Automatic Guidance System in Real-time Orchard Application (Part 2)

—Development of Low-cost and Small Scale Electronic Robot Vehicle for Orchard Application—

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Abstract

The objective of the research was to develop a low-cost and small scale robot vehicle for an orchard application. The platform used was an electronic utility vehicle also called as E-GATOR. The electronic vehicle was modified into a robot vehicle that can control functions such as steering, movement (forward, backward, neutral), vehicle speed, and emergency stop (by manual and remote control). The robot vehicle was tested to run autonomously on a straight-line path using an RTK-GPS (real-time kinematic global positioning system) and an IMU (inertial measurement unit) as the navigation sensors. The results showed that the robot vehicle could follow the straight-line path with lateral and heading RMS errors of 0.08 m and 1.2 deg, respectively.

[Keywords] robotics technology, orchard, CAN (controller area network) bus system, small scale robot vehicle

I Introduction

Development of robot vehicles for agricultural purposes is one of the interesting topics in the recent decade. There are many applications of robot vehicles such as weed detection (Thomas and Jakobsen, 2004). In their research, a robotic platform for mapping of weed populations in fields was used to demonstrate intelligent concepts for autonomous vehicles in agriculture. Also, Khot et al., 2005, developed a prototype robot vehicle for posture estimation of autonomous weeding robots navigation in nursery tree plantations greenhouse application. Furthermore, Khot et al., (2005) developed an autonomous tractor for intra-row mechanical weed control in row crops. Another application is on paddy field, Nagasaka, et al., (2004) developed an automated rice transplanter. Many researches also have desire to modernize agriculture (Linker and Blass, 2008). This desire led researches to numerous studies related to the development of agricultural robot and semi-robot vehicles (e.g. Debain et al., 2000; Pilarski et al., 2002; Han et al., 2004; Morimoto et al., 2005).

Moreover, a robot vehicle can also be used in an orchard application which is a novel innovation since only a few institutions are focused on this. Subramanian, et al., (2006) discussed a related research on orchard application which is the development of an autonomous guidance system for citrus grove application entitled “Development of machine vision and laser radar based autonomous vehicle guidance systems for citrus grove navigation”. The expensive cost and the largeness of these robot vehicles posed a problem in their development.

Barawid et al., (2006) conducted a research entitled “Development of an autonomous navigation system using a two-dimensional laser scanner in an orchard application”. In this research, the robot vehicle was successfully run between tree rows in an orchard. The robot vehicle used was KUBOTA MD 77 56-kW. Also, Barawid et al. (2008) developed a guidance system which used a KUBOTA GL320 tractor that was modified into a robot tractor.

The main objective of this research is to develop a small-scale and low-cost robot vehicle in order to address the problems of expensive costs and largeness of the robot vehicle’s development. This robot vehicle can be used in any given orchard application (citrus, apple, grape, coconut field, strawberry, etc.) because of the manageability of its size and relatively low-cost compared to the already developed robot tractors. Even if the orchard tree-row distance is narrow, this

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The robot vehicle could run between the tree rows unlike the other developed robot tractors in our laboratory which couldn’t run between the tree rows because of the largeness of the size. This type of robot vehicle can help the orchard farmers in gathering the crop information such as growth, disease and status, harvesting fruits, weeding, etc.

One of the originalities of this research is that it is the first time in our laboratory to use electronic vehicle as a platform for robotic development. And, it is also the first time to develop our own ECU and steering systems because these systems usually developed by the private companies for our robot vehicles.

The research used Gator Electric Utility Vehicle as a platform manufactured by Deere and Company. The vehicle electric motor is powered by 48-VDC (volt direct-current) with 8 batteries (6-volt each battery). In this research, the vehicle was modified into a robot vehicle that can control different functions that include steering, movement (forward, backward and neutral), vehicle speed, and emergency stop (by manual or remote control). In order to communicate to the electric vehicle, an ECU (electronic control unit) was made. This controller sends the signal to the vehicle to do different tasks. The controller is connected to the electronic vehicle using an analog signal and can receive commands from the desktop PC (personal computer) using a CAN (control area network) bus system.

