

**AN EVALUATION OF A GEOMAGNETIC DIRECTION SENSOR
FOR VEHICLE GUIDANCE IN PRECISION AGRICULTURE
APPLICATIONS**

By

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Summary:

Agricultural vehicle automation has increased in recent years. In this project, a fluxgate magnetometer (geomagnetic direction sensor or GDS) was calibrated on an agricultural tractor to provide heading information. The accuracy of the GDS (1.13 degrees) was within the consistency of the GPS reference (1.32 degrees).

A PID steering controller and three guidance controllers (GPS, GPS with a position estimator and GPS with GDS assistance) were developed. The steering controller and guidance controllers were implemented and evaluated on a 115-kW 2WD agricultural tractor. GPS / GDS assisted guidance was the most accurate and consistent of the three methods investigated. With GPS / GDS assisted guidance, both the average error and deviation were within the precision of the GPS position reference.

Keywords:

Vehicle Guidance, GPS, Automation, Geomagnetic Direction Sensor, GDS

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INTRODUCTION

People have always been looking for an easier way to do things. Agriculture was developed to reduce the amount of travelling that the life of a nomadic hunter-gatherer required. Man quickly found that it was easier to find someone or something else to perform the required labor. Domestic animals and the spoils of war were tried; modern agriculture uses mechanization to help farmers work more land. Automated equipment allows each farmer to work more land with less input.

Automation is not new to agricultural mechanization. Mechanical furrow followers and magnetic cable guidance systems have been developed to guide agricultural vehicles (Richey, 1959, Rushing, 1971, Widden and Blair, 1972). Laser, radio and optical field-based positioning systems have been developed and applied to vehicle guidance with varying degrees of success (Gordon and Holmes, 1988, Noguchi *et al.*, 1997). Field-based systems require equipment to be permanently or temporarily located in a known location in or near the field. Satellite-based systems (e.g. Global Positioning System or GPS) can provide the location, in degrees of longitude and latitude, of a receiver anywhere in the world (Langley, 1997). Satellite-based systems use a ground receiver and a constellation of satellites to triangulate the position of a receiver. Machine vision has been used to determine the posture of a vehicle relative to an object, e.g. a row of corn (Reid and Searcy, 1991). Each of the approaches had both strengths and limitations.

Field-based systems, for example, are accurate, but range limited. Satellite based systems can not provide information about the local environment. Machine vision can provide relative, local information, but not global information.

Combining sensors can help to reduce the problems inherent to one sensor or type of sensor. Differential GPS (DGPS), for example, can provide highly accurate (1 – 5 m) position information. Calculating the vehicle velocity or heading from a time series of GPS positions involves differentiation, which amplifies any noise in the system. Other sensors, such as radar or heading sensors can supply additional accurate information.

One simple way to provide heading information is with a magnetic compass. Grovum and Zoerb (1970) used a directional gyroscope to provide heading information, noting that magnetic compasses tended to have poor damping qualities. Gyroscopes tend to drift with time (0.3 – 1.5 degrees per minute) and need to be periodically re-aligned. Noguchi *et al.* (1997) used a geomagnetic direction sensor (GDS) to provide heading for a tillage robot.

A magnetometer senses the magnetic field around the sensor. Magnetometers have a variety of uses; a compass is a primitive but simple magnetometer. The slightly more complicated fluxgate magnetometer uses two oppositely wound coils to detect the magnetic field. Originally developed during the 1930's, the

fluxgate magnetometer became important during World War II as a means of detecting submerged submarines (Vacquier et al., 1947).

For each direction measured, two solenoids are wound in opposite directions around a high permeability core and connected in series to an alternating current. As the magnetic flux in the core changes, a voltage is induced. When two coils are combined and driven in opposing directions in the absence of an external magnetic field, the induced voltage is cancelled out. In the presence of an external magnetic field parallel to the detector, the flux through the two coils will not be balanced. An asymmetry will be evident in the output (Noble, 1991). The asymmetry can be detected and related to the signal field (Gordon and Brown, 1972).

For vehicle automation, the geomagnetic sensor's value is in supplying instantaneous heading information. Although the price of GPS equipment continues to decrease, GPS receivers are expensive and have limited update rates. In contrast, a GDS is relatively inexpensive. A GDS, combined with velocity information, can supply dead reckoned position information between GPS updates, allowing the user to operate with a slower and less expensive receiver.

