Nebraska Lincoln EXTENSION
EC706

Precision AGRICULTURE

Satellite-Based Auto-Guidance

Viacheslav I. Adamchuk, Precision Agriculture Engineer

RESOURCES

For more information about precision agriculture research, education and demonstration programs at the University of Nebraska–Lincoln, visit the Web site at *http://precisionagriculture.unl.edu/*

The rapidly rising cost of farm inputs persuades cost-conscious producers to search for new ways to minimize the use of energy and various consumable materials. For many, precision agriculture has been a focal point of their quest. The one area of precision agriculture that has received overwhelming attention in the past few years is the technology of auto-steer or, more generally, auto-guidance.

Recently, rising energy costs and more reasonably priced auto-guidance systems have made a clearer cost justification for investment in this new technology. As many of the benefits of auto-guidance technology become increasingly evident, early adopters continue discovering additional advantages. The most obvious rewards are reduced skips and overlaps, lower operator fatigue, and an ability to work in lower visibility conditions. In addition, as the systems being offered are refined and simplified, the skills needed to operate them have diminished. With the recognized shortage of skilled labor, technologies like auto-guidance can be taught in just a few hours, which makes it possible to reduce the overall labor cost.

Evolving Technology

The idea of automated guidance of agricultural vehicles is not new. It has been under development since the 1920s when primitive mechanical systems were installed to steer tractors along a desired track. Later, a variety of local triangulation systems allowed implementation of electronics to make such guidance more reliable and applicable in diverse conditions.

Additional innovations have involved vehicle guidance with respect to row crops using laser sensors, mechanical feelers and machine vision approaches. Currently, interest in guided machinery that uses range measuring sensors is growing in situations, such as orchards, where the applicability of navigation satellite technology has been limited. In field crop production, however, the guidance of agricultural vehicles using satellite-based positioning equipment (e.g., GPS receivers) has rapidly expanded during the last decade.

The benefits of satellite-based guidance include: reduced skips and overlaps, ability to work in conditions of poor visibility, negligible setup and service time, ease of use and more. Today, numerous farmers have suspended the use of conventional markers from their operations and rely on cost-effective alternative methods to steer their farm equipment based on continuously measured geographic coordinates.

There are three levels of automation for steering an agricultural vehicle, including: 1) navigation aids, 2) auto-guidance, and 3) field robots. Relatively inexpensive navigation aids, known as parallel tracking devices or, more commonly, lightbars, are being used by operators to visualize their position with respect to previous passes and to recognize the need to make steering adjustments if a measured geographic position deviates from the desired track.

More advanced auto-guidance options include similar capabilities with the additional option of automatically steering the vehicle using either an integrated electro-hydraulic control system or a mechanical steering device installed inside the cab. When implementing an auto-guidance option, the operator takes control during turns and other maneuvers and oversees equipment performance when the auto-guidance mode is engaged.

IANR
Institute of Agriculture and Natural Resources

Finally, with autonomous vehicles, the operator's presence on board is not required and the entire operation is controlled remotely (via wireless communication) or in robotic mode. This can be beneficial, for example, when applying chemicals that are hazardous to human health. The greatest liability of autonomous vehicles, improper response in unpredictable field situations, has been the major drawback of robotic agriculture. Therefore, auto-guidance has been recognized as the most promising option for today's farming operations.

After browsing through information from different vendors of auto-guidance systems (some of the most popular products are listed in *Table I*), producers can purchase either factory-installed or after-market equipment packages with costs ranging between $7,000 and $35,000, which typically include: positioning sensor (GPS receiver), controller, user interface module, attitude (vehicle orientation in space) and steering feedback sensors, and a steering actuator. The most expensive systems also include the base station required for the ultimate level of steering precision. Generally, the more expensive products involve positioning sensors with greater accuracy, better compensation for unusual attitude caused by rolling terrain, and more advanced control algorithms.

Table I. Examples of satellite-based auto-guidance systems available in 2007.

