Automatic Steering System for Electronic Robot Vehicle

Oscar C. Barawid Jr.*, Noboru Noguchi**

* Researcher, Vehicle Robotics Laboratory, Graduate School of Agriculture, Hokkaido University, Kita-9, Nishi-9, Kita-Ku, Sapporo, 065-8589 Japan
   Email: oscar@bpe.agr.hokudai.ac.jp
** Professor, Vehicle Robotics Laboratory, Graduate School of Agriculture, Hokkaido University, Kita-9, Nishi-9, Kita-Ku, Sapporo, 065-8589 Japan
   Email: noguchi@bpe.agr.hokudai.ac.jp

Abstract: This research developed an automatic steering system for electronic robot vehicles that is economical in comparison with commercial automatic steering systems today. A 48-VDC battery-operated electronic vehicle was used as a platform that has been modified the steering system into an automatic steering system using the following steps. First, the motor specification determination using strain gauges attached to the steering shaft; second, steering controller method/algorithm selection; third, steering system calibration; fourth, steering angle determination; and finally, autonomous navigation test runs. The lateral and heading errors were 0.08 m and 1.2 deg, respectively. These results indicated that the developed automatic steering system could control the robot vehicle accurately in an autonomous navigation.

1. INTRODUCTION

An automatic steering system for robot vehicle has various applications, depending on which platform is used. In this research platform, the automatic steering system had been used to modify the electronic vehicle into a robot electronic vehicle that is designed to run on flat lands such as orchards or golf courses. Related researches of developing robot vehicles in flat land application were conducted (Keicher and Seufert 2000; Noguchi, et al., 1997; Torri, 2000). Other application, a research developed a steering system on sloping ground entitled "Generalized steering strategy for vehicle navigation on sloping ground" (Asharf, et al., 2003). Also, a research studied a crawler guidance system using internal sensors on 11° sloping terrain (Tamaki, et al., 2001).

Prior to this research, the researcher’s laboratory had already developed fully-automated and fully-functional two (2) wheel-type and one (1) crawler-type robot tractors intended to navigate on rough terrains and paddy fields. This was the first time in the researcher's laboratory to include the automated steering system in robot vehicle modification. The common practice has been to use the automatic steering systems that were provided for by the tractor’s company.

A 48V DC (direct current) battery operated electronic utility vehicle (E-GATOR) was used as the research platform. This research aims to modify the E-GATOR’s steering system into an automatic steering system that is inexpensive compared to commercial ones while ensuring high accuracy in following predetermined paths in an autonomous navigation. Of course, there are commercialized retrofit automatic steering systems available in the market for E-GATORs. However, these systems are too costly. There are two major advantages to developing one’s own automated guidance steering from scratch. It is more affordable compared to what is readily available in the market, and it will appeal to the researcher’s natural inclination for solving a challenge.

One of the technical challenges in modifying agricultural tractors is to make sure that an adequate level of promptness and accuracy of the steering controller has been achieved for its electro-hydraulic (E/H) steering system (Wu, et al., 2001). Nowadays, modern agricultural vehicles are equipped with E/H steering system. A patent for an automatic guidance system that uses fluid power to actuate the steering linkage was published and a research was developed E/H control techniques for a parasitic steering valve (Van Der Lely, 1985; Laine, 1994). Methodology for designing the E/H steering PID controllers for agricultural vehicles was also developed (Noh and Erbach, 1993).

The steering system of the vehicle is rack and pinion Ackerman steering. This type of steering system is difficult to modify because it needs a motor with high torque in order to control the steering wheel. To obtain an appropriate motor for this type of steering system, an experiment was conducted and strain gauges were used to get the torque requirement of the motor.

One important consideration of an automatic steering system is the steering controller. The steering controller design
differs from each other due to various factors such as operating conditions of the field, the vehicle's physical dynamics, and the steering controller algorithm (Reid, et al., 2000). It was found that neither negligible nor constant friction could produce significant and unpredictable side-slip. The presence of these factors will affect the accuracy of the steering controller. A research developed a steering controller based on a set of linear motion equations which can compensate for the non-linearity and many unknown factors involved in steering system (O’Conner, et al., 1996).