GDS can increase the effectiveness of the other sensors on the vehicle. Machine vision can provide the heading relative to field characteristics, but not a global orientation. GPS can provide the position and a time series based vehicle heading, but not the instantaneous orientation of the vehicle. GDS can supply the missing link.

EQUIPMENT AND PROCEDURES

A 115-kW Case-IH (Racine, WI) 7220 Magnum 2WD¹ tractor was modified to serve as the research platform for several ongoing autonomous guidance projects. Further information on the equipment and methodology is available in Will et al., (1998).

A pulse width modulated electrohydraulic valve was installed in parallel with the existing steering handpump. A High Country Tek (Nevada City, CA) dual-coil PWM valve driver card was used to control the valve.

A linear potentiometer was attached to the side of the steering cylinder to provide wheel angle feedback. A slider-in-slot mount was used to constrain the actuator rod of the linear potentiometer relative to the tractor frame.

¹ Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the University of Illinois, The Ohio State University, or Hokkaido University and does not imply the approval of the named product to the exclusion of other products that may be suitable.

A 150 MHz Pentium-based Dolch (Freemont, CA) portable computer was used to integrate the information from different sensors and to execute the control routines. A National Instruments (Austin, TX) AT-MIO-16XE-1 data acquisition board, serial card and an Imagination CX-100 vision board were installed in the computer. The portable computer processed information from the GDS, GPS and steering sensor and controlled the PWM driver card.

A NovAtel (Calgary, Alberta, Canada) RT-20 kinematic GPS receiver was installed in the tractor to provide position information. Two 9600 baud Pacific Crest (Santa Clara, CA) radio modems were used to connect the surveyed base station with the tractor receiver. With the local differential correction network in place, the mobile NovAtel receiver had an accuracy of 20-cm at a 5-Hz update rate.

A three-axis Watson (Eau Claire, WI) FGM-301 magnetometer was used as the geomagnetic direction sensor for the project. The Watson fluxgate magnetometer is a 4-kHz analog sensor. The output from the magnetometer is a DC voltage proportional to the field intensity. A National Instruments I/O board was used to convert the voltage signal from the GDS into a digital signal. Each axis of the magnetometer was read 25 times (include how fast the readings were taken) and averaged for each calculation. The Watson GDS was powered directly from the tractor electrical system.

Several different mounting configurations and locations for the GDS were investigated during the course of the project. Vibration, physical and magnetic interference with other equipment restricted the mounting of the sensor. An aluminum support frame was constructed to hold the sensor above and behind the cab of the tractor (Figure 1).

GDS CALIBRATION

The GDS was calibrated on the vehicle in three stages. A center-offset method (Noguchi et al., 1997) was used to remove localized magnetic distortions. An eight-direction calibration method based on the method of Peters (1986) was used to improve sensor performance. A second-order curve fit further improved the output of the sensor.

The center-offset method involves manually driving the geomagnetic direction sensor-equipped vehicle in a constant radius circle and sampling the output from the sensor. Five thousand data points were collected per test; least-squares analysis was used to calculate the center offset of the circle. The calibration was repeated five times per direction per velocity for seven velocities (0.45 m/s, 0.89 m/s, 1.34 m/s, 1.9 m/s, 2.24 m/s, 2.68 m/s and 3.13 m/s). The entire calibration procedure was repeated twice. The calibration results are specific to the individual vehicle installation.

The sensor repeatability appeared to be related to the velocity. At 1.12 m/s, the deviation was $\sigma_x = 0.235$ V, $\sigma_y = 0.308$ V. At a higher velocity (3.36 m/s), the deviation decreased to $\sigma_x = 0.052$ V, $\sigma_y = 0.054$ V. The apparent increase in sensor precision was due to the testing procedure used. The sampling program logged data from the magnetometer as quickly as possible; 5000 data points were taken per test. The number of data points was experimentally determined to allow the vehicle to make one complete revolution of the circle at the slowest test velocity. The number of samples was kept fixed; at higher vehicle velocities, the tractor made multiple revolutions on the circle. At low speed, incomplete or partial circles would tend to weight the least squares center location; as the velocity increased, the impact of an incomplete circle decreased.

The calculated center offset values were divided into two ranges, a low speed range (< 1.34 m/s) and high-speed range (> 1.79 m/s). The grouping was selected by observation; the behavior appeared to change between the two regions. There was no statistically significant difference at the 5% level between the calculated low speed and high-speed center offset. Since there was no statistical difference between the two speed ranges, the final center offset was calculated by averaging all 35 tests from calibration 2 ($X_c = -0.606$ V, $Y_c = -0.409$ V).

