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# Agricultural automatic guidance research in North America

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## Abstract

A review of the recent research in agricultural vehicle guidance automation in North America is presented. A conceptual framework of an agricultural vehicle guidance automation system includes navigation sensors, navigation planner, vehicle motion models, and steering controllers. © 2000 Elsevier Science B.V. All rights reserved.

*Keywords:* Automatic guidance; Agriculture; Vehicle guidance

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## 1. Introduction

Automation of machine guidance functions has been an interest for agricultural researchers in North America since the early days of the tractor. Patents in the early 1920s diagram systems that can follow furrows to guide a machine across a field (Willrodt, 1924). In the late 1930s, Andrew developed a complete system of circle farming based on piano wire winding upon a large diameter spool positioned centrally in a field (Sissons, 1939). In the 1970s, wire carrying a low-current, low-frequency signal was used to identify pathways machinery should follow in the field (Schafer and Young, 1979).

In the 1980s the potential for combining computers with image sensors provided opportunities for machine vision-based guidance systems. During the mid-1980s,

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researchers at Michigan State University and at Texas A&M were exploring machine vision guidance. Also during this decade, a successful program in robotic harvesting of oranges was performed at the University of Florida (Harrell et al., 1990).

The potential for vehicle automation in North American agriculture has increased by the advent of precision agriculture. Precision agriculture has helped advance vehicle guidance firstly in terms of providing position information that is required for vehicle guidance. Secondly, precision agriculture has placed the notion of vehicle automation within the conceptual boundary of equipment manufacturers and agricultural producers. In the late 1980s and the 1990s, changes in the funding structure of research in defense exposed new research teams to the opportunities in the agriculture sector and has resulted in traditionally non-agricultural research teams attacking the challenges of agricultural vehicle guidance. Researchers at Carnegie-Mellon University and Stanford University are representative groups who have played an active role. The University of Illinois also formed a research team to address the needs of vehicle automatic guidance to precision farming in the North Central USA.

A review of the research activities in vehicle automation in North America over the last fifteen years will be presented in terms of a framework for automation, as

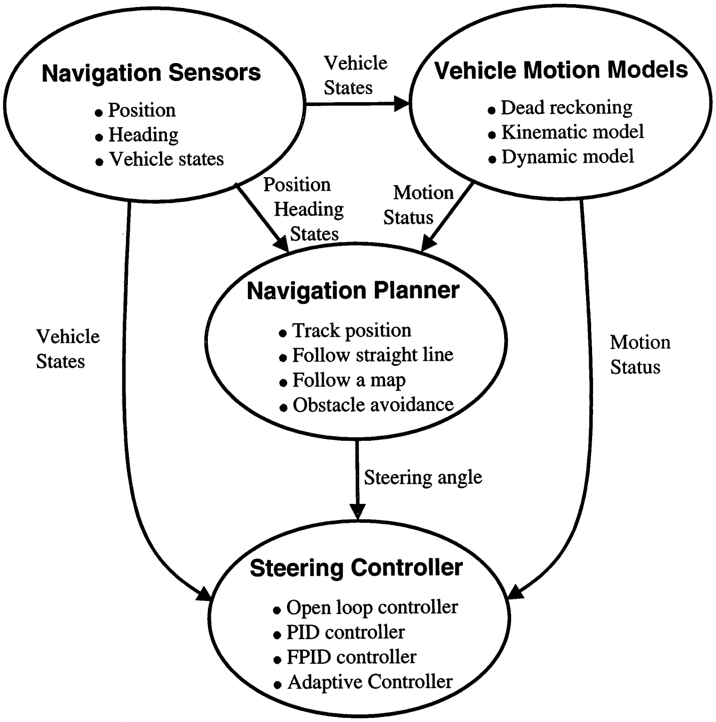

Fig. 1. Basic elements of agricultural vehicle automation systems.