Company	Product	URL
AccuTrak	Accutrak AX5	www.accutrak.ca
AGCO Global Technologies	Auto-Guide	www.auto-guidenav.com
AgGuide	RowGuide	www.agguide.com.au
AgLeader Technology	InSight (interface)	www.agleader.com
Beeline Technology	ArroUniversal	www.beeline.ag
Case IH (brand of CNH)	AFS AccuGuide	www.caseih.com
Hemisphere GPS (CSI Wireless)	Outback eDrive	www.outbackguidance.com
John Deere – AMS	AutoTrac (GreenStar and StarFire)	stellarsupport.deere.com
Topcon (KEE Technologies)	ZYNX Guidance (X20)	www.topconpa.com
TeeJet Technologies (Mid-Tech)	FieldPilot (220)	www.mid-tech.com
New Holland (brand of CNH)	IntelliSteer	www.newholland.com
Novariant (AutoFarm)	AutoFarm (AutoSteer and OnTrac)	www.gpsfarm.com
Raven Industries	SmarTrax (QuickTrax)	www.ravenprecision.com
Reichhardt	Ultra Guidance PSR	www.reichhardt.com
RINEX Technology	AutoSTEER (Saturn)	www.rinex.com.au
Terradox Corporation	SiteWinder	www.terradox.com
Trimble Navigation	AgGPS AutoPilot and EZ-Steer	www.trimble.com

Positioning Accuracy

As with any application of global navigation satellite systems, the ability to accurately determine geographic coordinates is essential to assure quality performance. Today, three different global satellite navigation systems have been deployed to allow real-time determination of geographic coordinates at every location and any time:

- Global Position System (GPS) — USA
- GLObal NAvigation Satellite System (GLONASS) — Russian Federation
- European Navigation Satellite System (GALILEO) — European Union (under development)

Despite the type of system used, since the radio signal processed by receivers can be affected by several factors (atmospheric interference, configuration of satellites in the sky, time estimation uncertainties, etc.), the applicability of uncorrected position estimates is rather limited. To adjust estimated geographic coordinates in real time, various differential correction services are used. In addition to the differential correction, most receivers apply signal filtering techniques to assure the best possible predictability of antenna location. Based on the quality of differential correction and internal signal processing, positioning receivers used for auto-guidance have been advertised according to the level of anticipated accuracy: sub-meter, decimeter, and centimeter.

Widely used in agriculture and other industries, single-frequency receivers with sub-meter level accuracy frequently rely on several alternative differential correction services provided by public and private entities. Popular in the past, the Coast Guard differential correction AM radio signal (known more commonly as Beacon) is broadcast through a network of towers located near navigable waters. More recently, Wide Area Augmentation System (WAAS) has been deployed by the Federal Aviation Administration to broadcast a satellite-based differential correction service. A similar service is available through free-of-charge John Deere StarFire I (SF1) and subscription-based OmniSTAR Virtual Base Station (VBS) options.

To achieve decimeter level accuracy, dual-frequency receivers can be used with subscription-based John Deere StarFire2 (SF2) or OmniSTAR XP/HP differential correction services, or with a local base DGPS station. A local base station is also required to implement a Real Time Kinematic (RTK) differential correction service, which provides the ultimate centimeter level of accuracy. In certain locations around the US, local networks of permanent RTK base stations have been established by private entities to provide fee-based coverage of areas with relatively high demand for superior positioning accuracy.

Although a standardized test procedure is still under development, positioning accuracy claims listed in current advertisement literature frequently originate from a short-term dynamic test (referred to as pass-to-pass accuracy) or a long-term static test (referred to as year-to-year accuracy). Except for RTK-level receivers, pass-to-pass error claims are significantly lower than the year-to-year error estimates. The latter is important when attempting field operations requiring coming back to exact locations at different times. For example, while implementing controlled traffic, strip tillage, or similar techniques, it is necessary to conduct any new operation in strict geometrical relationship to previous tracks. On the other hand, many conventional field operations (e.g., tillage, seeding, chemical application, harvesting) are performed according to a travel pattern in which consecutive parallel passes are made with a fixed swath width. In such cases, every new pass relies only on the previous pass (usually in the opposite direction), and a certain level of tolerance can be accepted in terms of long-term position estimate drifts.

Frequently emphasized pass-to-pass error estimates can be related to the expected skips and overlaps between two passes occurring within a 15-minute time interval. In most instances, the claimed level of error should not be exceeded 95 percent of the time. However, the exact definition of pass-to-pass error may vary from vendor to vendor.

As shown in *Table II*, both pass-to-pass and year-to-year error estimates are mainly affected by the type of differential correction service. The reason for the diversity in available options is that the cost of equipment and services providing greater level of accuracy is typically higher and certain farm operations can tolerate less accurate and therefore less expensive selections.

