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Performance Tests of Three-Point Mounted Implement Guidance Systems: I. Procedure

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Performance Tests of Three-point Mounted Implement Guidance Systems: I. Procedure

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Abstract. *A procedure is presented for determining the performance of three-point mounted implement guidance systems. A test track with tractor ramp, implement ramp, sine wave, and curve path shapes was used as the desired path to guide the tractor and implement, and as a reference location for measuring implement positional errors. Potentiometers were used with mechanical frames to measure the tractor and implement positional errors (lateral displacement between the intended and actual travel paths). An optoelectronic sensor triggered acquisition of data from all sensors at known locations [15.2 cm (6 in.) intervals] along the track. The accumulated errors for the tractor and implement positional error transducers included components of calibration, orientation angle, and wobble. The estimated accumulated errors for the tractor positional error transducer and implement positional error transducer were 0.91 cm (0.36 in.) and 0.99 cm (0.39 in.), respectively. The percentages of implement positional errors within an acceptable error band provide more relevant information for producers in row-crop agricultural situations than means, ranges and standard deviations. Tests were conducted with an articulated implement guidance system on fields with 0% side slope and fields with 5% side slopes at travel speeds of 4.8 and 8.0 km/h (3 and 5 mph). The tractor guidance system kept at least 70% of the tractor positional errors within a ±3 cm (±1.2 in.) error band except on the curve on the field with 0% side slope at 4.8 km/h (3.0 mph). When the error band was widened to ±5 cm (±2 in.), the tractor guidance system controller kept 94% of the tractor positional errors within the allowable error band on the curve on the field with 0% side slope at 4.8 km/h, and 100% of the tractor positional errors within the allowable error band for all other test combinations.*

Keywords. *Automated guidance, Guidance systems, Implements, Testing, Transducers.*

Automatic guidance of agricultural equipment can reduce stress on the operator from the demands of steering. This permits the operator to pay more attention to equipment function and improve performance.

In the past 10 to 15 years, several manufacturers have developed automatic guidance systems to control the position of three-point mounted implements. The main use for these guidance systems has been controlling cultivator position so the cultivating tools travel down the center of the furrows between the crop rows. Other uses have been for planting row crops (by following marker furrows), applying post-emergent sprays, and harvesting certain crops.

Current implement guidance systems were classified into three groups based on method of operation. These groups were side-shift, disk-steer, and articulated guidance systems. The guidance systems typically have electrohydraulic valves that control the direction and flow rate to the hydraulic cylinder(s) that power the mechanical control action.

Side-shift guidance systems require sway blocks to prevent the three-point hitch arms from moving laterally. These systems typically have a frame that mounts to the tractor three-point arms, and a plate that moves laterally on the frame. A hydraulic cylinder is used to move the plate. The implement is connected to the plate and moves laterally with it.

The articulated and disk-steer guidance systems do not use sway blocks to prevent the three-point hitch from moving laterally. These systems depend on soil resistance to generate side forces on the implement to move the implement laterally. Therefore, the three-point hitch arms must be left free when used with the articulated and disk-steer guidance systems.

Articulated guidance systems typically have a frame that mounts to the tractor three-point arms. The top link of the implement connects to the frame and the bottom two links of the implement connect to hydraulic cylinders. These cylinders operate in opposition to each other to rotate the implement about a vertical line at the guidance system hitch. For example, when the left cylinder extends, the right cylinder retracts an equal amount and the implement articulates in a counterclockwise direction about the vertical line. This rotation results in soil resistance placing

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side forces on the right side of the cultivator tools thereby pushing the implement to the left.

Disk-steer guidance systems typically have a frame that mounts to the implement and allows one or more steering disks to be attached to the frame at the rear of the implement. A hydraulic cylinder operates a tie-rod that causes rotation of the steering disks. This generates side forces on the steering disks which move the implement laterally.

Automatic guidance systems produced by different manufacturers are based on different operating principles. This has raised questions regarding the performance of the different guidance system types in different operating situations. Producers and consultants alike have not had independent, objective performance information on which to base purchasing decisions for selecting an automatic implement guidance system. The test procedure presented in this article can be used to determine the performance of automatic implement guidance systems in different field situations.

Literature Review

The two main reasons for development of guidance systems for agricultural equipment are economic and ergonomic. Palmer and Matheson (1988) cited reduced production cost as a benefit of guidance systems. Precise placement of seed and fertilizer reduced overlap in field operations and minimized expenses for these operations.

Richey (1959) realized that tractors and field machines were increasing in size and complexity and were taxing the ability of the operator to steer tractors accurately while monitoring implements for proper operation. Smith (1987) surveyed Maryland farmers and found that 80% of the respondents recognized fatigue as having the greatest effect on operator performance. Becker et al. (1983) determined that steering was the one task that caused the most operator stress because of the large number of stimuli required to accomplish this task.

Several different types of guidance systems for row crop agriculture have been researched. Many of the systems studied involved guiding the tractor with the implement trailing behind. Liljedahl and Strait (1962) suggested an alternate method of improving the accuracy of cultivation was steering the tractor manually and using a control unit for the lateral position of the cultivator gangs. They concluded this method would provide faster response for a given amount of available hydraulic power. Suggs et al. (1972) came to the same conclusion and suggested this method would be especially useful on curved, contoured, or hillside areas where vehicle position was frequently different from implement position. Morrison (1991) developed a system that controlled lateral movement of the three-point arms to keep the attached implement correctly positioned between crop rows. The current commercially available implement guidance controllers are based on this concept of steering the tractor manually with an automatic controller for the lateral position of the implement.

Many tests have been devised to determine the effectiveness of tractor guidance systems. Julian (1971), Warner and Harries (1972), and Hilton and Chestney (1973) developed and evaluated tractor steering devices designed to follow plow furrow walls. Grovum and Zoerb (1969) and Darcey and Pool (1985) evaluated tractor guidance systems that followed marker furrows. Young et al. (1981) evaluated an "off- wire" tractor guidance system. Choi et al. (1990) evaluated a radio navigational tractor guidance system. Fehr and Gerrish (1989) evaluated a vision-guidance system for a tractor. These evaluations involved a desired path to be followed and measured positional errors as the difference between the actual path the tractor followed and the desired path.

