Automatic Steering of Farm Vehicles Using GPS

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ABSTRACT

Operating agricultural equipment accurately can be difficult, tedious, or even hazardous. Automatic control offers many potential advantages over human control; however, previous efforts to automate agricultural vehicles have been unsuccessful due to sensor limitations. With the recent development of Carrier Phase Differential GPS (CDGPS) technology, a single inexpensive GPS receiver can measure a vehicle's position to within a few centimeters and heading to within 0.1°. The ability to provide accurate real-time information about multiple vehicle states makes CDGPS ideal for automatic control of vehicles.

In this work, a CDGPS-based steering control system was designed, simulated, and tested on a large farm tractor. A highly simplified vehicle model proved sufficient for accurate controller design. After various calibration tests, closed-loop heading control was demonstrated to a one-σ accuracy of better than 1°, and closed-loop line tracking to a standard deviation of better than 2.5 cm. Future plans for research include the use of a pseudo-satellite to eliminate any position bias and extending the current control system to control a towed implement.

INTRODUCTION

Autonomous guidance of agricultural vehicles is not a new idea, however, previous attempts to control agricultural vehicles have been largely unsuccessful due to sensor limitations. Some control systems require cumbersome auxiliary guidance mechanisms in or around the field [1,2] while others rely on a camera system requiring clear daytime weather and field markers that can be deciphered by visual pattern recognition [3,4]. With the advent of affordable GPS receivers, engineers now have a low-cost sensor suitable for vehicle navigation and control. GPS-based systems are already being used in a number of land vehicle applications including agriculture. Meter-level code-differential techniques have been used for geographic information systems [5-7], driver-assisted control [8], and automatic ground vehicle control [9].

Using precise differential carrier phase measurements of satellite signals, CDGPS-based systems have demonstrated centimeter-level accuracy in vehicle position determination [10] and 0.1° accuracy in attitude determination [11]. System integrity becomes impeccable with the addition of pseudo-satellite Integrity Beacons [12]. The ability to accurately and reliably measure multiple states makes CDGPS ideal for system identification, state estimation, and automatic control. CDGPS-based control systems have been utilized in a number of applications, including a model airplane [13], a Boeing 737 aircraft [10], and an electric golf cart [14].

This paper focuses on the automatic control of a farm tractor using CDGPS as the *only* sensor of vehicle position and attitude. An automatic control system was developed, simulated in software using a simple kinematic vehicle model, and tested on a large farm tractor.

Figure 1 - Experimental Farm Tractor

EXPERIMENTAL SETUP

The primary goal of this work was to experimentally demonstrate precision closed-loop control of a farm tractor using CDGPS as the only sensor of vehicle position and attitude. This section describes the hardware used to do this.

Vehicle Hardware

The test platform used for vehicle control testing was a John Deere Model 7800 tractor (Fig. 1). Four single-frequency GPS antennas were mounted on the top of the cab, and an equipment rack was installed inside the cab. Front-wheel angle was sensed and actuated using a modified Orthman electro-hydraulic steering unit. A Motorola MC68HC11 microprocessor board was the communications interface between the computer and the steering unit (Fig. 2). The microprocessor converted computer serial commands into a pulse width-modulated signal which was then sent through power circuitry to the steering motor; the microprocessor also sampled the output of a feedback potentiometer, the *only* non-GPS sensor on the vehicle, attached to the right front wheel. The 8-bit wheel angle potentiometer measurements were sent to the computer at 20 Hz. through the serial link.

GPS Hardware

The CDGPS-based system used for vehicle position and attitude determination was identical to the one used by the Integrity Beacon Landing System (IBLS) [10] (Fig. 2). A four-antenna, six-channel Trimble Vector receiver produced attitude measurements at 10 Hz. A single-antenna nine-channel