It is also known that performance of satellite-based positioning system can be greatly affected by the geometry of satellites in the sky and the quality of signal reception in a given location at certain times. If the number of navigation satellites used to determine geographic location is relatively low (less than 5-6) and/or they are not spread around the sky, the position dilution of precision (PDOP) is low and poor quality performance of any satellite-based positioning device can be expected. Low PDOP can result from an obstacle such as a line of trees at the edge of the field or simply be due to the time of day when the geometry of satellites in the sky is not favorable for a given location. Likely, the latter can be predicted using several Web-based services. Those receivers that are based on G3 technology providing the capability to simultaneously track satellites that belong to different global navigation satellite systems (GPS, GLONASS and GALILEO) would be less likely to suffer from the lack of visible satellites around the clock and when the view of the sky is partially obstructed.

In addition, it is important to maintain quality reception of the differential correction signal. For example, the Coast Guard beacon signal strength diminishes at a distance range of approximately 300-350 km (180-220 miles) from the tower. Most communication satellites used to broadcast satellite-based differential correction signals occupy low latitude geostationary orbits, which means that for fields located at northern latitudes, it is important to maintain good visibility of the sky in the southern direction. Keeping the source of the differential correction signal in sight is very important when using a local base station. Signal routers can be used to overcome obstacles such as hills, tall trees, etc. In addition, most manufacturers cannot guarantee superior quality of differential correction at locations more than 10 km (6 miles) away from the base station, which should be considered when developing and/or using a local area network of RTK base stations.

Overall Performance

When adapting auto-guidance to a particular farm operation, it is necessary to understand that positioning error is just one factor causing less than perfect field performance. In addition, the ability to maintain desirable geometric relationships between passes is affected by vehicle dynamics, ability of the field implement to track behind the vehicle, and actual conditions of the field surface. Therefore, poor quality of the steering control system, sloped terrain, or misalignments in the implement will cause the overall field performance to suffer.

Currently, hands-free steering of agricultural vehicles is accomplished using either a steering device attached to the steering column or through an electro-hydraulic steering system. An easy-to-setup steering column device can be attached to an existing steering wheel or the steering wheel can be replaced with an actuator module that includes its own steering wheel. Auto-guidance systems integrated with electro-hydraulic steering control circuits alter the travel direction similar to conventional power steering. A control valve is used to properly direct hydraulic oil when a steering adjustment needs to be made. When retrofitting old tractors some manufacturers provide other hydraulic drive components to guarantee the required steering performance. It is obvious that actuators adjusting direction of travel through a steering column can be less responsive than those that change the orientation of vehicle wheels directly. In most instances, a wheel angle sensor is used as a steering feedback in addition to the records of heading obtained from the GPS receiver. This makes electro-hydraulic steering systems even more reliable.

Table II. Frequently claimed error estimates[1].

Option	Correction Source	Pass-to-Pass Accuracy	Year-to-Year Accuracy
Sub-meter	Beacon, WAAS, John Deere SF1, or OmniSTAR VBS	± 15-33 cm (6-13 in)	± 76-100 cm (30-39 in)
Decimeter	John Deere SF2, OmniSTAR XP or HP, or Local Base DGPS	± 5-12.5 cm (2-5 in)	± 10-25 cm (4-10 in)
Centimeter	Local Base RTK	± 2.5 cm (1 in)	± 2.5 cm (1 in)

[1]Error estimates are summarized based on Trimble, John Deere, and AGCO product promotion literature.

Control of vehicle dynamics becomes more challenging when farming sloped ground. Thus, roll (tilt from side to side), pitch (tilt from front to back) and yaw (turn around vertical axis) alter location of the positioning antenna with respect to other parts of the vehicle *(Figure 1)*. For example, when driving along a slope, the horizontal position of the antenna located on the top of a cab shifts to one side of the tractor with respect to the projected center of the tractor. This causes an engaged steering control system to guide the vehicle so that the point directly below the antenna (not the center of the vehicle) would follow the desired pass. To compensate for these attitude-caused challenges, most auto-guidance systems include a combination of gyroscopes and accelerometers or several antennas placed in different locations on the cab. Less advanced terrain compensation modules can deal only with roll and pitch angles, while more sophisticated sensing systems, frequently called 6-axes, can measure the total dynamic attitude of the vehicle in space.

Vehicle stability and proper alignment of the implement attached to the vehicle are also important when implementing auto-guidance. If a skip followed by an overlap takes place with every alternating pass in the opposite direction when making straight and level trips from one end of the field to the other, offset of the implement with respect to the vehicle and/or a source of a consistent side force can be the reason. However, even a properly adjusted pulled implement will not follow the tracks of the vehicle when making curved passes and/or operating on sloped terrain. In that case the implement will tend to stay close to the center of a turn or shift downward.