The center-offset calibration was repeated twice as shown in Figure 2. An unequal variance z test failed to reject at the 5% level ($z_{xc} = -1.941$, $z_{yc} = 0.564$). This implies that the results from the two tests were constant over the roughly two-month study period.

The eight-direction calibration was based on the method of Peters (1986). Peters suggested that a fluxgate magnetometer could be calibrated by aligning the vehicle along a known axis and calculating the required correction for each axis. The vehicle was driven along a known direction (e.g. N) and the output from the GDS and a time series GPS vehicle heading was recorded. Five hundred data points were collected per test with five replications per direction. The correction factor was calculated as the average difference between the GDS and GPS headings. Range markers or lines painted on the ground were used as visual references for the eight directions tested. The eight-direction test was repeated twice during a two-week period on two non-consecutive days.

The results of the two tests are shown in Figure 3. During the first replication, a software offset to the indicated output was added to account for misalignment of the sensor with the vehicle centerline. The offset was removed for the second test. The error between the GPS and GDS was found to depend strongly on the direction of travel. The error pattern was virtually identical for both replications. The average error was 2.3 degrees with a 4.0 degree standard deviation. The GDS was more stable and had a lower standard deviation (0.61 degrees) than the GPS (1.32 degrees).

A second order curve fit was used to reduce the indicated error in the GDS output. The developed curve had a high correlation ($R = 0.999$).

$$\phi_{GDS} = -0.0001\phi_{GDS}^2 + 1.0148\phi_{GDS} \quad (1)$$

The sensor performance was validated at two other sites within radio range of the GPS base station. The same procedure as before was used; due to space restrictions, only four directions (N, S, E and W) were evaluated. With the two step calibration method and the second order curve fit, the average error decreased to -1.13 degrees with a deviation of 3.66 degrees.

Electrical sources are a potential source of localized disturbances in the electromagnetic field around an object. Two major potential sources of magnetic interference were the tractor heater / air-conditioner fan and a nearby set of high-tension electrical wires. The vehicle was tested with and without the influence of these interference sources. GPS position, GPS indicated heading angle and the GDS heading angle were recorded. The test was repeated three times per direction or condition. SAS statistical software was used to analyze the results from the interference tests.

The tractor air conditioner had a significant effect on the average indicated heading; electrical wires effected the repeatability of the sensor (deviation).

VEHICLE GUIDANCE

A frequency response model of the steering system was experimentally developed for the vehicle. A PID steering controller was developed and implemented in Microsoft Visual C. The steering controller was experimentally tuned using the values from the Ziegler–Nichols turning rules and adjusted until the maximum overshoot for a 20 - degree step input was approximately 30%.

After tuning the steering controller, a simple guidance controller was developed. The guidance controller used the information from the GPS, GDS and wheel angle sensor to calculate the steering angle required to direct the vehicle to the desired position. A heading angle only guidance controller would cause the vehicle to follow any number of parallel paths; this approach would not guarantee a specific path. The guidance controllers used the position error and a look-ahead factor to calculate the desired steering angle. The look ahead was experimentally determined; a look ahead of 2.5 m was used for this project. The desired steering angle was sent to the PID steering controller to actuate the electrohydraulic steering valve.

Three versions of the guidance controller were developed: GPS only, GPS with a position estimator and GPS / GDS assisted control. The position estimator estimated the position of the vehicle between GPS updates based on the

heading and velocity. The GPS with position estimator used the vehicle track over ground to calculate the heading and velocity; the GPS / GDS assisted guidance controller used the GPS velocity and GDS heading to calculate the interim positions. In addition, both the GPS with position estimator and GPS / GDS assisted guidance controllers used the vehicle heading to virtually relocate the GPS indicated position from the center of gravity antenna location to the front weight bracket of the tractor to add phase lead to the system.

The guidance controllers were used to guide the vehicle along a straight path at 1.12 m/s. The performance of the GPS with position estimator and GPS / GDS assisted guidance controllers had significantly better performance than the performance of the GPS only guidance controller. Other researchers (Stombaugh, 1998 and Noguchi et al.1998) noticed problems with a steady state offset of 12 cm to 20 cm. During testing, the average lateral distance from the desired course for pure GPS guidance ranged from -27 cm and +10 cm. The lateral deviation of the vehicle was significant; the standard deviations of the position error for the tests ranged from 0.5 m to 2 m. Adding a position estimator to the guidance controller did not change the average lateral error (which ranged from -7.0 cm to -44 cm), but did substantially reduce the lateral deviation (19 cm to 58 cm). With GPS / GDS assisted guidance, the steady state position error was largely eliminated, as shown in Figure 4. For the test shown in Figure 4, the average error was less than one centimeter with a 7.9 cm deviation. Replacing the GPS heading with the vehicle fixed GDS improved the accuracy and improved tracking. The indicated position tracking accuracy was within the 20-cm accuracy of the kinematic differential GPS (KDGPS) reference.

