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Agricultural Vehicle Navigation Using Multiple Guidance Sensors

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ABSTRACT

Agricultural vehicle navigation includes both on-road and on-field operations. The objective for on-road navigation is to guide the vehicle traveling on paved or prepared road according to a scheduled path plan, and for on-field guidance is to guide the vehicle following crop rows without overrun on crops. In this paper, the authors have presented an on-field navigation system with redundant sensors of a vision sensor, a fiber optic gyroscope (FOG), and RTK GPS. A steering controller has been developed to implement steering control based on guidance information obtained from guidance sensors. The navigation system has evaluated on an agricultural vehicle. A research platform has been developed based on a Case-IH Magnum[1*] 8920 2-wheel drive agricultural tractor. Results indicated that the multiple sensor based agricultural vehicle navigation system was capable of guiding the tractor traveling between crop rows accurately.

INTRODUCTION

Agricultural vehicles are designed to perform various agricultural operations, and often operated on unprepared and changing terrain at relatively high speed. Human operators use a significant amount of intelligence to combine job functions, visual and audio cues, motion sensations, and experience to maneuver the vehicle. Long hours and repetition easily result in operator's fatigue, which in turn causes safety issues and decrease operation efficiency. Automatically guided vehicles will not fatigue, and can reduce operator's work intensity, resulting in enhanced efficiency, and increased operation safety. Recent developments in precision farming technology demands increased automation, efficiency, and safety. The development of automated guidance control for agricultural tractor has significant commercial and societal importance.

Automated guidance control aims to steer the vehicle following a desired path automatically. It requires a guidance system be able to detect vehicle posture, create proper steering signal, and steer the vehicle according to the signal. The posture is the position and orientation of the vehicle (Kanayama and Hartman, 1989). Different guidance sensing systems, including mechanical, optical, radio, ultrasonic, and leader cable systems have been developed for agricultural vehicles during the past several decades (Richey, 1959; Kirk *et al.,* 1976; Tillet, 1991). In the past two decades, vision sensors and GPS sensors have been added to the list of available guidance sensors. Although each system uses different technologies to guide vehicles, most of the systems use the same guidance parameters, heading angle and offset, to control steering. Heading angle is the angle between the tractor centerline and the desired path, and offset is the displacement of the tractor central mass off the desired path.

Stanford University demonstrated high accuracy carrier phase differential GPS for the guidance of a John Deere 7800 series tractor (O'Connor *et al.* 1996). A four antennae system provided a heading accuracy of 0.1 degrees and offset accurate to 2.5 cm in tracking parallel straight rows at 3.25 km/hr. Carnegie-Mellon Robotics Institute developed an autonomous New Holland 2550 Speedrower for cutting forage using vision-based perception on the cut and uncut regions of the crop (Ollis and Stentz, 1997). The speed of operation was reported as 7.2 km/hr. In addition to guidance, vision sensing provides inputs for "end-of -row" detection, correction of

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[1] Case-IH and Magnum are trade markers of Case Corporation, and used with permission.

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illumination due to shadows and obstacle detection. Sensor fusion methodologies were included to resolve conflicts from information coming from various sensor modules (Hoffman *et al., 1996*). Michigan State University has attempted to implement vision guidance on a Case 7190 MFD tractor (Gerrish *et al.,* 1997). The camera was mounted 2.8 m above the ground on the left side of the vehicle with a tilt 15 degrees below the horizon and a view beyond the vehicle. The system was tested for straight row guidance at speeds on 4.8 and 12.9 km/hr with maximum tracking errors of 6.1 and 12.2 cm, respectively.

An automated agricultural vehicle requires a steering controller to implement the steering signals provided by guidance sensor. An electrohydraulic (E/H) steering controller is often used to implement steering according to the steering signal provided by the guidance sensor. Steering controllers for agricultural vehicle face a number of difficulties not commonly found in on-road vehicles. Vehicle dynamics and E/H valve properties will both affect the performance of steering control (Laine, 1994). The surface properties vary with the location, weather, field conditions, and equipment status. Nonlinearity, deadband and hysteresis associated with the hydraulic steering system add difficulties to the design of steering control system (Wu *et al.,* 1998). Much of the recent literature on control of hydraulic systems involves the application of advanced controls, such as adaptive control (Fullmer and Ananthakrishnan, 1993) and predictive control (Mare, 1996). Alleyne and Hedrick (1995) applied a "persistence of excitation" method for parameter identification.