Several manufacturers have addressed implement tracking concerns by providing add-on implement steering systems. One such solution allows accurate sensing of the implement's position with respect to the vehicle and mechanical adjustment of this position using a set of large-diameter disc coulters to overcome the occurring side shift. Additional developments are focused on compensating for known shifts of the implement by adjusting the vehicle's trajectory to assure proper tracking of the implement instead of the vehicle. Optical and mechanical crop-based guidance systems can also be useful when it comes to the position of the implement with respect to previously established rows.

System Testing

To illustrate the overall performance of several auto-guidance systems for participants of the August 2005 Field Day that took place at the Agricultural Research and Demonstration Center near Mead, Neb., a light test cart was equipped with a coulter and a survey-grade RTK-level GPS receiver. Every tractor pulled the test cart along a J-type course starting with a variable radius curved section and continuing into a straight section that contained a portion with significant elevation change. During the return pass, every vehicle was operated along the same pass in the hands-off steering mode. The marks left by a single shank coulter installed in the center of the cart served as a visual illustrator of the overall performance. To confirm these

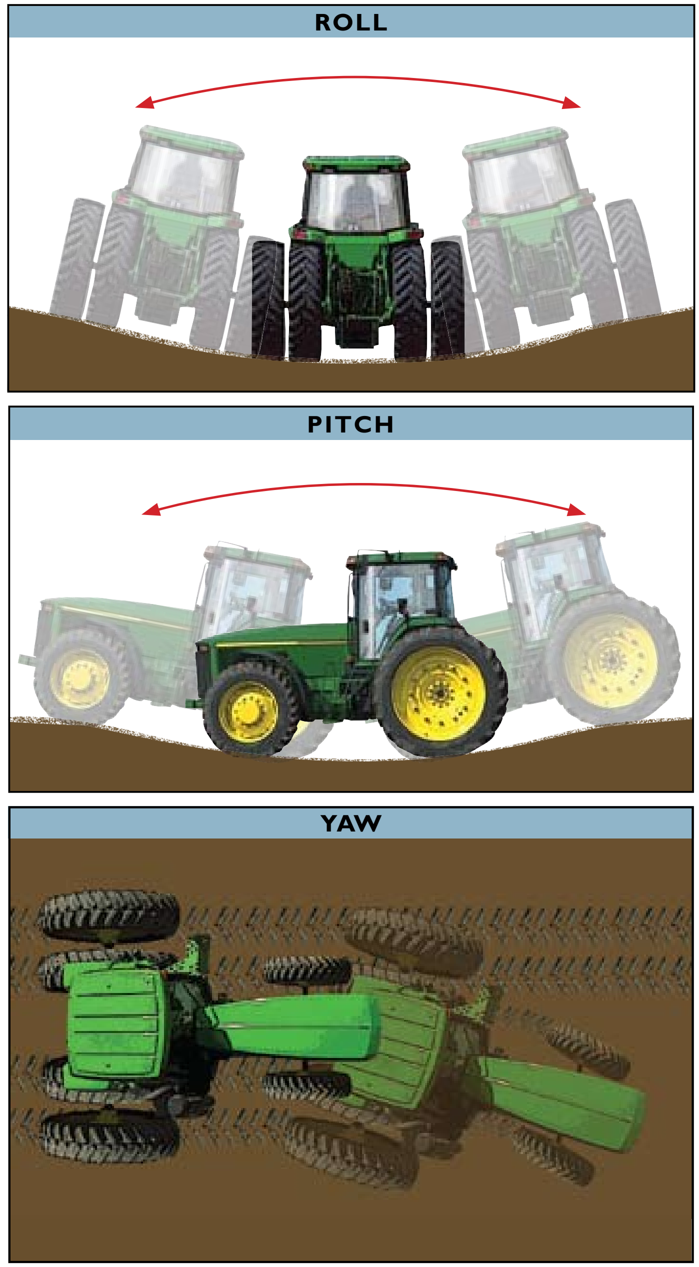

Figure 1. Changes of vehicle orientaion in space that need compensation.