The GPS with position estimator and GPS / GDS assisted guidance controller were tested with a step-reverse step combination. A step-reverse step tested both the response of the vehicle to a sudden course change as well as the ability of the vehicle to return to a desired position. The vehicle velocity was 1.12 m/s for the step-reverse step tests. Each test was repeated three times.

The GPS position estimator controller was able to respond to the course changes; however, the vehicle overshoot the desired lateral position by over 50%. The vehicle went through several oscillations before returning to the desired course. The position estimator updated the position based on the last known heading and velocity information. The guidance controller sends commands to the steering controller based on "old" heading information. In actuality, the vehicle has begun to respond to the steering commands; the vehicle posture changes between position updates.

GPS / GDS assisted control improved the ability of the vehicle to respond to a sudden change in the desired path. The vehicle followed an initial path, performed the desired step with little overshoot and returned to the original path (Figure 5). With a GPS position estimator, the maximum overshoot was close to

50%; adding the GDS to the system reduced the overshoot to approximately 12%.

CONCLUSIONS

The use of a fluxgate magnetometer for agricultural vehicle guidance was investigated. A 115-kW Case 7220 2WD tractor was outfitted with an electrohydraulic steering, a KDGPS, a GDS and the associated control software.

An on-vehicle calibration scheme for a fluxgate magnetometer on an agricultural vehicle was developed. The calibration procedure consisted of three parts: a circular calibration to remove the effects of vehicle induced magnetic field distortion, a heading comparison method to correct for misalignment and other errors and a second order curve fit to improve sensor precision.

The three-axis fluxgate magnetometer was calibrated within the limit of the reference sensor. With a second order compensation, the average difference between the GDS and GPS reference was -1.1 degrees with a 3.66-degree standard deviation.

A GPS / GDS assisted guidance controller was the most accurate of the three vehicle control scheme tested. The GPS / GDS assisted guidance controller was able to track a straight line within the accuracy of the GPS position reference. The average error (< 1 cm) was less than the accuracy of the GPS (20-cm). The maximum overshoot for a 3 m step response with the GPS / GDS assisted guidance controller was 12%. A GPS with position estimator had over 50% overshoot for a similar step.

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 9659 USA.



Figure 1. The Watson FGM-301 three-axis fluxgate magnetometer was installed on an aluminum frame mounted above and behind the tractor cab.

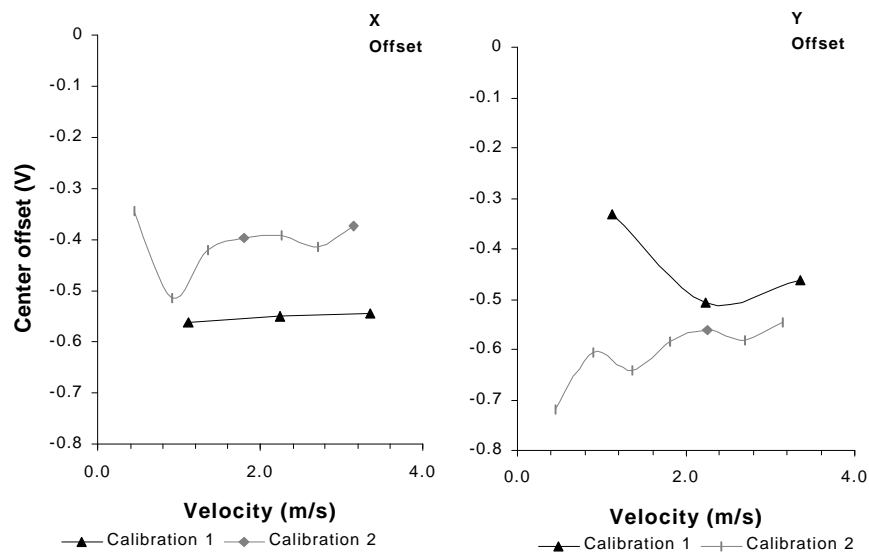


Figure 2. The center offset calibration procedure was repeated twice over a velocity range from 0.45 m/s to 3.13 m/s. Each point represents five repetitions per direction (CW and CCW) per velocity.