The desired paths included straight lines (Grovum and Zoerb, 1969; Choi et al., 1990; Fehr and Gerrish, 1989; Hilton and Chestney, 1973; Young et al., 1981), step functions (Choi et al., 1990; Fehr and Gerrish, 1989; Grovum and Zoerb, 1969; Julian, 1971; Warner and Harries, 1972; Young et al., 1981), curves (Darcey and Pool, 1985; Schafer and Young, 1979), and sine waves (Choi et al., 1990; Hilton and Chestney, 1973; Julian, 1971; Warner and Harries, 1972; Young et al., 1981). Travel speed ranged from 0.6 km/h (0.4 mph, Fehr and Gerrish, 1989) to 11.3 km/h (7.0 mph, Warner and Harries, 1972). Hilton and Chestney (1973) found no difference in the positional error rates when they evaluated their guidance system that sensed the plow furrow wall on a level field and one with 12.5% slope.

Most researchers studying experimental tractor guidance systems measured the magnitude of the positional error at the rear axle of the tractor (Larsen et al., 1991; Fehr and Gerrish, 1989; Julian, 1971; Young et al., 1981). Hesse (1974) studied control of implement position and measured positional error at the edge of the sweep.

The variety in types of guidance systems, test procedures (including paths, travel speeds, and field slope), locations of measurements, and means of obtaining data is illustrated in these reports. The analyses and means of reporting results also varied considerably. The guidance systems evaluated in these reports were primarily experimental tractor guidance systems, and did not provide information regarding the performance of commercially available systems designed to guide working implements being pulled behind the tractors. The reports were helpful in establishing test parameters such as travel speeds, paths, and measurement locations for evaluating the performance of these guidance systems.

Objectives

The goal of this research was to develop a procedure for evaluating the performance of guidance systems that sense the location of crop rows and control three-point mounted implement position. The procedure was to simulate field operating conditions as closely as possible. Specific objectives were to:

1. Develop consistent paths (including shapes expected in row-crop agriculture) for the tractor and implement to follow during tests of implement guidance system performance.
2. Develop methods for measuring the positional errors of the tractor and implement during tests of implement guidance system performance.
3. Determine an analysis that presents the results of the implement guidance performance tests in a format that is easy for producers to understand.

Materials and Methods

Track Description

A precise pair of crop rows was simulated by a track system, constructed to provide the desired paths for steering the tractor and implement and as a reference location for the positional error measurements. The track was also used to indicate 15.2 cm (6 in.) increments in travel distance for use in triggering data collection events.

Two track rails each held a row of wires to simulate two crop rows with 76 cm (30 in.) row spacing (fig. 2). The wires were spaced 15.2 cm (6 in.) apart representing a plant population of 86,100 plants/ha (34,800 plants/acre). These rails were placed on "cross-ties" and the track resembled a railroad track. The track was constructed in 2.44 m (8 ft) long sections for ease in storage, transport and handling. The sections were connected in sequence to form the desired paths.

Crop-sensing wands on the implement guidance system position sensor sensed the relative orientation (distance left or right of the furrow center) of the wands between the simulated crop rows and provided that information to the guidance controllers to adjust the position of the implement. A third rail placed between the two crop row rails represented the desired tractor path. This rail was painted with alternating black and white bars each 7.6 cm (3 in.) wide across the rail. These bars provided black-to-white transitions at 15.2 cm (6 in) intervals for an optical sensor used to trigger data collection events.

Figure 1 is a schematic of the full track indicating the desired paths. The first 9.75 m (32 ft) of track was a straight start-up section. No data were collected on this portion of the track. Data were collected in all subsequent sections of the track except the final shut-down section. The next 9.75 m (32 ft) of track was a straight settling section. In the next 8.53 m (28 ft), the tractor followed a ramp that moved the tractor 15.2 cm (6 in.) to the right while the cultivator followed a straight path. A settling section of straight track 9.75 m (32 ft) long followed each path shape. In the next 8.53 m (28 ft), the tractor followed a straight path while the implement followed a ramp that moved the implement 15.2 cm (6 in.) to the right. After the next settling section, the tractor followed a 34.14 m (112 ft) straight path while the implement followed a sine wave with an amplitude of 15.2 cm (6 in.) for one full cycle. After the next settling section, the tractor and implement followed a 61 m (200 ft) radius curve to the left for 48.5 m (159 ft) to simulate operation on a contour. The 61 m (200 ft) radius was recommended by Taylor et al. (1978) as the minimum curve radius for harvesting crops planted with 76 cm (30 in.) row spacing. Because the center of track was 3.05 m (120 in.) to the left of the tractor, the radius of the curve at the center of the track was 58 m (190 ft) and the length of the curve was 46.0 m (151 ft). The shut-down straight section at the end of the curve served to keep the positional error transducers out of the ground while the tractor was slowed and stopped.

The tractor and implement ramps, and sine wave paths required lateral travel of the tractor and implement. The maximum lateral displacement was determined by subtracting the rear tire tread width of 45.7 cm (18.0 in.) from the row width of 76.2 cm (30.0 in.) and dividing by two to obtain the maximum lateral displacement of ±15.2 cm (±6.0 in.) from the furrow center. The minimum travel distance for a full sideways displacement of ±15.2 cm (±6.0 in.) depended on the maximum travel speed and the minimum lateral travel speed of the implement guidance systems. This length was rounded up to the nearest one-half track section to simplify track construction.