This paper presents a solution to challenging problems for automatically guided agricultural vehicles with multiple sensors. This solution includes guidance parameter identification using multi-sensor data fusion for real-time vehicle guidance. A feedforward-plus-PID steering control algorithm is used to compensate the variation in tractor dynamics for ensuring a satisfactory steering performance. A platform was developed to support the research on a Case-IH Magnum[1] 8920 two-wheel drive agricultural tractor. Results from field tests are presented.

Figure 1. Image of crop rows obtained from a CCD visual sensor. This image will provide guidance directrix which contains heading and offset for tractor guidance.

REDUNDANT GUIDANCE SENSORS AND SENSOR FUSION

Vehicle heading and offset are the critical parameters for vehicle guidance. Our research has a history of using vision guidance sensors, which utilizes a camera mounted on the vehicle to provide information on the vehicle motion relative to a guidance directrix which is defined by the rows across the field (Fig. 1). This guidance directrix provides a steering control signal based on the geometric relationship between the camera, the vehicle and the field-of-view. A machine vision system, consisting of a CCD camera, a frame grabber and a computer, has been developed in this research. A near infrared filter (800 nm) was installed on the camera to improve discrimination between the plant material and soil based on the work of Reid (1986).

A heuristic method was used for detecting the guidance directrix. By this method, the directrix position was enhanced in the image by highlighting the center position of run-length encoded segments. Points in various directrix classes were determined by unsupervised classification. Each directrix class was used to determine a trajectory of the directrix in the image, then used to determine the vanishing point of the trajectories. This vanishing point was related to the heading of the vehicle and the offset of the vehicle relative to the directrix. An alternative algorithm used the Hough Transform to detect line features representing crop rows.

The image from the camera provided a field-of-view ahead of the vehicle. The image coordinates (x_i, y_i) represent a 2-D projection of a 3-D field pathway, the image coordinates could be represented by the homogeneous actual pathway coordinates (x_p, y_p, z_p) (Fig 2):

$$\begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix} \qquad (1)$$

In vehicle guidance planning, we were interested in a 2-D directrix related to the vehicle. A static calibration was to map the image coordinates (x_i, y_i) into the vehicle coordinates (x_v, y_v) for converting the directrix referred to the camera to the directrix referred to the camera vehicle in support of automated guidance.

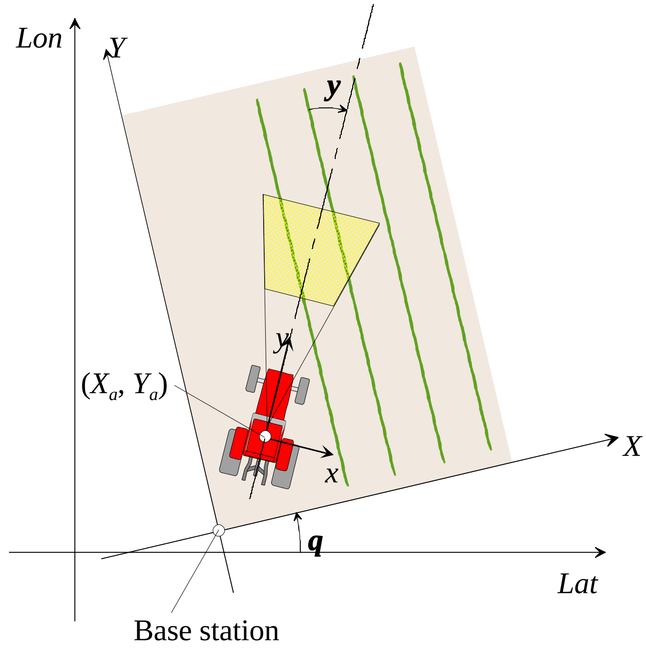

Figure 2. Coordinates of the agricultural vehicle guidance system.

$$\begin{bmatrix} x_v^i \\ y_v^i \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} \quad (2)$$

In agricultural automation, no individual sensing technology is ideal 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 an individual sensor. In this research, a fiber optic gyroscope (FOG) and a real time kinematics DGPS were added to the guidance system in order to improve the reliability of the system for vehicle guidance (Benson *et al.* 1998, Will *et al.*, 1998).

