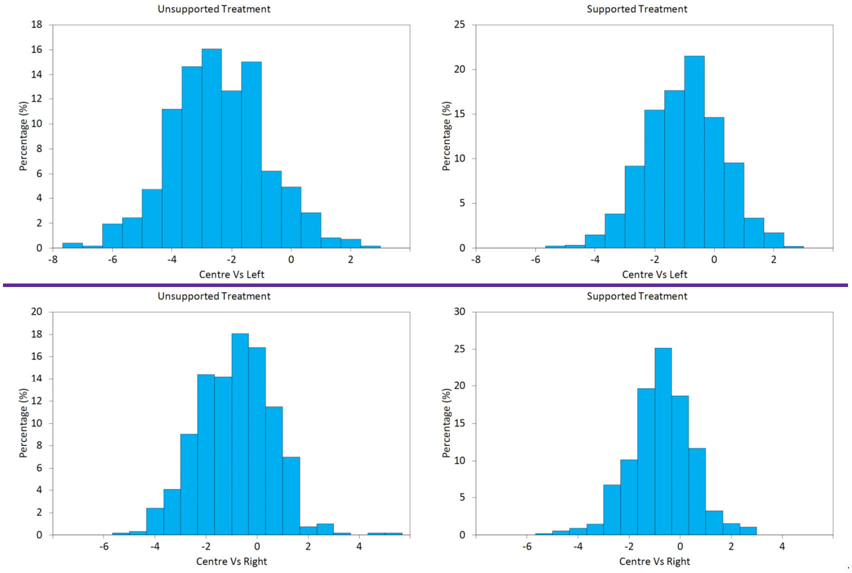


Figure 10~~9~~. Histograms showing the distributions of plant alignment, comparing the plant locations of the right and left to the centre for unsupported (control) and supported treatments on left and right planter

Conclusion

T~~he goal of t~~his work~~ was to~~ developed and analysed the performance of a new and ~~highly accurate~~ plant placement technology to improve the plant position accuracy and synchronization of the planting pattern for adjacent tomato transplanting modules. The new design implemented a 3-row plant synchronization system to consistently space tomato seedling along the row and to align the plants across three adjacent rows in a grid-like rectangular planting pattern. One of the important design changes, in addition to mechanically linking the rotation of adjacent planting wheels, was to eliminate the use of a pair of ground wheels for powering the motion of the planting wheels and replace them with a digital speed control that created a virtual coupling between an unpowered ground wheel speed sensor and a feedback control circuit for controlling the planting wheel rotation. A statistically significant (α = 0.01) improvement of improvement of 24% or more was observed in the planting pattern synchronization as a result of the new design.

A plant kinematics-based planter design assessment tool was created to provide the ability to characterized the dynamic path of the root ball of tomato seedlings using digital image-based time and motion analysis during planting when using a finger-type transplanter. Path characterization, from the time of release by the human operator until the final root bulb position in the soil, provided insight into the tangential velocity and acceleration of the root ball during this critical time segment and allowed the deviation between the planter's stem release point and the final planting location in the soil to be documented for different planter designs. Analysis results of the digitized path of the root ball indicated that for tomato seedlings planted with a traditional finger-type transplanter, the level of root ball path variation was affected by the length and flexural strength of the unsupported main stem.

A design modification, incorporating additional mechanical support of the seedling stems past the end of the finger during planting with a finger-type transplanter was successfully created and deployed. Dynamic root ball path analysis during the critical period just prior to root bulb positioning in the soil indicated that the design improvement resulted in a statistically significant reduction in the variance in tangential velocity and acceleration during this critical period. The variance in distance between the planter's stem release point and the final planting location was also significantly lower for the new design compared to the traditional transplanter design. Analysis of field tests data showed that the precision in adjacent row plant placement synchronization was significantly improved when the transplanted root bulb was fully supported during planting. The absolute deviation values of the final plant location in the soil between adjacent rows were reduced by approximately 25% by using the new design.

~~In the future, this will allow, among other things, synchronized plant placement in adjacent tomato rows to reduce plant-to-plant competition and facilitate the use of an automatic intra-row weeding co-robot system based on an accurate odometry sensing technique.~~

The study provided new insights into plant dynamics during the transplanting process. The high-speed video analysis led to the design and testing of an improved plant support mechanism for the improved control and precision of the transplanting of vegetable crops. The feasibility of synchronization for adjacent transplanting units with vegetable crops was demonstrated. These results serve as the fundamental basis for a mechatronic system that can precisely plant transplanted vegetable crops in a grid-like pattern across rows as a critical first step in a systematic approach to fully automated individual plant care. In the future, this new transplanter design will allow, among other things, synchronized plant placement in adjacent tomato row to reduce plant-to-plant competition and facilitate the use of an automatic intra-row weeding co-robot system based on an accurate odometry sensing technique.

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Con formato: Justificado

Con formato: Fuente: Cursiva

Con formato: Espacio Antes: 3 pto

Con formato: Sangría: Izquierda: 0 cm, Primera línea: 0 cm

Con formato: Sangría: Izquierda: 0 cm, Primera línea: 0 cm, Espacio Antes: 0 pto

Con formato: Fuente: Cursiva

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Figure Captions

Figure 1. Photograph showing the PTO-style synchronization shafts (black with yellow safety end covers) connecting the three precision planting wheels.

Figure 2. A planting wheel with the splined, PTO-style, index shaft used for synchronization.

Figure 3. View inside the year 1 synchronized transplanter showing the splined PTO-style connecting shafts used to synchronized the rotation of the planting wheels. The red outer ground wheels supplied power.

Figure 4. (a) The PTO-style synchronization shafts connecting the three planting wheels and (b) the ground –wheels speed sensor and feedback control system for maintaining the desired plant spacing.

Figure 5. (a) Conventional 5-arm planting wheel designed to allow mechanical linkage to connect adjacent planters and (b) Experimental 5-arm planting wheel with the metal spoon supports mounted.

Figure 6. Photograph showing the position of the root ball relative to the fingers of the transplanter. The root ball (held inside the person's hand in the foreground) is typically cantilevered 75 mm past the end of the finger.

Figure 7. Histograms showing the distributions of plant alignment, comparing the plant locations of the right and left sides to the centre. The dotted vertical lines are placed at the origin, as a reference. Ideally all plants would be close to this line.

Figure 8. a) Example of root bulb trajectories from the unsupported control treatment and b) supported treatment.

Figure 9. Box plots showing the mean and spread of the distance between the location at which the planting arm holder released the tomato plant and the final plant location in the soil for the two treatments.

Figure 10. Histograms showing the distributions of plant alignment, comparing the plant locations of the right and left to the centre for unsupported (control) and supported treatments on left and right planter.