Table 1
Navigation systems developed for US agriculture

| Institute | Machine | Sensor | Comments |
|---|---|---|---|
| Michigan State University (1984–1996) | Lawn tractor and Case 7110 tractor | Machine Vision | 6 cm accuracy at 4.9 km/h, 12 cm accuracy at 12.8 km/h |
| Texas A&M (1984-92) | Ford Tractor | Machine Vision | |
| Carnegie-Mellon (1994–1998) | New Holland Speedrower | Machine Vision, GPS | Autonomously harvested over 40 hectares |
| Stanford (1996) | John Deere 7800Tractor | GPS | 1 degree accuracy in heading, line tracking accuracy with 2.5 cm deviation |
| University of Illinois (1996–present) | Case 8920 MFD and 2WD Tractors | GPS, Machine Vision, GDS | Vision guidance at 16 km/h on row crops |

shown in Fig. 1. The key elements of automatic guidance are navigation sensors, a vehicle motion model, a navigation planner, and a steering controller. Table 1 summarizes some of the investigations that have taken place.

## 2. Navigation sensors

Navigation sensor research in the US has focused on sensors for providing vehicle position and vehicle heading, but also includes sensors providing the current state of the vehicle (speed, wheel position, etc.). Some guidance sensors provide information for absolute positioning. Others only provide relative positioning (e.g. mechanical feelers and machine vision) between the vehicle and the guidance directrix. The key position sensors have been mechanical feelers, machine vision and GPS sensors. The key heading sensors have included machine vision, GPS, with some work taking place with geomagnetic direction sensors (GDS) and inertial sensors.

### *2.1. Mechanical feelers*

Mechanical feelers are relative position sensors that provide a linkage between the desired trajectory and the vehicle. Several commercial products are available that use a mechanical feeler to track a ridge, furrow, or crop. Today these products have evolved to two primary forms. One is a mechanical feeler system mounted on the tractor or combine, which provides a control signal to an electro-hydraulic valve added in parallel to the steering system for steering the vehicle. The second type is based on providing precise lateral control of the implement, ignoring the deviations of the tractor within some limits. In the vehicle-mounted systems, the products are typically made to add onto most tractors and combines. The retrofit includes a mechanical feeler to sense the crop, a wheel angle sensor (potentiometer), an electro-hydraulic valve steering actuator, and a control module. The steering actuator is mounted in-line with the steering hand-pump to allow normal operation along with automatic control. The control module allows the operator to engage/disengage the system and to change the sensitivity of the controller. A variety of feeler devices have been devised to vehicle position under different modes of operation including crops and furrows made from markers. A limitation of these systems is the absence of a control signal at the mechanical feeler interface due to a lack of crop. These systems are popular with a small number of farmers, but they have undergone limited engineering tests. Recent field trials have shown that these systems are quite effective at speeds up to 10 km/h in maize, providing that the course is limited to straight rows (Qiu et al., 1999). At slower speeds, the systems can be used on curved rows, but have limited accuracy since the feeler position on the curve affects the timing of the steering actuation of the controller. One key failure mode is an insufficient position signal at the interface between the feeler and the crop. This can be a result of low rigidity of the crop or due to skips in the plant population. The crop rigidity becomes increasingly important at higher speeds since the impact of the feeler tends to push smaller plants down. In the case of traveling through tall crops such as maize, these systems are effective on straight courses.

### 2.2. Machine vision

Machine vision is a relative position and heading sensor with the image sensor mounted on the vehicle. There are several aspects of machine-vision based sensing. Different types of sensor modalities can be selected to measure the guidance information. Standard image sensors provide a color or monochrome response, but even special purpose cameras have been developed by combining standard sensors with optical filters (Reid and Searcy, 1987). Positioning of the sensor on the vehicle requires an understanding of the geometric relationship between the image sensor, the vehicle and the field-of-view that the sensor uses for guidance information. Researchers in North America have explored the use of vision sensors for detecting a guidance directrix on row crops, soil tillage, and the edges along harvested crops. Various methodologies of image processing have been investigated for extracting the guidance information. The processed images provide an output signal that can be used to provide a steering signal for the vehicle.

Gerrish and his colleagues (Gerrish and Surbrook, 1984; Gerrish and Stockman, 1985) investigated the potential of vision-based tractor guidance by studying the accuracy that could be achieved through automatic guidance, and by evaluating several images processing techniques to determine their applicability. This research led to the development of a vision-guided lawn tractor (Fehr and Gerrish, 1995). This work was later implemented on a Case 7110 tractor (Gerrish et al., 1997). In the final system, a standard RGB sensor was used to measure crop vegetation from a position to the left of the operator's cab over the rear axle at a height of 2.79 m above the ground and tilted downward 15 degrees below the horizon. During setup, the user selected pixels representing crop and soil material in the image for segmentation based on RGB values. The vehicle guidance signal was based on a single 'look-ahead' point in the image. The position of the crop row at the single position in the image provided an offset that was used with a steering gain to directly control the wheel position. In their final system, the tractor was able to follow rows of corn plants in straight rows with an accuracy of maximum 6 and 12 cm from a mean trajectory at speeds of 4.8 and 12.9 km/h, respectively.