In this research, a PID (proportional-integral-derivative) algorithm was used as the algorithm in order to control the steering system. The PID controller was tuned manually and will be discussed in length at the materials and methods section. A similar study was conducted using a self-tuning PID controller on a PLC (programmable logic controller) (Karasakal, et al., 2005). Another research designed a PID steering controller in frequency domain for an agricultural tractor guided by a GDS (geomagnetic directional sensor) (Benson, et al., 1998). Another related research is the classical model based steering controller for high speed agricultural tractor (Stombaugh, et al., 1998), found that the steering controller must compensate the dynamics of both the vehicle and the steering systems when the systems were in the same frequency range.

After tuning the PID controller, a calibration method was made between the input and the output steering of the wheels. Then, autonomous test runs of the electronic robot vehicle were conducted using the developed automatic steering system. To evaluate the test runs’ accuracy, two sensors were used. An RTK-GPS (real-time kinematic - global positioning system) was used as the positioning sensor to obtain the absolute position which has an accuracy error of ±2 cm. And, an IMU (inertial measurement unit) was used as the posture sensor to obtain roll, pitch, and yaw angles. The IMU is basically a gyroscope which has an accuracy of 0.5 deg/hour.

2. MATERIALS AND METHODS

2.1 Research platform

The research platform was an electronic utility vehicle or E-GATOR manufactured by Deere and Company. The vehicle can be used in 8-hour operating condition with a re-charging time of 16-hours depending on the condition of the batteries. This electronic vehicle is easy to maintain as it only needs the battery charger to be plugged-in after using the vehicle. Another thing is that the input cost for the energy is cheaper compared to vehicles which use petroleum fuel. On the other hand, the drawbacks are the bulkiness of wet/large batteries. Proper maintenance is necessary in order not to shorten the battery's life such as maintaining the liquid electrolyte level, discharged capacity should not be below 20% of its full capacity, etc. Its life-span is also dependent on the frequency of use. Thus, when the vehicle is frequently used, the more the batteries is being worn off. If the battery is maintained properly, it could last beyond six years of regular use.

2.2 Determination of motor specifications

The E-GATOR steering is rack and pinion Ackerman-type. This type of steering is a pair of gears which converts rotational motion into linear motion. The steering is not hydraulic or power steering instead, it is manually operated in order to rotate the wheels. In this stage, the initial task is find the motor requirements to be used (torque, voltage, power, weight, etc.). The motor should be able to perform in different working conditions (on-road, off-road, and steady-state).

To know the parameters in each condition, experiments were conducted. The most important parameter is the torque requirement of the motor. Prior to the experiment, a set-up was made to obtain some parameters. The strain gauges were attached opposite to each other and parallel to the steering shaft. The vehicle was run manually in different conditions (on-road and off-road) and rotated the steering shaft in different directions. Also, the steering was manually rotated in a steady-state position. To obtain the output of the strain gauges, a bridge amplifier was used. The amplifier was then connected to the data logger. The output data obtained from the strain gauges is shown in Fig. 1. The x and y axes correspond to the time in sec and torque in Nm, respectively. The blue, pink, yellow and red color projections represent the off-road, on-road, right-turn and left-turn, respectively. From these data output, the motor specifications were decided. The maximum torque needed for motor that could perform in different running conditions was about 24 Nm. For safety reason, a much higher torque was selected which is 49 Nm to prevent from overloading and over steering the motor. From these data output, the motor specifications were decided.

![Fig. 1 Output data obtained from the strain gauges](image_url)

2.3 PID controller

After obtaining the necessary information about motor specification, it's time to choose an algorithm to control the motor. This research used a PID (proportional-integral-derivative) controller as the steering controller algorithm for the motor. Equation 1 shows how to calculate the controller output, $u(t)$ theoretically.

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de}{dt}$$

(1)

Proportional gain ($K_p$), Integral gain ($K_i$) and Derivative gain ($K_d$) are the tuning parameters, $e$ is the steering angle error, $t$
is the present time and \( \tau \) is the time in the past contributing to the integral response.

The PID controller was tuned using manual-tuning. A manual tuning requires to first set \( I \) and \( D \) values to zero. Increase the \( P \) until the output of the loop oscillates, and then the \( P \) should be left set to be approximately half of that value for a "quartar amplitude delay" type response. Then increase \( I \) until any offset is correct in sufficient time for the process. The tuning was performed in a stationary position to easily understand the behavior of the vehicle's steering system such as maximum current that is needed to rotate the steering shaft in heavy loads which is in stationary position and tuning the vehicle while in motion/moving is difficult. Manual tuning was selected because it is recommended by the manufacturer of the motor and the motor driver.