The location for this research was at the University of Nebraska-Lincoln Rogers Memorial Farm east of Lincoln, Nebraska. A field with 0% side slope was used to represent furrow irrigated row crop land. Fields with 5% side slope (slope perpendicular to the direction of travel) were used to represent operation on side slopes as is normally done with row crops planted on contour. There were no furrows in the fields as there was no way to way to make the furrows in the desired path patterns and make them the same for all tests. All four path shapes (tractor ramp, implement ramp, sine wave, and curve) were used on the field with 0% side slope making the total length 136.2 m (447 ft) so 895 data collection events occurred. The curve was not used on the fields with the 5% side slope as a curve going uphill or downhill did not simulate contour farming. In addition, the curve greatly increased the land area needed for each test run. This extra land area was not available on the fields

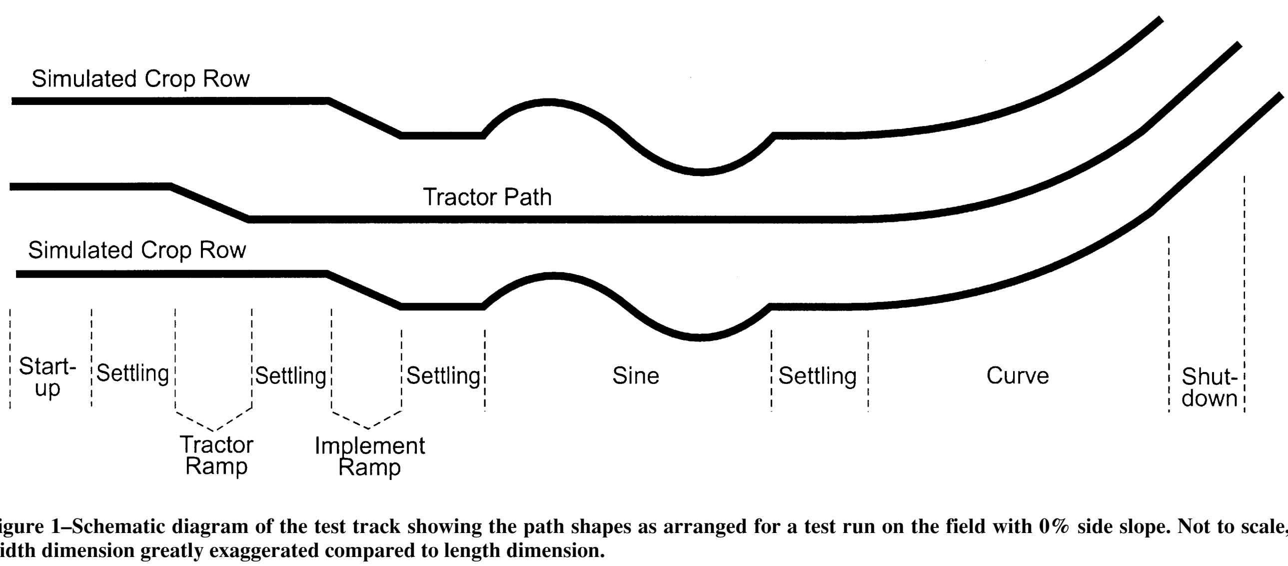


Figure 1–Schematic diagram of the test track showing the path shapes as arranged for a test run on the field with 0% side slope. Not to scale, width dimension greatly exaggerated compared to length dimension.

with the side slope. The total length of the track used for data collection on the field with the five percent side slope was 90.2 m (296 ft) so 593 data collection events occurred. Smith (1993) reported on this research in detail.

Tractor and Implement Guidance Systems

An automatic steering device (model Agtronics Electronic Steering Pilot, Sigmanetics, Incorporated, Concord, California), available on loan from the manufacturer, was used to steer the tractor down the desired tractor path. This unit had a field feature sensor that could be used to follow a marker furrow. A roller cart similar to the ones on the tractor and implement positional error transducers was attached to the field feature sensor to enable it to follow the center (desired tractor path) rail of the track.

The implement guidance system used in the preliminary tests reported in this article was an articulated type (model Buffalo® Scout, Fleischer Manufacturing, Inc., Columbus, Nebraska).

Tractor and Implement Instrumentation

The lateral location of the desired path was a function of distance along the track (fig. 1). Thus, the location along the track where each set of measurements was obtained also had to be known in order to reference measurements to the different path shapes. Data were obtained at 15.2 cm (6 in.) increments along the track, rather than at selected or unknown time intervals. The instrumentation system was designed to measure positional errors for the tractor and implement, torque from side forces on two of the residue-cutting coulters, and travel speed at each 15.2 cm (6 in.) increment along the track.

A six-row cultivator (model Buffalo 4630, Fleischer Manufacturing, Inc., Columbus, Nebraska) with 76 cm (30 in.) row spacing, a pair of barring-off disks, a non-swiveling, residue-cutting coulter, and a sweep at the back for each furrow was used. The sweep was the widest soil engaging tool so the positional error of the implement was measured at the outside point on the sweeps, similar to Hesse (1974). These positional errors indicated how far the sweeps were cutting into row area reserved for the crop.

The cultivator was used to cultivate the soil behind the tractor to simulate crop cultivation as closely as possible in this test. This prevented placing the track between the tractor tires during testing. The center of the track was placed 3.05 m (120 in.) to the left of the tractor centerline so neither the tractor nor the cultivator ran over the track. An outrigger was constructed to provide the framework to hold the tractor guidance field feature sensor and the tractor positional error transducer in fixed positions relative to the tractor (fig. 2). The outrigger was attached to the bottom of the tractor frame, just in front of the rear wheels. The tractor guidance field feature sensor was attached to the front of the outrigger so the sensor was 15.2 cm (6 in.) in front of the tractor front axle, as recommended by the tractor guidance system manufacturer. The tractor positional error transducer was attached at the rear of the outrigger so the tractor positional error measurements were obtained in the vertical plane containing the tractor rear axle centerline. The tractor guidance system manufacturer assisted with installation and adjustment of the tractor guidance system prior to the experiment.