Reid and Searcy (1987) began development of a vision-based guidance system for steering a tractor through row crops. Near infrared images were used to segment row crops into crop and soil using a Bayes classifier to segment each image. Segmented images were processed to produce sets of points representing crop row centers using run-length encoding and marking the center pixel of each run. Regression equations describing crop row locations in images were determined using an unsupervised classifier that clustered pixels based on vertical proximity to classified pixels or the distance to a projection of the regression line passing through classified pixels. Final classes representing crop rows were separated based on the number of points in each class and used to determine the vanishing point of crop rows. Brandon and Searcy (1992) designed and built a vehicle control system to steer a tractor through row crops. The algorithms developed by Reid (1987) were implemented for computing heading and offset errors. The algorithms were limited to straight rows when the guidance signal from images was used directly, since the information came from positions well ahead of the vehicle. For curvature in rows, the control information was integrated into a trajectory planner to buffer control information until the vehicle reached the proper turning point. Testing demonstrated that the system could detect heading errors within 0.5 degrees and offset errors within 5 cm. A limitation of this early work was that machine vision systems were bulky and had limited capabilities. Reid and Searcy (1986) also used the Hough transform for detecting the guidance signal. This method has advantages in that rows of crop transform to clusters of points in the image parameter space.

Carnegie-Mellon University and the USA governments National Aeronautics and Space Administration (NASA) researchers, developed a guidance system for a New Holland hay windrower using machine vision to sense the edge of the uncut crop (Ollis and Stentz, 1996). A color camera on either side of the vehicle was used to track the edge of cut/uncut vegetation. The guidance signal was based on a vertical weighting of the crop edge and a calibration of the steering valve with the horizontal displacement of the crop edge in the image. An unsupervised classifier segmented images into cut/uncut regions. Additional software was developed for compensation of shadows that are cast by the vehicle and for detecting obstacles based on their dissimilarity to cut/uncut classified crop. The system operated successfully under field conditions and logged over 40 hectares of autonomous operation (Ollis and Stentz, 1997).

University of Illinois researchers, building on the work of Reid (1987), integrated machine vision with other sensors required for automation. Will et al. (1998) described their research platforms consisting of two Case 8920 tractors. Vision guidance on row crops was successful in row crop tracking at speeds of up to 17 km/h on straight rows and up to 10 km/h on significantly curved rows. Pinto and Reid (1998) developed an alternative algorithm for row crop detection by considering the detection of the heading and offset as a pose recognition problem utilizing principal component analysis. The main goal of the vision part of a guidance system is to output the heading angle and the offset of the crop rows relative to the vehicle. A set of poses (images) was collected and used as a training set. The training stage of the algorithm used principal component analysis (Hotelling Transform) to output a low-dimensional eigenspace on which each pose was represented by its projections. Given a new image, the pose (heading angle and offset) recognition was done by projecting the image onto the eigenspace and determining the closest training image projection. While this methodology requires substantial time in training, it offers fast and robust results in implementation. In earlier work, researchers developed a split image vision sensor to be used in parallel swathing of an agricultural sprayer tracking foam markers (Von Qualen et al., 1991). The image taken from cameras at the ends of spray booms were divided into an upper portion for measuring the deviation in the path and a lower segment for lateral position estimation. Heading error was able to be predicted to 0.17° under all conditions tested. Offset errors were less than 7.4 cm from the desired straight line trajectory when the heading angle was less than 5°.

Klassen et al. (1993) developed image processing algorithms for vehicle guidance in tillage based on the detection of tilled/untilled boundary in soil as well as other crop conditions.

### 2.3. Global position systems

Several studies have explored the use of high accuracy GPS for vehicle guidance. Some researchers used the GPS signal for position estimation while others used it to maintain the vehicle on a constant heading.