2.4 Steering calibration

The motor was attached to the steering shaft using sprockets and chain. This connection was adapted because the backlash error was minimal and the installation was simple compared to other connection such as rack and pinion, gears, etc. The ratio of sprockets is 1:1. To check if the motor is rotating the wheels accurately with respect to the input angle from the computer, a calibration was made. Figure 2 shows how to measure the exact rotation of the wheels. In the figure, measurement scales were made to measure the actual rotation of the wheels. In this calibration, the wheels were removed and attached a rod directly to the kingpin both right and left side of the vehicle. At the end of the rod, a plumb was attached at each end. In each signal sent to the vehicle ECU (electronic control unit), a manual measurement was made.

A computation was made to get the steering angle for the Ackerman-type steering. Theoretically, the computation of the left and right rotation of the wheels can be calculated in Eqns (2) and (3). And the actual rotation (\( \theta_{\text{actual}} \)) of the vehicle can be calculated in Eqn (4).

\[
\theta_{\text{right}} = \cot^{-1}\left( \frac{R + B}{L} \right) \tag{2}
\]

\[
\theta_{\text{left}} = \cot^{-1}\left( \frac{R}{L} \right) \tag{3}
\]

\[
\theta_{\text{turning}} = \cot^{-1}\left( \frac{2R + B}{2L} \right) \tag{4}
\]

Where \( \theta_{\text{right}} \) is the angle of the wheel on the right-side, \( \theta_{\text{left}} \) is the angle of the wheel on the left-side, and \( \theta_{\text{turning}} \) is the vehicle actual turning with respect the radius \( R \) center of rotation. \( B \) and \( L \) are the width and length dimensions of the vehicle.

To control the automatic steering system in an autonomous run, a function of lateral error (\( \phi \)) and heading error (\( \phi \)) is required. These lateral and heading errors are needed to compute the steering angle which is necessary as an input command to the steering system. A research on how to calculate lateral and heading errors was used (Kise, et al., 2001). Figure 3 shows the vehicle dynamics model. In the figure, \( (X_k, Y_k) \) is the position of the vehicle in UTM coordinate, \( \phi \) is the vehicle heading, \( V \) is the travel speed, respectively. To obtain the vehicle’s absolute position \( (X_{k+1}, Y_{k+1}) \) from \( k \) to \( k+1 \) time series with reference to the vehicle’s speed, least squares method (LSM) was adopted which can be calculated in the following equations

\[
X_{k+1} = X_k + \frac{1}{2} (\sin \phi_k + \sin \phi_{k+1}) \Delta t \tag{5}
\]

\[
Y_{k+1} = Y_k + \frac{1}{2} (\cos \phi_k + \cos \phi_{k+1}) \Delta t \tag{6}
\]

To calculate the vehicle's heading error (\( \phi_k \)), a sensor fusion of RTK-GPS and IMU was applied.

\[
\phi_k = \phi_{IMU_k} + D_k \tag{7}
\]
Where, $\phi_{IMU_k}$ is the relative angle measured by the IMU, and $D_k$ is the correction value which compensates the time drift error of the IMU.

To solve for the lateral error, let the reference coordinate to be UTM (Universal transverse Mercator) coordinate, $\phi$, to be the direction of the vehicle, and $\eta = E^2$ to be the position of the vehicle. $\omega_1^*$ and $\omega_2^*$ are defined as the closest and the next closest points from position of the vehicle ($\eta$) to navigation map ($\Omega^*$), respectively shown in Fig. 4, and can be expressed as Eqn (8) and Eqn (9)

$$\omega_{1^*} = \left\{ \omega_i \bigg| \min_{i=1}^N \left\| \omega_i - \eta \right\|, \omega_i \in \Omega^* \right\}$$

$$\omega_{2^*} = \left\{ \omega_i \bigg| \min_{i=1}^N \left\| \omega_i - \eta \right\|, \omega_i \in \Omega^*, \omega_i \neq \omega_{1^*} \right\}$$

Where $\left\| . \right\|$ means that the vector has an absolute value or represents a norm of a vector. The segment $\omega_1^* \omega_2^*$ can be expressed in Eqn (10).