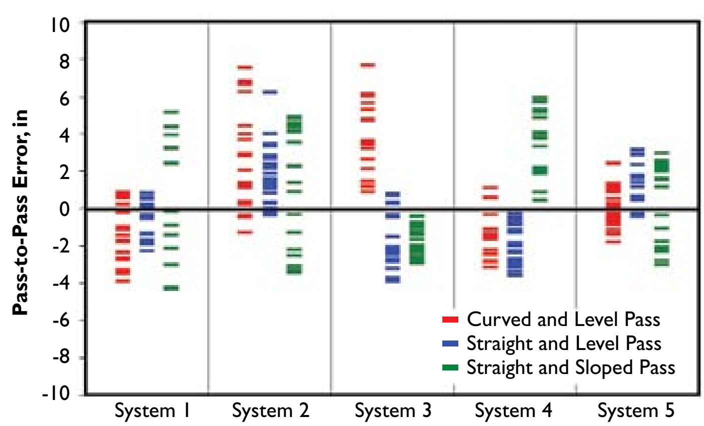

Figure 2. Pass-to-pass error distributions obtained while demonstrating five different RTK-level auto-guidance systems.

observations, centimeter-level position records were used to calculate the distance between the two tracks in opposite direction *(Figure 2)*. To make the calculations, 20-m (66-ft) long sections were extracted from the: 1) curved and level, 2) straight and level, and 3) straight and sloped portions of the J-type course.

Certainly, the test cart and the centimeter-level receiver were significant contributors to the errors shown in *Figure 2*. While pursuing a more representative and reliable testing procedure, another series of tests was accomplished using an improved test cart equipped with a linear potentiometer array sensor *(Figure 3)*. This sensor was able to measure the position of triggers placed around the concrete track of the Nebraska Tractor Test Laboratory with 2-cm (0.8-in) accuracy with respect to the center of the cart. As shown in *Figure 4*, this method allowed summarizing errors estimated for a pair of systems with two levels of accuracy (centimeter and decimeter). As mentioned earlier, the RTK-level centimeter system was found to be immune to time drifts and provided the same estimate for short-term and long-term errors, while the dual-frequency DGPS-level decimeter system presented higher long-term errors.

Similar to the field demo, it was observed that linear potentiometer sensor uncertainties together with inconsistent test cart tracking and vehicle dynamics delay increased the observed errors when compared to corresponding manufacturer claims. Recently, a newer concept for quantifying auto-guidance errors based on a visual sensor system has been developed. An international group of manufacturers, researchers, and customers was formed to create a standard that will define guidance error terms and provide basic codes for future tests.

Additional Considerations

Another important feature of any auto-guidance system is its ability to follow a particular traffic pattern, rapidly acquire the desired pass, and provide effective feedback to the operator on-board. Although every system can easily perform straight line patterns, some products have difficulty in steering vehicles along contours (such as field terraces). However, it has been noted that upcoming versions of these products include the capability for operating in odd-shaped fields *(Figure 5)*.

Although most auto-guidance systems are designed specifically for the task of vehicle steering, some systems allow using the same hardware to collect spatial data (such as yield maps) or to operate

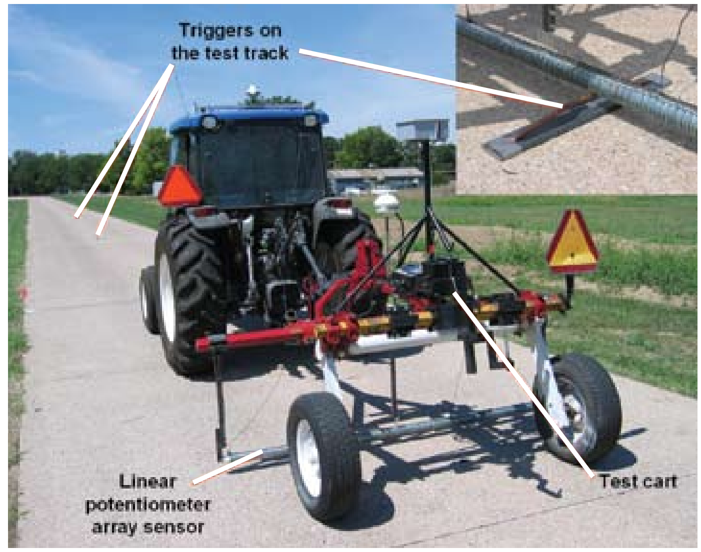

Figure 3. Testing auto-guidance systems using a linear potentiometer array sensor.