A transducer was designed and built for use in measuring the tractor positional error. The bracket for the tractor positional error transducer was attached to the

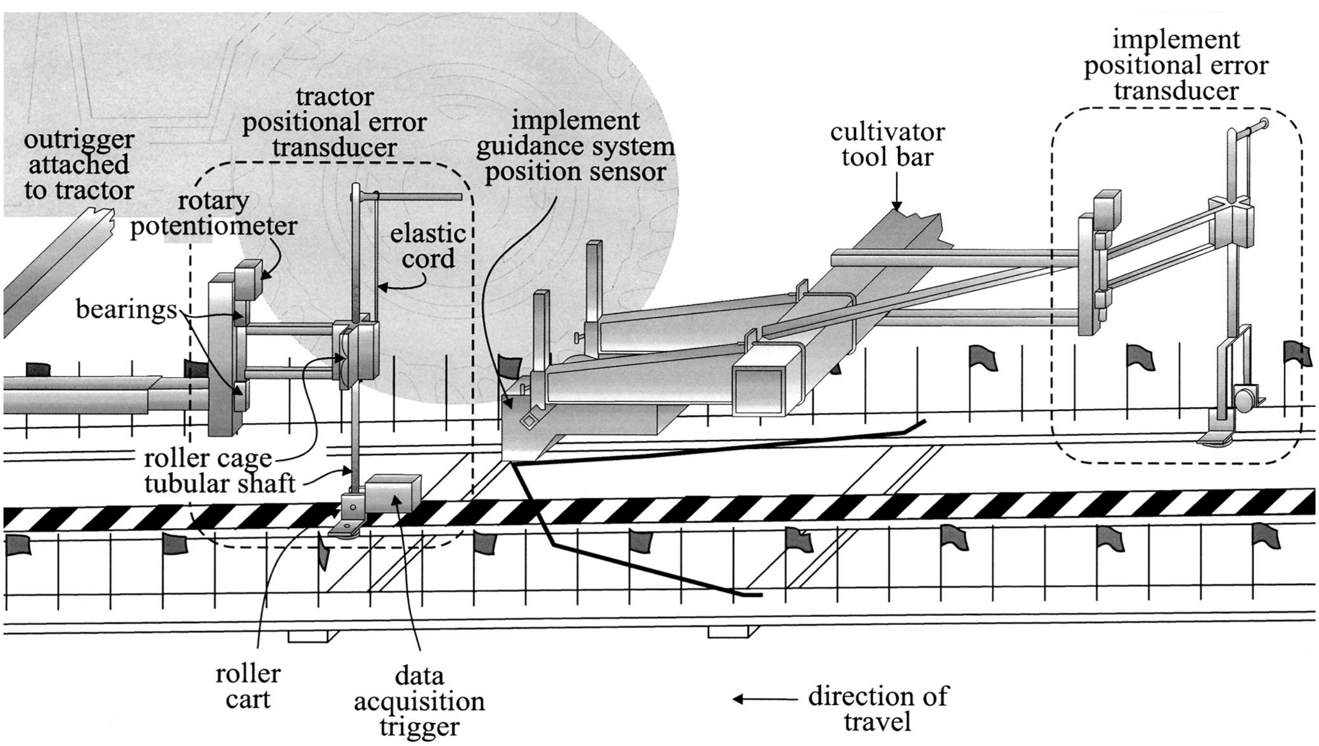


Figure 2–Schematic diagram of the tractor and implement positional error transducers and implement guidance system position sensor in operating position on the track.

outrigger (fig. 2) so this bracket was in a fixed position relative to the tractor. Two bearings attached to the positional error transducer bracket constrained a vertical shaft so it could only rotate about its vertical axis. A conductive-plastic rotary potentiometer (model 112-P19-102, Maurey Instrument Corp., Chicago, Illinois) coupled to the top of the shaft was used to determine the angle of rotation of the shaft. An arm attached to the shaft extended horizontally in the rearward direction, allowing the arm to swing from side to side as it trailed behind the positional error transducer bracket. A roller cage attached to the end of this arm constrained a tubular shaft to keep it perpendicular to the arm while allowing the shaft to slide freely up and down through the roller cage. The bottom of the tubular shaft was attached to a roller cart that rolled on the center tractor path rail of the track. An elastic cord was stretched between the horizontal arm and the top of the tubular shaft to provide a downward force on the cart to keep it on the track. The potentiometer on the bracket measured the rotation of the arm and this rotation was directly related to the positional error. Positive tractor positional errors indicated the tractor was to the left of its intended location, and negative positional errors indicated it was to the right. The maximum error obtained during calibration of this tractor positional error transducer was 0.15 cm (0.059 in.).

A similar transducer attached to the left end of the cultivator tool bar was used to measure the implement positional error. The maximum error obtained during calibration of this implement positional error transducer was 0.23 cm (0.091 in.).

A sensor attached to the tractor positional error transducer cart (fig. 2) was used to detect the black and white bars on the rail. Specifically, the sensor included a light source to illuminate the rail under the sensor and a phototransistor to detect the level of light reflected from the rail. A skirt made from black felt surrounded the sensor and prevented ambient sunlight from shining on the rail under the sensor. When the sensor was over a black bar very little light was reflected from the rail and the voltage output from the phototransistor was high (4.7 V). As the sensor moved over a white bar, the level of light reflected from the rail increased significantly and the voltage output from the phototransistor dropped (0.2 V). The voltage from the phototransistor was sent to a digital I/O line in the data acquisition system. The data acquisition system was programmed to initiate a data collection scan every time the digital I/O line switched from high to low.

There has been controversy regarding side forces placed on the residue-cutting coulters by the action of different guidance systems. A strain gage torque transducer was incorporated in the mounting bracket of two of the residue-cutting coulters. The torque transducers enabled measurement of the torques resulting from side forces placed on the coulters. One of these coulters with a torque transducer was mounted on the cultivator such that the coulter ran in compacted soil in the furrow behind the left (relative to the tractor operator sitting at the operator's station) rear tractor wheel (Coulter 1). The other coulter with a torque transducer was mounted on the cultivator such that the coulter ran in uncompacted soil in the furrow to the right of the right rear tractor wheel (Coulter 2). The torque transducers were calibrated using known weights and a measured lever arm. The maximum error was 14.5 N·m (10.7 lb·ft) with maximum torque values measured at 1500 N·m (1100 lb·ft).