Researchers at Stanford University (O'Connor et al., 1995, 1996; Bell, 1999) have successfully developed a 4 antenna carrier-phase GPS system for guiding a John Deere 7800 tractor on prescribed straight row courses with headland turns. Four single channel GPS sensors were mounted on the cab and the receiver produced attitude measurements at 10 Hz. The closed loop heading response was better than 1 degree and the line tracking standard deviation was better than 2.5 cm.

Researchers at the University of Illinois (Stombaugh et al., 1998) utilized a 5 Hz real-time kinematic (RTK) GPS for guidance of a 2WD Case 7720 tractor. In order to eliminate lag in the system responses the GPS was mounted in front of the front wheels on a mast extending to a height above the cab. Vehicle response in tracking a 3-m step change in position showed that the lateral position error at 4.5 m/s was within 16 cm (95% confidence).

### 2.4. Geomagnetic direction sensor

A geomagnetic direction sensor (GDS) is a magnetometer which senses the earth's magnetic field. It can be used as heading sensor similar to an electronic compass.

Benson et al. (1998) utilized a GDS with GPS for vehicle guidance along straight directional courses. A limitation of GDS sensors is the influence of external electromagnetic interference from the vehicle and surrounding sources. These sources can include electrical power transmission lines and the vehicle air conditioner. However, controlling these error sources, they were able to combine GDS with a medium accuracy GPS system (20 cm) and track a straight line with an average error less than 1 cm. The maximum overshoot for a 3 m step response was 12%, compared with 50% for GPS only.

## 3. Navigation planner

Navigation planning is important for agricultural vehicle control. Most guidance operations require that the vehicle follow some nominal trajectory or directrix. Local information can be the source of directrix and sensed directly. These include crop rows, swath edges, tilled/untilled boundaries. In parallel swathing, the directrix is parallel lanes to some prior path. The directrix might also be defined by a desired course from a map or script. Many research efforts in guidance have dealt with guidance in straight lanes and thus the role of the navigation planner is much simplified. For curved row guidance, the navigation planner must consider the sensor information and vehicle motion to navigate in the desired course. The navigation planner also plays an important role in autonomous operation, providing different machine 'behaviors' based on field conditions.

### *3.1. Dead reckoning*

Dead (deduced) reckoning technology is currently used in aircraft, military weaponry and marine navigation. Lawrence (1993) describes dead reckoning as essentially a motion memory system. "If a vehicle starts from a known location and travels in a known direction for a known time, its final position is known." On agricultural vehicles, dead reckoning sensors can be as simple as wheel encoders, which measure the rotation of vehicle or implement wheels. Patterson et al. (1985) developed a dead reckoning system for used on a towed planter using wheel encoders. The system was only tested under controlled laboratory conditions and under controlled conditions deviated 12.95 cm in traveling 38.1 m.

Freeland et al. (1992) experimented with a low cost electronic compass used together with wheel encoders to provide dead-reckoning posture information. They reported that the relatively high level of magnetism exhibited by agricultural machinery, compared to the earth's magnetic field makes the used of magnetic sensors for guidance challenging.

### *3.2. Kinematic model*

Several researchers have used a simplified kinematic model for describing the lateral error with respect to a nominal trajectory. (O'Connor et al., 1996; Ollis and Stentz, 1996; Benson et al., 1998; Noguchi et al., 1998).

### 3.3. Sensor fusion

The principle of sensor fusion is to combine information from various sensing sources since no individual sensing technology is ideally suited for vehicle automation under all modes of use. The appropriate sensor will depend on the field status at the time of operation. But even under a given field operation, the availability of data from multiple sensors provides opportunities to better integrate the data to provide a result superior to the use of the individual sensor. Fig. 2 illustrates one example of a sensor fusion system to combine information from multiple sensors.

Benson et al. (1998) used GDS and GPS together for vehicle guidance based on dead reckoning as a simple path planner. The system was tested at slow speeds (1.12 m/s) and had an average error of less than 1 cm, which compared favorably to GPS-based guidance. When implementing a 3-m step change in responses the sensor fusion system had a maximum overshoot of 12%. Under GPS-under mode the system experienced a 50% overshoot.