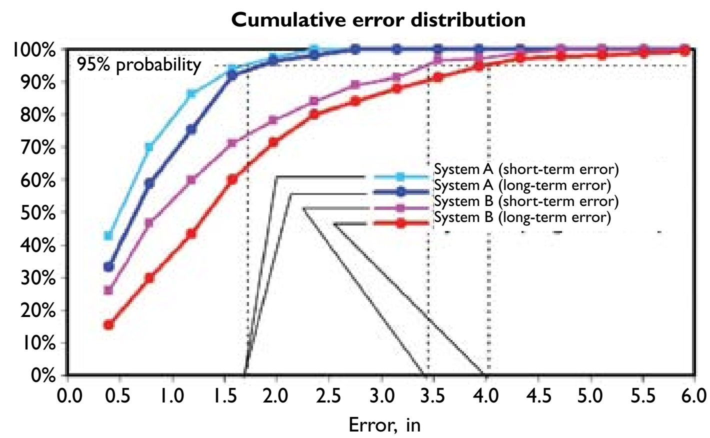

Figure 4. Comparing error estimates for a centimeter-level System A and a decimeter-level System B.

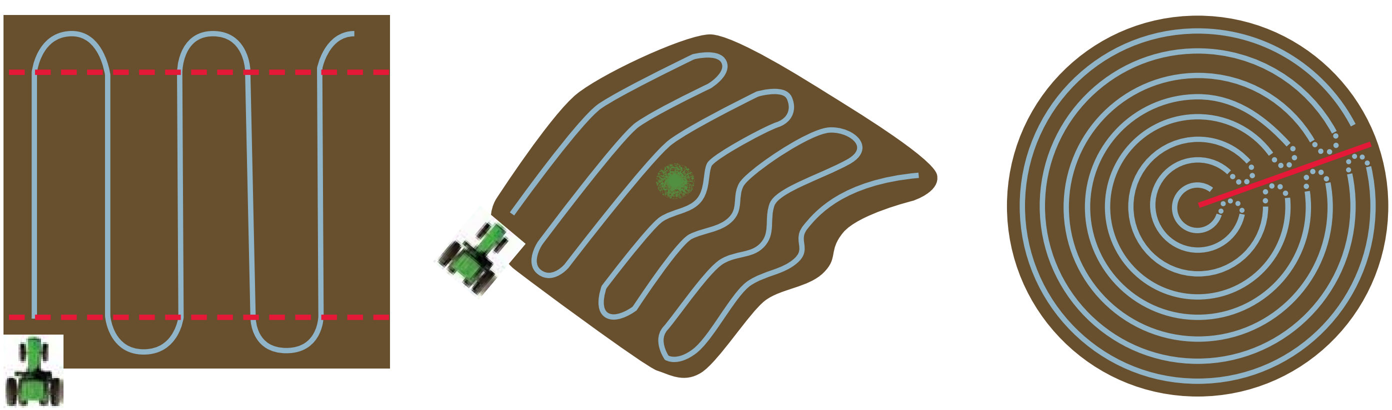

Figure 5. Examples of available field traffic patterns.

variable rate controllers. Versatility of these units is greater and, therefore, the cost can be spread among several tasks.

In addition, different makes of auto-guidance products frequently can be distinguished by the compactness of different components and the user interface. While some systems cause technical challenges when being installed and calibrated, others may be fully operational in less than one hour. User-interfaces also range from a very intuitive colorful graphic touch-screen display to older menu driven hard-key units with limited graphical feedback.

It has been noted that the skills necessary to properly operate any of the existing systems can be obtained in only a few hours. This allows fast training of low-skilled operators who may find it difficult to accurately operate field machinery equipped with traditional markers. The quality of field operations has been shown to be independent of previous tractor operation experience when auto-guidance systems are used.

Summary

Satellite-based auto-guidance represents one currently available technology that can provide significant benefits for the crop production industry in diverse growing environments. Once producers use auto-guidance equipment, they seldom want to return to conventional practices. Newer, improved versions of auto-guidance products provide better operation functionality which prevents the frustration and fears that early adopters experienced. The question "Should auto-guidance be used?" has now been replaced with the question "What auto-guidance option is best for a given operation?" Available variety of costs, guidance error levels, and other technical specifications suggests that virtually every cropping operation may be optimized if the appropriate type of satellite-based auto-guidance is implemented.

Note
Reference to commercial products or trade names is made with the understanding that no discrimination is intended and no endorsement by University of Nebraska–Lincoln Extension is implied.