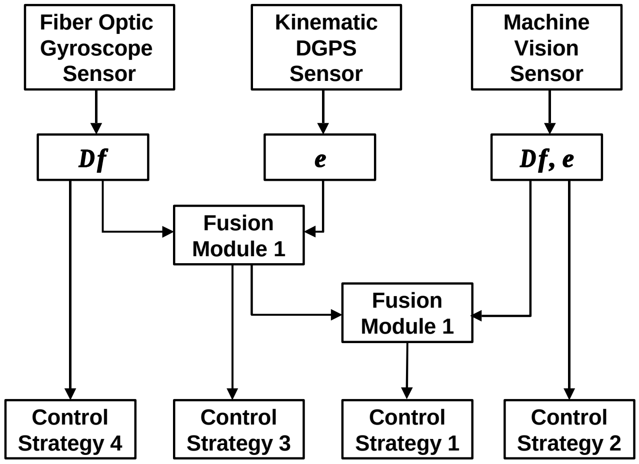

Figure 3. Block diagram of agricultural vehicle multiple guidance sensor fusion module.

The FOG sensor used in this system was a Japan Aviation Electronics Industry, ltd. (Tokyo, Japan) JG-108FD, single axis FOG*. It provided instantaneous heading information for vehicle guidance. The GPS sensor used in this system was a Trimble (Sunnyvale, CA) 7400MSi Kinematic GPS*, which operated off of a base station installed at our research facility. It provides the offset information of the vehicle related to its desired path. Current accuracy of this unit provides a position with a 3 cm circle of precision at a rate of 5 Hz. A time history of GPS position was used to calculate vehicle heading and velocity. The calculated heading and velocity were used to estimate the vehicle position between GPS updates. The accuracy of the predicted position depended on the accuracy of the heading and velocity.

Each sensor has factors that affect its performance. DGPS has already begun to make its mark on precision agriculture: satellite orientation, interference from trees and obstructions and other factors affect the accuracy of DGPS. Because a FOG outputs the angular velocity, drifting error is always involved in its output. The machine vision had high accuracy to detect guidance information such as lateral error and heading error by recognizing crop rows. However, weed infestation, soil color and changing light levels affected the reliability of the vision system. Sensor fusion helps to decrease the impact of the sensor errors. Figure 3 shows the schematic block diagram of the sensor fusion module integrated by a vision sensor, a GPS sensor, and a FOG sensor. This module would select one of four algorithms for steering control according to the available sources of vehicle guidance.

To integrate these sensors into a sensor fusion module requires unifying coordinate systems of all the sensors. The GPS provides vehicle position information referred to the global coordinates. To make it compatible to the directrix information obtained from the vision sensor, it is necessary to convert to the vehicle coordinates as well. However, since the GPS antenna was installed on the top of the cab, and roll and pitch angles of the vehicle would affect the accuracy of the position measurement, it is necessary to correct the error caused by vehicle inclination before mapping it to the vehicle coordinates.

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} a \\ b \\ h \end{bmatrix} \quad (3)$$

When the variation in the field elevation was limited, we could treat it as a plane, and the 2-D GPS coordinate could be converted into the vehicle coordinate.

$$\begin{bmatrix} x_v^g \\ y_v^g \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \begin{bmatrix} x_c \\ y_c \end{bmatrix} \quad (4)$$

The sensor fusion module is a control strategy decision maker. It evaluates the availability of vehicle directrix information from different sensors, and selects an appropriate control strategy corresponding to the available directrix information. This decision maker selects the principal guidance sensor based on the information availability for each sensor using a rule-base method and predicted error based on statistical analysis. The sensor fusion module provides the most appropriate heading and offset information in real time. An E/H steering control system was developed to implement the automated steering.

STEERING CONTROL

A steering controller is an actuator that adjusts vehicle steering angle based on input steering signals. Steering controllers for agricultural vehicles differ from those of automobiles due to differences in operating conditions. Agricultural vehicles often operate on the unprepared, changing and unpredictable terrain. These conditions require steering controllers capable of providing appropriate steering actions in response to the variations in vehicle-terrain interactions, travelling speed, tire cornering stiffness, and other factors.

The E/H steering system on our research platform consists of an electronic control unit with a PWM driver, an E/H directional control steering valve, a steering actuation cylinder, a mechanical steering linkage on the front-wheels. The position response of the steering system can be modeled by a linearized forth order system (Eq. 5), assuming a critical-lapped steering valve, no leakage, and incompressible fluid. The equation for this model is,

$$\frac{Y(s)}{X(s)} = \frac{K}{s(Ts+1)(s^2 + 2Vw_n s + w_n^2)} \qquad (5)$$

where ***K***, ***T*** and ***n*** are system constants.

However, an E/H steering system is typically nonlinear, with behaviors of load-related deadband, asymmetric gain, hysteresis, and saturation. These characteristics complicate the control of an E/H steering system. The load and speed dependent deadband and saturation have significant effects on the controller performance. Even when these effects were considered, a PID controller did not have satisfactory steering control due to a large time-delay (Wu *et al* 1998).