Noguchi et al. (1998) developed a guidance system by the sensor fusion integration with machine vision, RTK-GPS and GDS sensors. An Extended Kalman Filter (EKF) and a statistical method based on a two-dimensional Probability Density Function were adopted as a fusion integration methodology. To achieve the

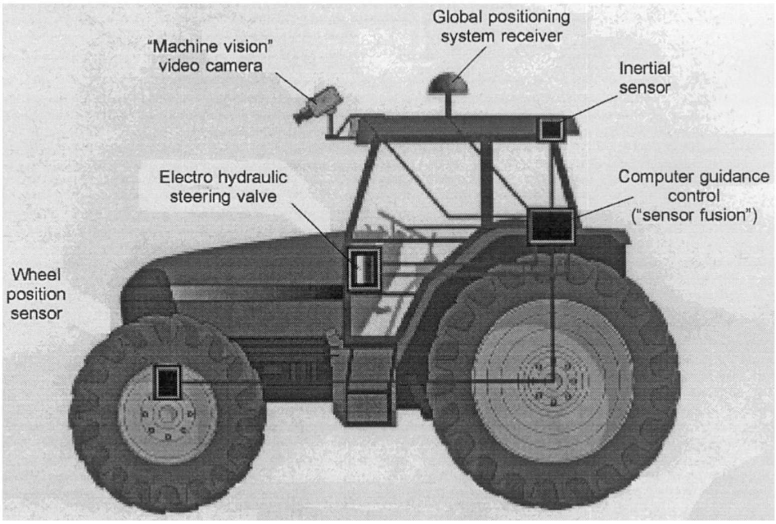

Fig. 2. Sensor fusion on an agricultural tractor. The wheel position sensor calculates the angle that the wheels are turned. The 'machine vision' video camera scans the immediate surroundings and watches for obstacles. The global positioning system determines the tractor's precise location on the field. The inertial sensor senses the movement of the tractor in the field and calculates its path. The computer guidance control uses 'sensor fusion' to combine all of the information coming from the different sensors. The electro-hydraulic steering valve receives orders from the computer and controls the steering.

navigation planner based on sensor fusion integration, four types of control strategies were built by changing combination of the three kinds of sensors. The developed navigation planner selected from a priority scheme of the control strategies using a knowledge-based approach. The average lateral error of the vehicle guidance based on the fusion of the RTK-GPS and the GDS was 8.4 cm. The developed sensor fusion methodology with the EKF performed with satisfactory precision, given that the lateral error was less than the precision of the RTK-GPS.

The CMU system for autonomous windrowing of hay also used multiple sensors. The system handled redundant and ambiguous information from sensors using an arbiter (Ollis and Stentz, 1996).

### 3.4. Autonomous functions

A limited number of researchers have dealt with the issues related to autonomous vehicle systems.

A finite state approach was developed by CMU in their autonomous windrower (Hoffman, 1996). Primary states of the machine triggered different behaviors or operations. Some basic states defined which side of the harvester was uncut crop, identified the proximity of a turn, and the implemented of turning functions. In each state of operation the machine performed one or more behaviors. For example, harvesting a rectangular field of alfalfa in a simple serpentine pattern required combinations of the following states with associated behaviors:

- Cut on right
  - Crop-line follower — detection of the boundary between cut/uncut crop in images;
  - Field coverage monitor — coordinates the activities of the harvester based on current position within the field.
- Near right turn
  - Crop-line follower;
  - End of row detector — seeks out the boundary indicating the end of the field from an image sensor;
  - Field coverage monitor.
- Turn right
  - Field coverage monitor;
  - Local trajectory tracker — performs dead reckoning to drive the harvester through turns and the ends or corners of the field.
- Cut on left
  - Crop-line follower;
  - Field coverage monitor.

Research tapping into the power of on-board and off-board computing is being explored in terms of benefits for vehicle guidance (Zhang and Reid, 1999). The basic concept of this research (Fig. 3) depends on integrating vehicle and implement control systems with off-vehicle resources and on-board decision-making tools.