### II Research materials and Methods

#### 1. Research Platform

The platform used in this research was a Gator Electric Utility Vehicle. The general vehicle specifications are illustrated in Table 1. The vehicle is electronically operated using 48-VDC composed of 8-batteries with 6-volt each and equipped with its own battery charger that automatically switches off when the batteries are fully charged. The vehicle can be used in 8 hours operating condition and takes 16 hours charging time depending on the condition of the batteries. This electronic vehicle is easy to maintain since one has to plug-in the battery charger after using the vehicle. Another thing is that the input cost for the energy is cheaper compared to vehicle which uses petroleum fuel. An example of which is the Mitsubishi’s electric car that can run through 500 km for US$5 compared to Mitsubishi’s gasoline car for US $43. Another example is the electricity in households. It is cheaper to buy to the electric company than to produce the electricity using generators that is using petroleum fuel. Also, electronic vehicle is environmental friendly because it doesn’t emit CO₂ (carbon dioxide) and the vehicle’s cost is less expensive compared to other tractor’s costs. On the other

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Fig. 1 Electronic Utility Vehicle (E-GATOR) before modifying into a robot vehicle

hand, the disadvantage of using a battery-operated vehicle is that the usable life-span of the batteries is dependent on the frequency of the vehicle usage. Figure 1 shows the electronic utility vehicle (E-GATOR) without any modification. The vehicle steering type is a rack and pinion Ackerman steering. This type of
steering is a pair of gears which converts rotational motion into linear motion. The steering is neither hydraulic nor powered steering but rather it is manually operated.

To test and evaluate the accuracy of the robot vehicle in an autonomous run, an RTK-GPS (MS 750 dual frequency, Trimble Navigation Ltd.) was used to obtain the absolute position of the vehicle with respect to the UTM (universal transverse Mercator) coordinates system with an accuracy of ±2 cm and an IMU (Japan Aviation Electronics, Ltd.) was used to get the heading direction of the vehicle with an accuracy of ±0.5 deg/hour.

2. ECU (Electric control unit) and vehicle control

A hardware called ECU was developed to communicate to the vehicle and control different functions. Figure 2 shows the developed ECU for the electronic vehicle referred as the vehicle controller. The vehicle controller can control steering, vehicle movement (forward, backward, and neutral), vehicle speed, and emergency stop (by manual switch and remote control switch). The vehicle controller used PIC18F458 as its microchip device which has a program memory of 32 Kbytes, data memory of 1536 bytes in SRAM (static random access memory) and 256 bytes in EEPROM (electrically erasable programmable read-only memory) with 33 pins of I/O and 8 channels of A/D in 10 bits. The vehicle has a computer and sends data using a controller-area network - based system (CAN-bus) to the vehicle controller. The CAN-bus also receives data from the controller as feedback of the other sensors such as potentiometers, and motor speed sensor. The controller can communicate to the vehicle using a D/A signal. In the steering system, the controller outputs analog voltage of 0-5V. For the vehicle speed, the controller outputs 0-5V to the electric vehicle's motor controller. The maximum speed with a 5V input to the electronic vehicle is 25 km/hr. In the case of the emergency stop, the controller cuts the supply voltage going to the vehicle's electric motor.

3. Steering system

To be able to control the steering of the vehicle, an appropriate motor is needed to rotate the steering shaft. An experiment was conducted to obtain the necessary information for motor selection, i.e. motor specifications. First, strain gauges were attached to the steering shaft in order to obtain the torque required for motor selection under different working conditions. The vehicle was run manually in off-road and on-road with different speeds and rotates the steering wheel in left and right directions manually. Also, the torque was obtained in the stationary position and turns the steering wheel in left and right direction manually. After getting the torque requirement for the motor, motor specifications were decided. Figure 3 shows the motor image and Table 2 shows the motor specifications that were used in the vehicle modification into a robot vehicle. The steering angular velocity was also calculated using the motor speed specification (50 rpm). The maximum steering wheel rotation in left and right directions is 1.5 revolutions. The steering angular velocity is 1.2 rps.