An unpowered "fifth-wheel" was used to measure travel speed. A 60 tooth gear was attached to and rotated with the ground-driven wheel. A magnetic pickup on the wheel forks was used to detect gear teeth passing the magnetic pickup. The magnetic pickup sent pulses to the data acquisition system. Travel speed was directly proportional to the frequency of the pulses sent to the data acquisition system.

A data acquisition system (model 10KUV, Daytronic Corp., Miamisburg, Ohio) was used with a laptop computer to obtain and store the data. A voltage signal conditioner card (model 10A60-4, Daytronic Corp., Miamisburg, Ohio) was used to obtain the positional error data for the tractor and the implement. A strain gage signal conditioner card (model 10A70-2, Daytronic Corp, Miamisburg, Ohio) was used to obtain the torque data from the strain gage torque transducers. A digital I/O card (model 10AIO16, Daytronic Corp., Miamisburg, Ohio) was used to enable the trigger sensor to initiate the data collection events every 15.2 cm (6 in.) along the path. A frequency signal conditioner card (model 10A40, Daytronic Corp., Miamisburg, Ohio) was used to determine the pulse frequency from the "fifth-wheel" speed transducer. Data were collected during each test run and stored in a file on the computer ramdisk. After each test run, the data were downloaded from the computer ramdisk to floppy disk for storage.

Pretest Setup and Measurements

Each guidance system manufacturer set up their guidance system to work with the tractor, cultivator, and track. They were free to adjust equipment settings during preliminary test runs with the track until they decided the performance of their system was acceptable. The final equipment settings for each system were then recorded and used for the test runs during the experiment.

The wooden track was stored in a shed to protect it from weathering by wind and rain. To prepare for a test run, the track was moved to the field and assembled in the appropriate plot for the particular test run. A string line was stretched from the start of the track to the end of the settling section after the sine wave. The individual track sections were aligned with the string line. On the field with 0% side slope, a measuring tape was used to locate the center of the circle for the curve section of the track. The center of the circle and the measuring tape were used to position flags in the plots to mark the location for the left edge of each section in the curve portion of the track. After the track was assembled, a check assured that wires simulating plants were straightened and replaced if needed. The track was staked down to keep it from moving during the test run.

Soil samples for moisture content determination were taken from the top 23 cm (9 in.) of soil at each end and the middle of the plot before each test run. A standard cone penetrometer was used ten times at each end of the plot before each test run to obtain cone index values. These data were taken to provide some description of the soil condition at the time of each test run.

Running the Test

The tractor with the tractor guidance system, implement guidance system, cultivator, and data acquisition system was driven into position at the start of the track and the cultivator was lowered into the operating position. The tractor guidance and positional error transducer carts were placed on the track, and the tractor guidance, implement guidance, and data acquisition systems were activated. The tractor was placed in the appropriate gear and the throttle adjusted to the desired engine speed. The tractor operator then released the clutch pedal and watched the carts running on the track to make sure none of them jumped the rails. When carts did jump the rails, the tractor was stopped as soon as possible to minimize damage to the track and the transducers. It only took one to two minutes for the tractor to travel the length of the test track. After completion of a test run, the data were saved to a disk file, the transducers were moved into their transport positions, and the tractor was driven away from the track. The stakes holding the track in place were pulled up and the process of moving the test track to the next plot for the next test run was begun.

Data Analyses

Variation in the mounting location of the implement guidance system position sensor on the tool bar results in corresponding variation in the implement positional error. The guidance system manufacturers provided a dial on the guidance system console for manual adjustment to center the guidance system in the furrows. It would have taken additional time and room in the field to make those adjustments. Instead, we chose to use the average positional error on the straight settling section before the tractor ramp to calculate the offset. This offset was subtracted from all subsequent implement positional error data for that test run to obtain the corrected implement positional data. Note that all subsequent mention of implement positional errors in this article refers to the corrected rather than raw implement positional errors.

Some additional understanding of the way implement guidance systems are used in row-crop agriculture suggests that positional error distributions may be more useful than means, ranges and standard deviations. As an example, consider a sweep being used to cultivate a row-crop with 76 cm (30 in.) spacing. Consider location 0 cm (0 in.) to be the plant on the left-hand side of the sweep and location 76 cm (30 in.) the plant on the right-hand side of the sweep. For the purpose of this explanation, assume that the roots of the crop extend into the furrow about 10 cm (4 in.) on each side. The operator will want the sweep to stay between locations 10 cm (4 in.) and 66 cm (26 in.) so the sweep does not cut any of the roots of the crop. Assume the width of the sweep is 50 cm (20 in.). If the sweep stays exactly in the middle of the furrow at location 38 cm (15 in.), the remaining 6 cm (2.4 in.) of the furrow width (3 cm (1.2 in.) on either side of the sweep) does not contain crop roots and will not be cultivated. In this example, the operator really won't care if the sweep stays centered exactly on location 38 cm (15 in.) as long as it does not deviate more than 3 cm (1.2 in.) to either side. The operator wants the sweep to stay at location 38 within a ±3 cm (±1.2 in.) error band. The question the operator is really concerned about is how much of the time will an implement guidance controller keep the implement inside this ±3 cm (±1.2 in.) error band? If the sweep width is 46 cm (18 in.) instead of 50 cm (20 in.), then the operator will be concerned with how much of the time an implement controller will keep the implement inside a ±5 cm (±2 in.) error band. For ease of explanation to producers, the analyses of the tractor and implement positional errors included positional error distributions consisting of the portion of positional error kept within the acceptable error band.