To solve the above problems, a feedforward-plus-PID (FPID) controller has been developed for this E/H steering system. Figure 4 shows the block diagram of the controller. It includes a PID loop and an inverse valve transform based feedforward loop. The input steering command was the desired vehicle Ackerman angle, and the system output was the actual angle.

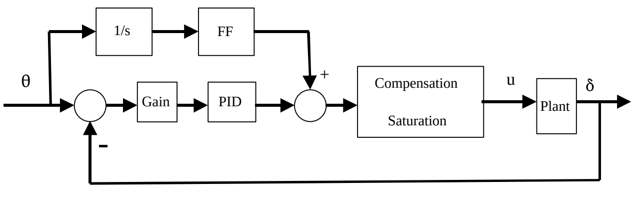

Figure 4. Block diagram of feedforward-plus-PID electrohydraulic steering controller.

To compensate the deadband, the feedforward loop of this FPID controller consisted of a differential operator and an inverse valve transform. The primary steering control signal was determined based on the desired steering rate $\dot{\boldsymbol{d}}$, which was differentiated from input steering angle command.

$$u = f^{-1}(\dot{\boldsymbol{d}}) \qquad (6)$$

To compensate the error between the desired and the actual Ackerman angles, the feedback loop of this FPID controller consisted of a coordinated gain schedule function, a PID controller, and a steering actuator displacement sensor. The feedback signal was original the linear displacement of the steering actuator, and converted into Ackerman angle based on the gain of the steering linkage. In the PID loop, the feedback gain was the summation of $\boldsymbol{K_p}$, $\boldsymbol{K_i}$, and $\boldsymbol{K_d}$ in terms of the proportional, integral, and derivative terms of measured error of Ackerman angle $\boldsymbol{q}$.

$$K(s) = k_p + \frac{k_i}{s} + k_d s \qquad (7)$$

Under a constant steering signal, the steering rate was zero, and the feedforward loop would be inactive. To ensure the effectiveness of FPID controller, a relatively large gain was required for its PID loop. Since the PID gains were tuned while the feedforward loop was disabled, a gain factor of 1 was assigned to the PID gains. When the system received non-constant steering signal, both the feedforward and the PID loops would be active. To ensure stable and accurate steering control, reduced gains on the PID loop was desired. The coordinated gain function, $\boldsymbol{K_{nf}}$, was introduced for an automated adjustment of the PID gains based on the equation below.

$$\boldsymbol{K_{nf}} = \begin{cases} \boldsymbol{1} & \boldsymbol{Err \le E_0} \\ \boldsymbol{K} & \boldsymbol{else} \end{cases} \qquad (8)$$

The control input was converted into a voltage signal through a PWM to drive the solenoid E/H valve. A linear potentiometer was installed on the actuating cylinder to provide steering feedback. An inverse function of steering linkage gain was developed to convert the actuator displacement into a vehicle Ackerman angle based on the steering linkage kinematics model.

RESEARCH PLATFORM AND FIELD TESTS

A Case-IH Magnum[1] 7220 two-wheel drive agricultural tractor has been modified as the research platform (Noguchi, 1998) for automatic guidance with multiple

Figure 5. Research platform of automated guidance tractor with multiple guidance sensors.

sensors (Fig. 5). This tractor has mass 8120 kg and estimated yaw moment of inertia 23,000 kg-m according to data provided by Case Corporation. This research platform has equipped a Dolch (Freemont, CA) PAC* 150 MHz portable computer as the sensor fusion unit and a Gateway (Sioux City, SD) Solo 2500* 300 MHz Laptop computer as the steering control unit. Additional Imagination CX-100 card was added to the sensor fusion unit for vision processing, and National Instruments I/O card to the steering control unit for sensor and steering control interfaces.

This platform has also equipped with redundant guidance sensors, including machine vision, GPS, and FOG, steering angle sensors, to provide vehicle posture and steering angle information. Software for data processing, image processing, and control was developed using Microsoft Visual C++ and installed on the platform.

Test results show that the FPID controller was capable of providing satisfactory automatic steering function for automated guidance of the agricultural vehicle. Figures 6 and 7 show the steering control performance of the FPID to track a step and sinusoidal steering commands. The step steering test resulted in a small overshoot less than 12% and a reasonable short rising time of 0.25 second. The sinusoid steering test, with steering angle command ±5 degree at 0.1Hz frequency, resulted in a 0.4 degree maximum tracking error. Tests with different frequency showed that the error could be increased if the frequency was higher. When the steering input frequency was higher than 4 Hz, the E/H steering system could not respond to the steering command. These results provided adequate performance for automatic agricultural vehicle steering control.