$$\omega_{1^*}, \omega_{2^*} = \left[ \begin{array}{c} \omega_{1^*} \\ \omega_{2^*} \end{array} \right] = [\kappa \tau \omega_{1^*} + (1-\tau) \omega_{2^*}, 0 \leq \tau \leq 1, \kappa \in E^2]$$

Where $\kappa$ represents the point on the segment $\omega_1^* \omega_2^*$. Using the above equations, the lateral offset ($d$) can be calculated as:

$$d = \min_{\omega_1, \omega_2} \left\| \omega_1 - \omega_2 \right\|$$

Finally, Eqn (12) was adopted to obtain steering angle ($\delta$) of the robot vehicle (Barawid, et al., 2007).

$$\delta = -(\Omega^* \gamma + \Delta^* \phi)$$

The steering angle ($\delta$) is represented as the function of lateral error ($\gamma$) and heading error ($\phi$). The control parameters $\Omega$ and $\Delta$ are the lateral and heading gains, respectively. To obtain the appropriate values of the control parameters, the robot vehicle was run at several speeds by trial-and error method, satisfying line-following performance.

### 2.6 Autonomous test runs

After calibrating the steering system of the vehicle, autonomous test runs in different speeds were conducted by following a predetermined path inside Hokkaido University, Sapporo, Japan. In this research, a 4-path navigation map was generated using a geographic information system (GIS) software (Noguchi and Terao, 1997; Takai, et al., 2010). The navigation map has 2.64 m path distance with a length of about 73 m. In this experiment, RTK-GPS and IMU were used as the navigation sensors. The RTK-GPS obtained the absolute position of the vehicle in universal transverse Mercator (UTM) coordinates and the IMU obtained the posture of the vehicle (roll, pitch, and yaw angles). The research used a switchback-turning method to get into the next target line (Kise, 2003).

### 3. RESULTS AND DISCUSSION

#### 3.1 Automatic steering system

The selected motor specification was enough to rotate the steering wheel in different road conditions. Aside from the motor, there are different components that were used to develop an automatic steering system. These components and the developed automatic steering system for the electronic robot vehicle are illustrated in Fig. 5. In the figure, the vehicle PC sends digital signal (0 to 255 bytes) to the ECU, then the ECU converts digital signal into an analog signal (0 to 5 V). An amplifier was used to amplify the 0 to 5 V into 0 to 20 V. Then, a motor driver was used to send -10 to 10 V. It means that 0 to 10 V and 0 to -10 V correspond to the clockwise and counter clockwise rotation of the motor, respectively. The amplifier and motor driver were chosen according to the motor specifications and correspond to the motor’s company recommendations. Two potentiometers were used to get an actual steering voltage feedback. The left potentiometer was used to get a steering voltage feedback, which is sent to the motor driver, and stop the motor when the sent voltage of the driver is equal to the output voltage of the potentiometer. The right potentiometer obtains the steering voltage feedback and sends it to the computer. This feedback signal is the actual rotation of the wheel. Figure 6 shows the analog feedback circuit. In this feedback circuit, first, the computer will send a digital signal to the ECU. The ECU will convert the digital signal to analog signal, and then the amplifier amplifies the voltage and sends it to the driver. The driver will command the motor to rotate either clockwise or counter clockwise. The potentiometer will also rotate according to the rotation of the motor. An analog feedback from the potentiometer will be sent to the computer. Using this information, the computer can compute the angle offset between the actual vehicle rotation angle and the input steering angle using Eqn (13).

$$\theta_{input} = \theta_{actual} + \theta_{error}$$

Where $\theta_{error}$ is the error between vehicle rotation angle and input steering angle, $\theta_{actual}$ is the actual computed angle using Eqn (4) and $\theta_{input}$ is the input angle to the computer.
3.2 Calibration results of the steering system

Before the actual autonomous test runs, a calibration method was made in the steering system. In this calibration method, manual reading from the measurement scale of the steering angle was recorded in each sent command of the computer. The right and left wheel rotations were not similar because of the effect of chamber angle of wheels. It is the angle between the vertical axis of the wheel and the vertical axis of the vehicle when viewed from the front or rear. From the measurement results, the actual turning angle was computed using Eqn (14). The result from the computed actual steering angle was compared to the input steering angle from the computer. Figure 7 shows the comparison of the actual and input steering angle. The next step is to calibrate the input data to the ECU so that it will have an approximately equivalent to the actual turning angle of the vehicle. The calibrated input angle ($\theta_{\text{calibrated}}$) can be computed using Eqn (14).