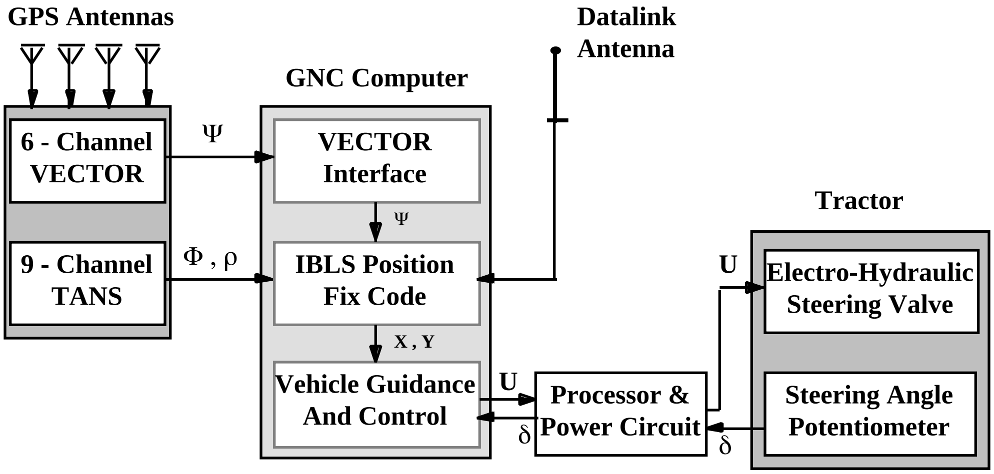


Figure 2 - Vehicle Hardware Architecture

Trimble TANS receiver produced carrier- and code-phase measurements at 4 Hz. which were then used to determine vehicle position. An Industrial Computer Source Pentium-based PC running the LYNX-OS operating system performed data collection, position determination, and control signal computations using software written at Stanford.

The ground reference station (Fig. 2) consisted of a Dolch computer, a single-antenna nine-channel Trimble TANS receiver generating carrier phase measurements, and a Trimble 4000ST receiver generating RTCM code differential corrections. These data were transmitted at 4800 bits/sec through Pacific Crest radio modems from the ground reference station, which was approximately 800 m from the test site, to the tractor.

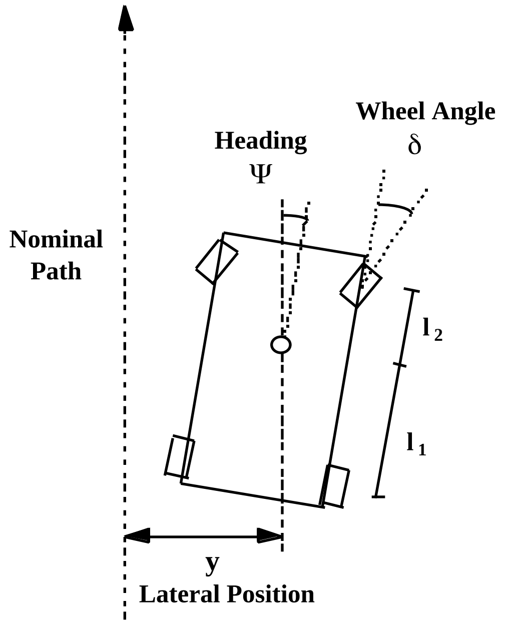
VEHICLE MODELING

Performing a valid tractor simulation required a good model of dynamics and disturbances. Ground vehicle models in the literature range from simple to complex, and no single model is widely accepted [15]. The most sophisticated models are not always appropriate to use [16], especially since controller and estimator design require a simple, typically linearized, model of plant dynamics.

Kinematic Model

The simplest useful model for a land vehicle is a kinematic model, which is based on geometry rather than inertia properties and forces. Assuming no lateral wheel slip, constant forward velocity, actuation through a single front wheel, and a small front wheel angle, the latter two equations of motion shown in Figure 3 can easily be derived. The first equation of Figure 3 can be applied if we also assume small heading deviations from a desired path. Although some of these assumptions are violated for a tractor making large turns on loose soil, the control system based on this model was able to compensate for the small modeling errors.

The kinematic equations were derived in state-space form for ease of controller and estimator design. The state vector is composed of the lateral position deviation from a nominal path (y), heading error (Ψ), and effective front wheel angle (δ).



Linearized Equations of Motion:

$$\dot{y} = V_{X0}\,\Psi + \frac{V_{X0}\, l_1}{(l_1 + l_2)}\,\delta$$

$$\dot{\Psi} = \qquad + \frac{V_{X0}}{(l_1 + l_2)}\,\delta$$

$$\dot{\delta} = u$$

Figure 3 - Vehicle Kinematic Model

Steering Calibration

Initially, calibration tests were used to create two software-based “look-up” tables, one which linearized the output of the steering potentiometer versus the effective front wheel angle and the other which linearized the computer-commanded wheel-angle rate to the actual wheel-angle rate (Fig. 4).