Results and Discussion

The tests reported in this article were conducted during the summer of 1992. The soil moisture content was within the range from 20 to 24%. Cone index values ranged from 363 to 567 kPa (52.6 to 82.2 psi) for the 0 to 7.6 cm (0 to 3.0 in.) depth range, 621 to 1126 kPa (90.1 to 163.3 psi) for the 7.6 to 15.2 cm (3.0 to 6.0 in.) depth range, and 590 to 1473 kPa (85.6 to 213.6 psi) for the 15.2 to 22.9 cm (6.0 to 9.0 in.) depth range.

There was some concern that the orientation of the tractor would affect the tractor positional error measurements. To illustrate this concern, imagine a top view of the tractor and track with the longitudinal axis of the tractor parallel to the desired tractor path, and the tractor exactly where it is supposed to be so the tractor positional error is zero. Now imagine the tractor rotated counterclockwise about a vertical line through the center of the left-rear tire. Theoretically, the tractor position is the same as before, so the tractor positional error should be zero. However, the outrigger, firmly fixed to the tractor, has rotated through the same counterclockwise angle as the tractor, so the tractor positional error transducer bracket, mounted 3.05 m (120 in.) to the left of the tractor on the outrigger, is now slightly to the right of, and behind its original position. The positional error transducer arm has one end attached to the vertical shaft in the bracket, and the other to the vertical tubular shaft above the roller cart that remains on the desired tractor path track. The positional error transducer arm (with the attached potentiometer) has therefore rotated through a clockwise angle, indicating a small right positional error for the tractor. A review of the tractor positional error data showed the angle of rotation was frequently less than 0.9° with a maximum of about 2.7°. The associated error in tractor positional error measurement was calculated to be ±0.038 cm (±0.015 in.) and ±0.34 cm (±0.13 in.) for those angles, respectively.

A similar review of the implement positional error data showed the angle of rotation was frequently less than 2.9° with a maximum of about 5.8°. The associated error in implement positional error measurement was calculated to be ±0.33 cm (±0.13 in.) and ±1.3 cm (±0.51 in.) for those angles, respectively.

The tension from the elastic cords and trailing action of the positional error transducers worked well in keeping the carts on the track as long as the rollers in the roller cages were properly adjusted. The vertical tubular shafts attached to the carts of the positional error transducers were not machined to a uniform diameter. This required the rollers to be adjusted so the shafts would never bind in the rollers. This ensured that the tension in the elastic cords was sufficient to move the carts downward as necessary to keep the carts on the track. If the rollers were set too close together, there was too much drag on the shafts at some points in the vertical travel of the shafts and the elastic cords could not provide enough tension to move the shafts downward to keep the carts on the track. If the rollers were set too far apart, there was extra room between the vertical shafts and the rollers. This extra room resulted in the shafts wobbling more than necessary in the roller cages and reduced the precision of the positional error measurements. In order to determine the magnitude of the error resulting from the wobble, the positional error transducers were set in place on a track section and the shafts were manually wobbled from side to side while data were collected. The maximum error from the wobble was 1.8 cm (0.71 in.) with an average less than 0.9 cm (0.35 in.). Machining the vertical shafts to uniform diameter would have reduced the error from the wobble in the positional error transducers.

The accumulated error for each of the implement positional error transducers would have included components from calibration, orientation angle and wobble. The accumulated error was estimated using the square root of the sums of the squared error components as given in Dally et al. (1993). The estimated accumulated errors for the tractor positional error transducer and implement positional error transducer were 0.91 cm (0.36 in.) and 0.99 cm (0.39 in.), respectively.

An example of the tractor and implement positional error data is shown in figure 3. These data were obtained from the test run with a travel speed of 4.8 km/h (3.0 mph) on the field with 0% side slope. The mean plus one standard deviation, mean minus one standard deviation, maximum (maximum left deviation), and minimum (maximum right deviation) were determined for the tractor positional error and the implement positional error for each path shape on each field at each travel speed. These results for the tractor positional error are shown in figure 4. The means of tractor positional errors were between –1 cm (–0.4 in.) and 3 cm (1.2 in.) except on the curve on the field with 0% side slope at 4.8 km/h (3.0 mph).

The portion of positional errors within ±3 cm (±1.2 in.) and ±5 cm (±2 in.) error bands was determined for the tractor and implement for each path shape on each field at each travel speed. The tractor guidance system kept at least 70% of the tractor positional errors within a ±3 cm (±1.2 in.) error band except on the curve on the field with 0% side slope at 4.8 km/h (3.0 mph) (fig. 5a). When the error band was widened to ±5 cm (±2 in.) (fig. 5b), the tractor guidance system controller kept 94% of the tractor positional errors within the allowable error band on the curve on the field with 0% side slope at 4.8 km/h, and 100% of the tractor positional errors within the allowable error band for all other test combinations.