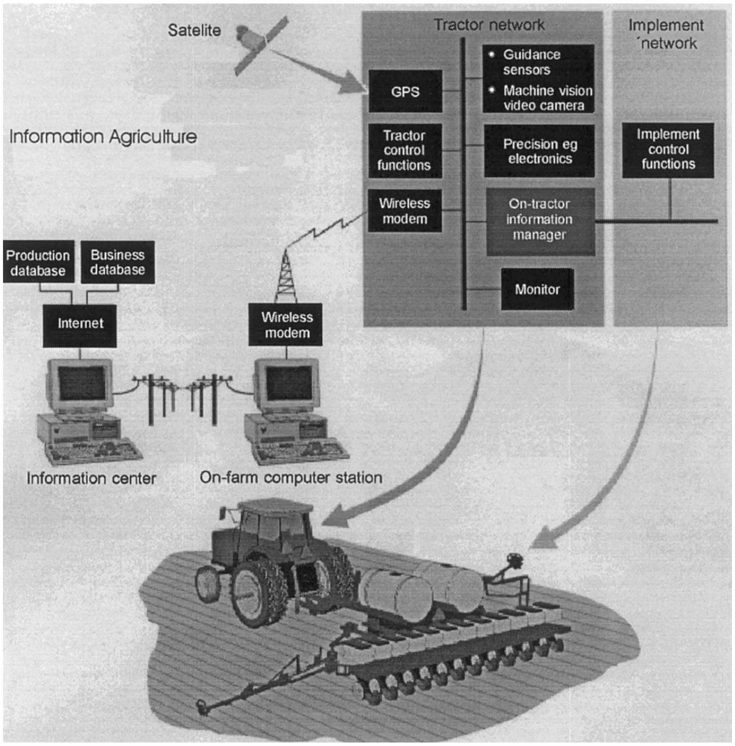

Fig. 3. Information agriculture will allow an autonomous or semi-autonomous guidance system to access information off of the vehicle.

## 4. Steering controller

The steering controller is the actuator that converts a control signal from a feedback controller to an appropriate mechanical adjustment in steering angle.

Steering controller design needs for agriculture differ from that of on-highway vehicles due to operating conditions of the vehicle in the field. Agricultural equipment often operates on unprepared, changing and unpredictable terrain, ranging from asphalt to spongy topsoil in the field. In the case of automatic or autonomous operation, steering controllers should be able to provide appropriate steering actions in response to the variations in equipment operation states, travelling speed, tire cornering stiffness, ground conditions, and many other parameters influencing steering dynamics.

Since most modern agricultural vehicles employ some form of hydraulic steering system, recent developments in automatic steering controllers are merely modifications to the existing hydraulic system. As an example, Van Der Lely (1985) holds a patent for an automatic guidance system that uses fluid power to actuate the steering linkage. Laine (1994) analyzed E/H control techniques for a parasitic steering valve. US equipment manufacturers primarily offer electrohydraulic (E/H) steering systems for agricultural vehicles.

The steering controller design depends on many factors other than E/H steering elements and vehicle dynamics, including ground conditions and vehicle speeds. Noh and Erbach (1993) found that neither negligible nor constant friction could produce significant and unpredictable side-slip. O'Connor et al. (1996) developed a steering controller based on a set of linear motion equations. Automation requires a steering controller with stable and fast response. The design of steering controllers should compensate for non-linearity and many unknown factors involved in steering agricultural equipment.

Stombaugh et al. (1998) developed a classical model based steering controller for high speed agricultural tractor. A double integrator transfer function was used in this feedback controller. They found that the steering controller must compensate for the dynamics of both the vehicle and the steering system when these two systems were in the same frequency range. The compensation of the deadband characteristics of the steering valve was also critical in achieving satisfactory steering performance.

Benson et al. (1998) designed a PID steering controller in frequency domain for an agricultural tractor guided by a GDS. Its closed loop transfer function was obtained experimentally. Test results showed that steering controller played an important rule in achieving satisfactory automated guidance of an agricultural tractor. It was necessary to tune the PID controller to achieve satisfactory steering performance.

Wu et al. (1998) developed a methodology for designing E/H steering PID controllers for agricultural vehicles. In their approach, a linearized dynamic model of the steering system was used to design the controller. This linearized model compensated for the deadband and asymmetry gain. In addition, a kinematic model of steering linkage was used to close the PID loop on the hydraulic steering actuator. Test results indicated that this PID steering controller was capable of achieving satisfactory steering control performance.

## 5. Conclusions

Agricultural-related automatic guidance research in North America has been reviewed. Over the last ten years, advances in E/H and sensing technologies have made promising advances that have utilized individual sensing technologies and have combined others together in novel ways for automatic guidance. The future of automation will hinge on the ability of researchers to maximize the performance of these systems while maintaining usability for the agricultural equipment operator.

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