To calibrate the potentiometer readings of effective front wheel angle, steady turn tests were performed to find the heading rate (dΨ/dt) of the tractor at various potentiometer readings. For each test, the tractor was driven in a circular path with a constant front wheel angle and constant forward velocity while GPS heading data was taken and stored. By compiling all these tests, a function was generated that related steady-state heading rate to potentiometer reading. The

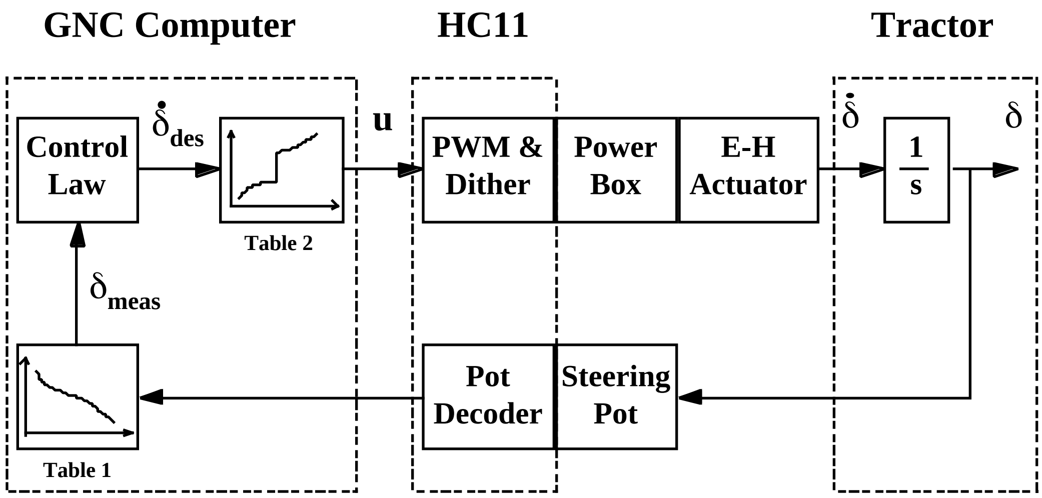


Figure 4 - Steering Inner Loop with “Look-Up” Tables

kinematic model described above suggests that the effective wheel angle is directly proportional to the steady-state heading rate, so the data collected during the tests was also used to generate the “Table 1” shown in Figure 4.

Calibration of the commanded wheel angle rate was simpler. Constant steering slews were commanded by the computer at varying levels of actuator authority (u) while wheel angle data was taken and stored. The time rate of change of the effective wheel angle was later estimated for each steering slew and stored in “Table 2” (Fig. 4).

CLOSED-LOOP HEADING RESULTS

The first controller designed, simulated, and tested on the tractor performed closed-loop heading. The computer code was written so a user could command a desired heading using a keyboard input. The computer would then send the appropriate commands to the electro-hydraulic actuator to track the desired heading. The first tests were closed-loop heading tests designed to verify the kinematic vehicle model. These initial tests also yielded a better feel for tractor disturbances.

Heading Controller Design

A hybrid controller was designed to provide a fast response to large desired-heading step commands. A non-linear “bang-bang” control law generated actuator commands when there were large errors or changes in the vehicle heading or effective wheel angle states. Typically, these large changes occurred in

Figure 5 - Closed-Loop Heading, Regulator Performance

Figure 6 - Closed Loop Heading, Step Response

response to a large heading step command. When the vehicle states were close to zero, a controller based on standard Linear Quadratic Regulator (LQR) design [17] was used.

“Bang-bang” control is a standard non-linear control design tool based on phase-plane technique [18]. Unlike linear feedback controllers, bang-bang controllers use the maximum actuator authority to zero out vehicle state errors in minimum time just as a human driver would. For example, in response to a commanded heading step increase of 90˚, a bang-bang controller commands the steering wheel to hard right, holds this position, and then straightens the wheels in time to match the desired heading. In contrast, a linear controller would respond to the step command by turning the wheels to hard right, then slowly bringing them back to straight, asymptotically approaching the desired heading.

The drawback to bang-bang control is that when state errors are close to zero, the controller tends to “chatter” between hard left and hard right steering commands. For this reason, a linear controller was used for small deviations about the nominal conditions.