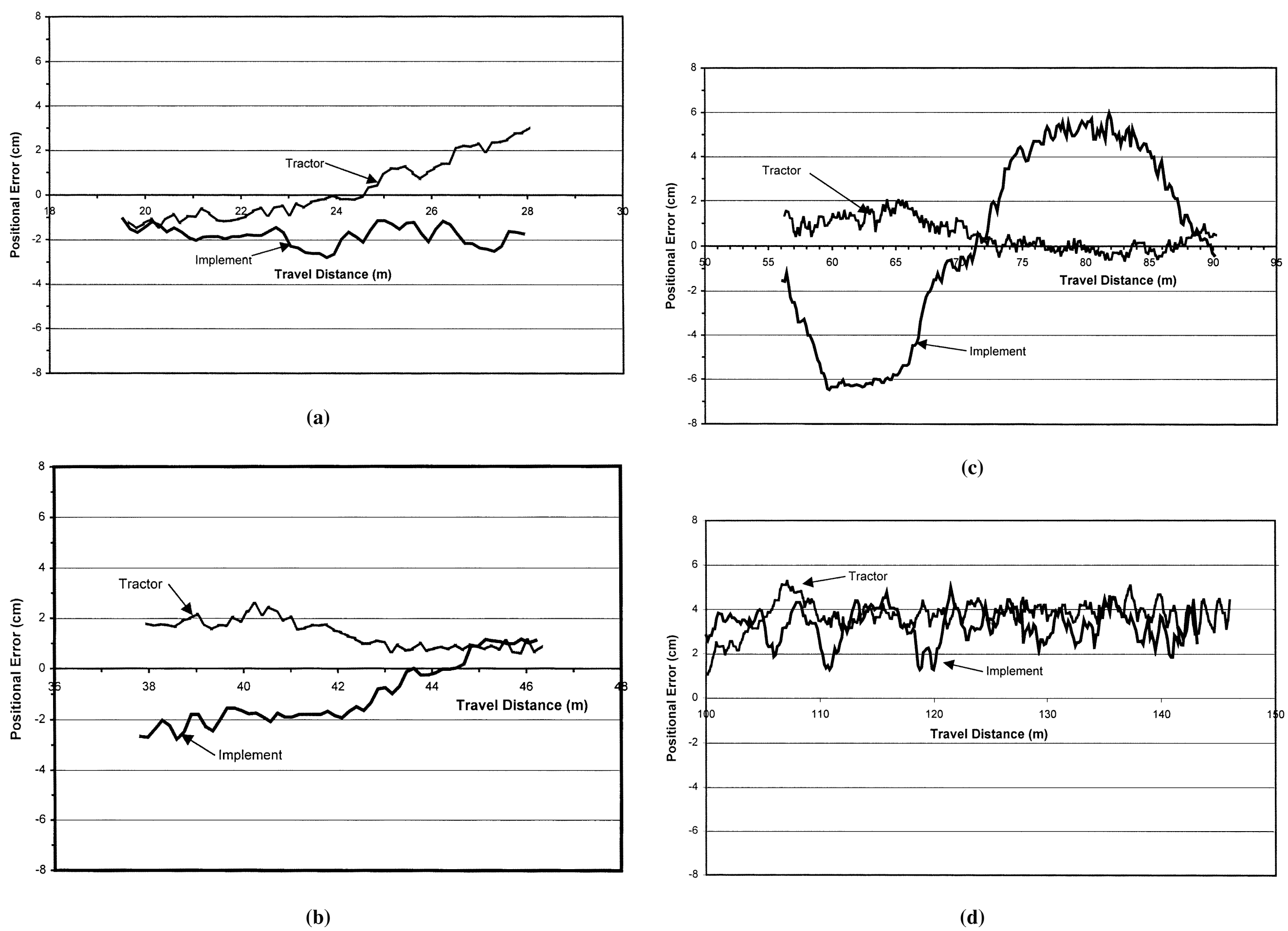


Figure 3–Example of the tractor and implement positional error data for the articulated implement guidance system on the field with 0% side slope at 4.8 km/h (3.0 mph) in the (a) tractor ramp, (b) implement ramp, (c) sine wave, and (d) curve.