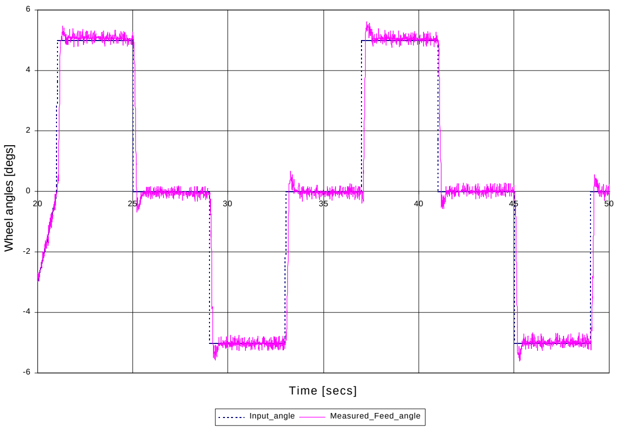

Figure 6. Steering angle tracking performance of the FPID under step steering commands.

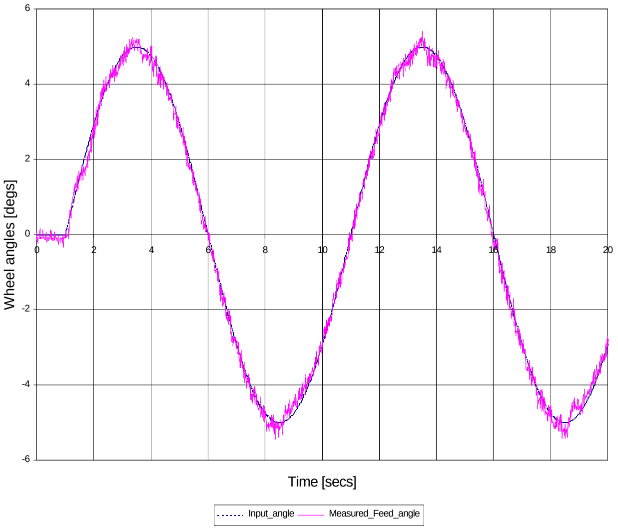

Figure 7. Steering angle tracking performance of the FPID under sinusoid steering commands.

Field navigation tests were conducted using the developed research platform with sensor fusion, vision only, and GPS-FOG only based navigation control strategies. Travel speed was set at 3.6m/s. Results indicated that the maximum offsets of the automatically navigated vehicle to a desired path were less than 0.15 m with sensor fusion, less than 0.20 m with GPS-FOG, and less than 0.15 m with vision-only based steering control strategies. Furthermore, the offset from sensor fusion module was always in between of the offsets from

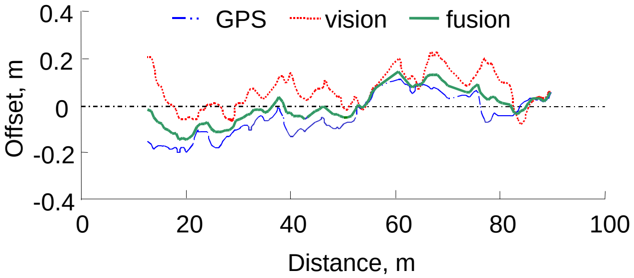

Figure 8. Comparison of navigation accuracy in vehicle offset from the desired path using sensor fusion, vision only, and GPS-FOG only based navigation controls.

the individual sensor-based controls. This indicates the capability of the sensor fusion in compensating large errors that might be caused by individual sensor. The tests also indicated that the sensor fusion-based navigation could provide satisfactory agricultural vehicle guidance even while losing individual navigation signals such as image of the path, or the GPS signal for short periods of time.

CONCLUSIONS

A research platform of automatically guided agricultural vehicle has been developed on a Case-IH Magnum[1] 7220 2-wheel drive agricultural tractor. This platform used an E/H steering system and a feedforward plus PID steering controller in support of automated guidance actuation. Redundant posture sensor, including GPS, geomagnetic direction sensors (FOG), and machine vision sensing systems were used on this platform for providing automated guidance information. Test results showed that this multi-sensor guidance system was capable of performing satisfactory agricultural tractor automated guidance in following desired paths. The sensor fusion navigation was capable of compensating large error from individual sensors, and resulting in satisfactory agricultural vehicle guidance.

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