Experimental Heading Results

During the heading tests, the tractor was driven over a bumpy field at a nearly constant velocity of 0.9 m/s. The driver commanded an initial desired heading and a number of desired heading step commands through the computer.

The tractor tracked the commanded headings very accurately, even in the presence of ground disturbances. Figure 5 shows a plot of CDGPS heading measurements during the longest closed-loop heading trial recorded. Over about one minute, the mean heading error was 0.03˚ and the standard deviation was

0.76°. From separate tests, the expected sensor noise was zero mean with approximately 0.1° standard deviation, so the true system heading error standard deviation was almost certainly less than 1°.

A plot of the time response for a 90° step in commanded heading is shown in Figure 6. The rise time of the controller for this particular command was approximately 7 seconds, and the settling time was less than 10 seconds. An small overshoot of about 4° occurred at the end of the heading step response.

CLOSED-LOOP LINE TRACKING RESULTS

After performing closed-loop heading, the next step toward farm vehicle automation was straight-line tracking. These series of tests were designed to simulate tracking a row. To track a straight line, vehicle position was fed back to the control system along with heading and effective wheel angle.

Line Tracking Controller Design

As in the closed-loop heading case, the line tracking controller was implemented as a hybrid controller with various modes. To get the vehicle close to the beginning of the “field” and locked on to each line or “row”, a coarse control mode was used based on the closed loop heading controller described above. Once a line was acquired, a precise linear controller based on LQR techniques took over.

Experimental Line Tracking Results

Two line-tracking tests were performed on the same field as the closed-loop

Figure 7 - Trajectory for Closed-Loop Line Following

Figure 8 - Line Following Experimental Results

heading experiments. The vehicle forward velocity was manually set to first gear (0.33 m/s), and the tractor was commanded to follow four parallel rows, each 50 meters long, separated by 3 meters (Fig. 7). Throughout these tests, the steering control for line acquisition, line tracking, and U-turns was performed entirely by the control system. CDGPS integer cycle ambiguities were initialized by driving the tractor as closely as possible to a surveyed location and manually setting the position estimate.

It is important to note that Figure 7 shows the CDGPS measurements taken during the two tests, not the "true" vehicle position. In fact, there was a small,

Table 1 - Summary of Line Following Control System Errors

Measured Lateral Position (cm)	Row #1	Row #2	Row #3	Row #4
Trial 1, mean	0.10	-0.85	-0.32	-0.66
Trial 2, mean	0.27	-0.58	-0.35	-0.68
Trial 1, 1-σ	1.98	2.01	1.33	2.45
Trial 2, 1-σ	1.86	2.13	1.39	1.93

steady position bias (about 10 cm) between the two trials due to the unsophisticated method that was used for GPS carrier phase integer cycle ambiguity resolution. A more sophisticated method involving pseudolites or dual frequency receivers would have eliminated this bias and is a topic of future research.

Line tracking measurements for both trials are shown in Figure 8 and summarized in Table 1. Since the plots show CDGPS measurements and not "truth", they represent the error associated with the control system and physical vehicle disturbances. The tractor controller was able to track each straight line with a standard deviation of better than 2.5 cm., the vehicle lateral position error never deviated by more than 10 cm, and the mean error was less than 1 cm for every trial.

CONCLUSION

This research is significant because it is the first step towards a safe, low-cost system for highly accurate control of a ground vehicle. The experimental results presented in this paper are promising for several reasons. First, a farm tractor control system was demonstrated using GPS as the only sensor for position and heading. Only one additional sensor—the steering potentiometer—was used by the controller. Second, a constant gain controller based on a very simple vehicle model successfully stabilized and guided the tractor along a straight, pre-determined path. Finally, it was found that a GPS controller could guide a tractor along straight rows very accurately. The lateral position standard deviation was less than 2.5 cm. in each of the 8 line tracking tests performed

Transitioning from automatic control of a lone farm tractor to automatically controlling the same tractor towing an implement is a large step since the combined system will have more complex dynamics and larger physical disturbances acting on it. Guiding a vehicle along curved paths will also present a challenge that has not been addressed. This work describes a control methodology that was successfully employed to control a real farm tractor to high accuracy. This same methodology, combined with a more sophisticated dynamic model may be sufficient to control the more complicated tractor-implement system. Further research is currently underway to explore this possibility.

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