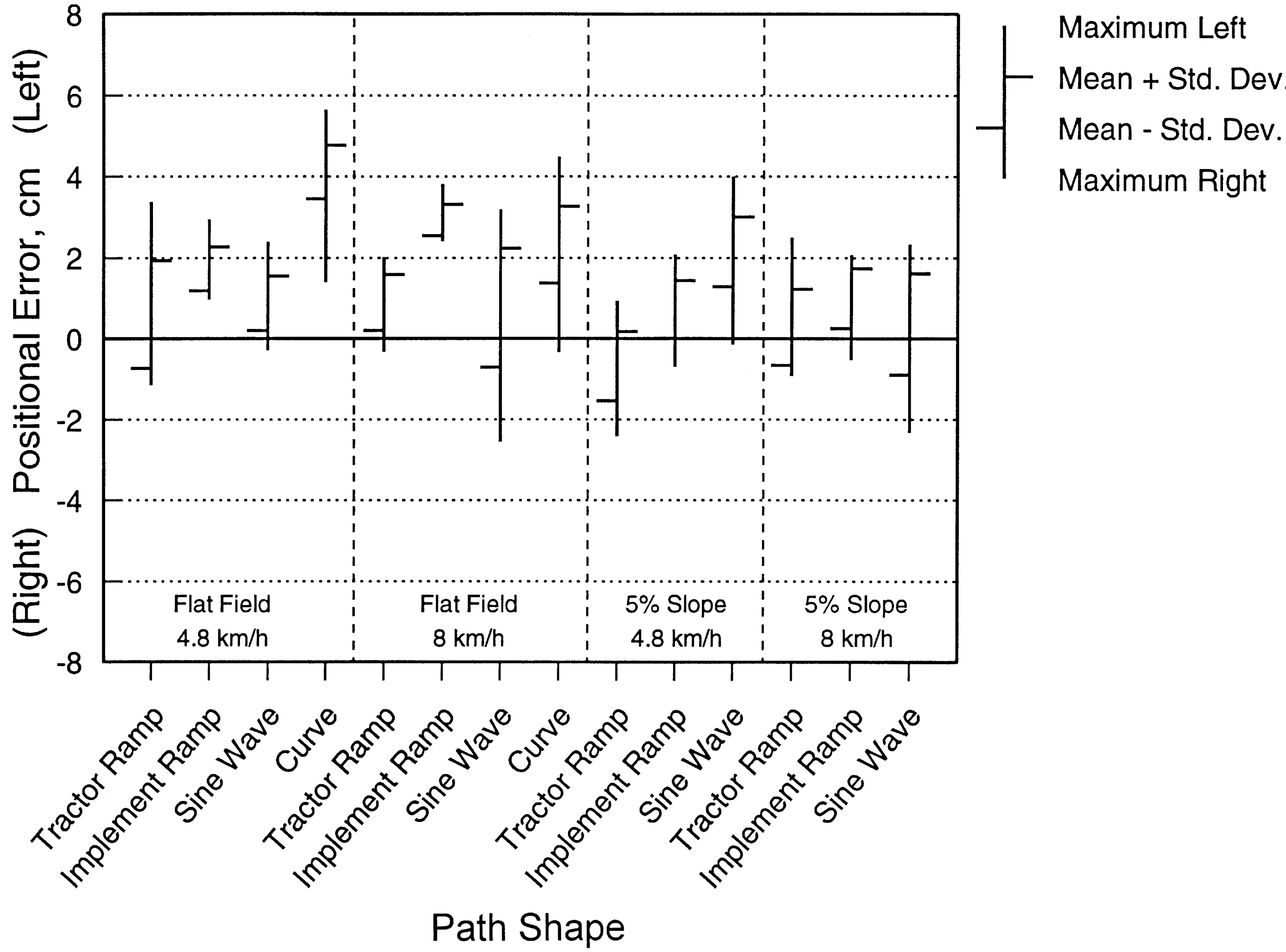
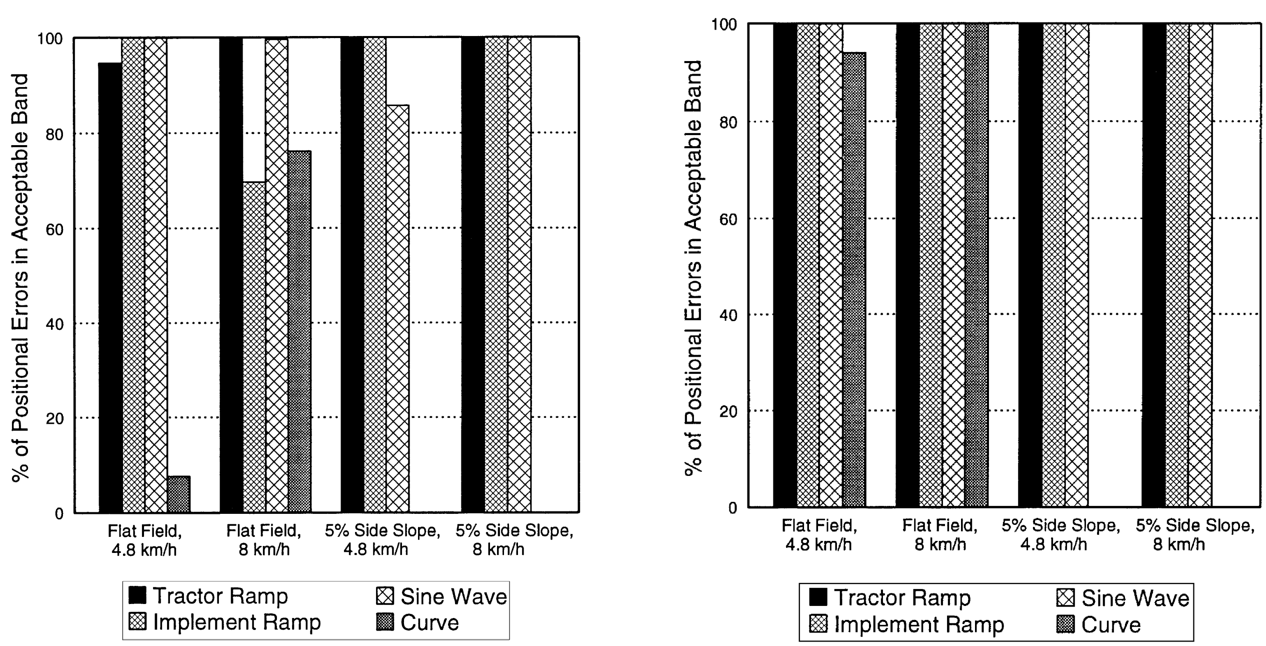


Figure 4–Descriptive statistics of tractor positional error data for each path shape on each field at each travel speed from test runs with the articulated implement guidance system. The descriptive statistics include: mean plus one standard deviation, mean minus one standard deviation, maximum (maximum left positional error), and minimum (maximum right positional error).



(a) (b)

Figure 5–Percentages of tractor positional errors within (a) ±3 cm (±1.2 in.), and (b) ±5 cm (±1.2 in.) of the intended tractor travel path for each path shape on each field at each travel speed from runs with the articulated implement guidance system.

Summary and Conclusions

A procedure was developed to evaluate the performance of guidance systems which sense the location of crop rows and control three-point mounted implement position. The procedure simulated operating field cultivation conditions as closely as possible. Specific conclusions were as follows:

1. A track was constructed to connect path shapes into desired tracks for the tractor and implement to follow. The path shapes expected in row crops included a tractor ramp, implement ramp, sine wave, and a curve simulating farming on the contour. The outside two rails of the track simulated crop rows for the implement guidance systems to follow. The middle rail formed the desired track for the tractor to follow. The sections of track were connected in the same sequence and aligned in each test plot to make consistent paths for each individual test run.
2. The bracket of the tractor positional error transducer was attached in a fixed location relative to the tractor thereby following the actual tractor travel path. The swinging arm of the tractor positional error transducer followed the center track rail which indicated the desired tractor travel path. The rotary potentiometer measured the angle of the swinging arm, which indicated the tractor positional error. A similar transducer indicated the implement positional error.

   The accumulated errors for the tractor and implement positional error transducers included components of calibration, orientation angle, and wobble. The estimated accumulated errors for the tractor positional error transducer and implement positional error transducer were 0.91 cm (0.36 in.) and 0.99 cm (0.39 in.), respectively.
3. The use of implement guidance systems in row crop agriculture suggested that a description of the positional error distributions would be easier for producers to understand than means, ranges and standard deviations. The analysis used was to determine the percentage of the positional errors within a ±3 cm (±1.2 in.) error band, and within a ±5 cm (±2 in.) error band.

The tractor guidance system kept at least 70% of the tractor positional errors within a ±3 cm (±1.2 in.) error band except on the curve on the field with 0% side slope at 4.8 km/h (3.0 mph). When the error band was widened to ±5 cm (±2 in.), the tractor guidance system controller kept 94% of the tractor positional errors within the allowable error band on the curve on the field with 0% side slope at 4.8 km/h, and 100% of the tractor positional errors within the allowable error band for all other test combinations.

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