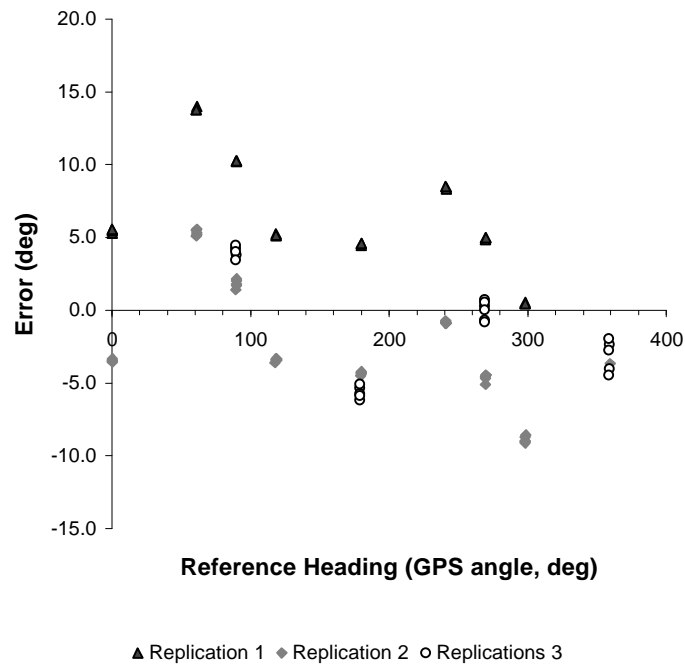


Figure 3. The GDS equipped tractor was driven at two alternate locations with the second order compensation in place. With the compensation in place, the accuracy of the sensor improved. Five samples were taken per replication per direction.

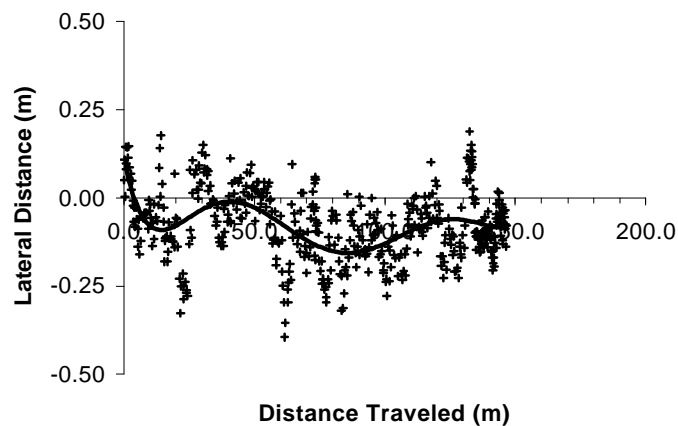


Figure 4. A plot of the vehicle path during straight-line guidance with the GPS / GDS assisted guidance controller. The darker line is a best-fit line of the indicated vehicle positions. Note: a 20-cm accuracy KDGPS served as the position reference. $V = 1.12$ m/s.

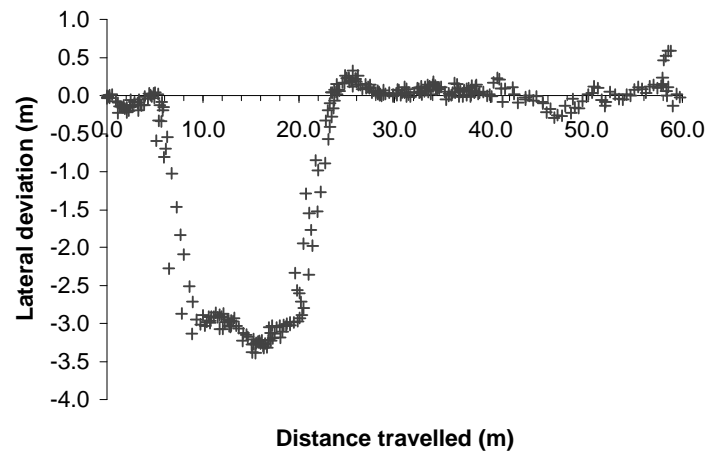


Figure 5. A plot of the vehicle position with the GPS / GDS assisted guidance controller during a 3 m step – reverse step. Note: a 20 cm accuracy KDGPS served as the position reference. $V = 1.12$ m/s.