$$\theta_{\text{calibrated}} = \theta_{\text{input}} + \theta_{\text{offset}}$$

Figure 8 shows the comparison of the calibrated input angle and the computed actual vehicle turning. In the figure, the data of the calibrated angle is not exactly equivalent to the computed angle because the ECU can only receive whole numbers as an input data.

3.3 Autonomous test run results

The electronic robot vehicle is equipped with a 2-way switch that can shift from manual mode into automatic mode. The developed automatic steering system was tested by running the electronic vehicle in an autonomous navigation by following a predetermined path (navigation map). A 4-path navigation map was generated using a GIS program. The test runs were conducted inside Hokkaido University campus. The electronic vehicle was run by following these paths in different speeds (0.86, 1.52, and 1.61 m/s). As the speed increases the RMS (root mean square) errors also increases. The accuracy of the automatic steering system was evaluated with the speed of 0.86 m/s for the reason that it has the minimum error by using RTK-GPS and IMU as navigation sensors. The autonomous navigation trajectory was shown in Fig. 9. The blue points correspond to the autonomous navigation points, green points correspond to the navigation map points. At the end of each navigation path, switchback turning method was performed as the pink points.

![Fig. 7 Comparison of actual and input vehicle turning angles](image)

![Fig. 8 Comparison of calibrated and computed vehicle turning angle](image)

![Fig. 9 Autonomous navigation trajectory of the electronic robot vehicle](image)

In the figure, the robot vehicle was started to run in autonomous mode with an offset distance of about 1 m from the target path. This kind of autonomous start-up was made in order to know if the robot vehicle could follow the navigation map even if there is an offset distance. The robot vehicle could follow the navigation map accurately in straight-line autonomous navigation and successfully made the autonomous switchback-turning at the end of each row to enter to the next target path. Then, after completing the task following the 4-path navigation map, the robot vehicle automatically stopped. Figure 10 shows the evaluated accuracy results with 0.86 m/s speed. The lateral and heading RMS errors are 0.08 m and 1.2 deg, respectively. The results showed that the robot vehicle could follow the navigation map accurately if there is an offset distance between the target line and the robot vehicle. Results proved that the developed automatic steering system was calibrated well and the errors (lateral and heading) are adequate enough to run the electronic robot vehicle in an autonomous run.

4. CONCLUSION

The research developed an automatic steering system for the electronic robot vehicle which was inexpensive compared to the commercialized retrofit steering system in the market. To determine the motor specification that could rotate the steering wheels in different conditions (off-road, on-road, steady-state), strain gauges were used to know the torque requirement, the most important parameter in determining motor specifications. The motor was installed in the vehicle using chain and sprockets. This connection was adapted because it has a minimum backlash error. A PID controller...
was adapted as the algorithm to control the automatic steering system. To see if the motor is rotating properly with respect to the command coming from the ECU, a calibration method was made. The actual rotation of the wheels was measured using a measurement scale. The actual vehicle turning was computed and compared to the input angle from the ECU. The data were calibrated so that the angle that will be inputted to the ECU would approximately equal to the actual turning angle of the vehicle. After calibration, the electronic robot vehicle was tested in a multi-path autonomous runs. RTK-GPS and IMU were used as navigation sensors to evaluate the trajectory of the vehicle. The speed used to evaluate the robot vehicle accuracy was 0.86 m/s. The lateral and heading RMS errors were 0.08 m and 1.2 deg, respectively. The results justified that the developed automatic steering system was successful in modifying the electronic vehicle into a robot vehicle. Also, these accuracies are enough to navigate the electronic utility robot vehicle in an autonomous navigation in following a multi-path. Not only was the result accurate enough, but also making the system operational only cost about four thousand dollars ($4000.00), an amount far more inexpensive as when you buy commercialized system in the market where prices range from twenty-five thousand (25,000) to thirty thousand (30,000) dollars inclusive of shipment and installation.

Fig. 10 Accuracy results in straight-line path navigation

REFERENCES