The motor was installed near the steering shaft and connected to the steering shaft using chain and sprockets. The motor can be controlled by sending an analog signal coming from the developed vehicle controller (ECU). In order to control the rotation of the motor, clockwise or counterclockwise, a DC motor driver and a position amplifier were necessary. A motor driver and a position amplifier were chosen according to recommendations by the motor manufacturer based on their compatibility with the motor. To get the correct tuning of the motor, a proper tuning of the motor amplifier should be made using a PID (proportional-integral-derivative) controller. A PID controller is a generic control loop feedback mechanism widely used in industrial control systems. This controller attempts to correct the controller input error between a measured process variable and desired set point by calcu-
The PID controller calculation or algorithm involves three separate parameters; the Proportional (P), the Integral (I) and the Derivatives (D) values which are shown in Figure 4. The Proportional value determines the reaction to the current error, the Integral value determines the reaction based on the sum of recent errors, and the Derivative value determines the reaction to the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control value or the power supply of a heating element. By tuning the three constants in the PID controller, the controller can provide control action designed for specific process requirements.

The output from the three terms in Figure 4, the Proportional, the Integral and the Derivative terms are summed to calculate the output of the PID controller. Defining \( u(t) \) as the controller output, \( u(t) \) can be calculated using Eqn. (1).

\[
u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de}{dt}
\]  

(1)

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

The vehicle controller sends analog signal (voltage) to the motor to turn the steering shaft. The signal used PWM (Pulse Width Modulation) to modulate its duty cycle. The PWM uses a square waveform whose pulse width is modulated resulting in the variation of the average value of the waveform and has a duty cycle of 0.5 or 50%. Considering a square waveform \( f(t) \) with a low value \( y_{min} \), a high value \( y_{max} \) and a duty cycle \( D \) and \( T \) is the time in seconds, illustrated in Figure 5, the average value can be estimated in Eqn. (2).

\[
y = \frac{1}{T} \int_0^T f(t) dt
\]  

(2)

One of the most important systems in developing robot vehicles is the steering system. One of the technical challenges in developing automated steering for agricultural tractors is the development of a prompt and accurate steering controller for its hydraulic steering system (Wu et al., 2001). If the robot vehicle has a good steering system, it is easy to control and the autonomous navigation run will have a high accuracy. But it is also the hardest part to develop because there are many things to take into account such as a system design, algorithms, and equipment resources. Figure 6 shows the schematic diagram of the vehicle steering system. A manual and automatic switch was attached to the vehicle for changing the vehicle’s application mode. The manual mode will return to the original operation of the vehicle but the steering motor is still connected to the steering shaft. This connection causes the steering wheel a little difficult to rotate due to the magnetic field inside the steering motor. For automatic mode, the switch cuts all the connection in manual mode and shift to automatic mode functions using the controller.

The motor was connected to the steering shaft using sprockets and chain. This connection method was adapted because the installation is easy and the backlash error is minimal compared to other methods. The sprockets ratio is 1:1. A potentiometer was mounted to the kingpin of the front wheel to get a feedback signal that commands the motor to stop at a certain degree or rotation. The motor will stop when the motor inputted voltage is equivalent to the outputted voltage of the potentiometer. Also, a feedback loop was made to the ECU to get the actual steering
Fig. 7 Electronic vehicle (E-GATOR) toe-in adjustment

angle. This loop obtained the offset for the steering angle. Separate batteries were purchased to supply the power needed for automatic steering system and its components in order not to affect the vehicle’s batteries operating-hour performance.

Microsoft Visual Studio 2008 was used to design a GUI (graphical user interface) in testing the steering system and other hardware of the electronic vehicle. In this GUI, the operator of the vehicle can easily command the different functions of the vehicle.

4. Toe-in adjustment and steering calibration

One of the important things prior to the steering calibration is ensuring that the toe-in is properly adjusted. This method was done to prevent tire wear and steering wander (irregular course). Figure 7 shows how to adjust the toe-in of the electronic vehicle. The upper figure showed that the rear and front driverside tires should be aligned using a 2 × 4 piece of angle iron as a guide. In the middle figure, the distance A and B were measured at hub height and center of the tire tread. The lower figure showed at the right side tie rod (C), the jam nut (D) was loosened and turned until the front distance (B) was 4 [mm] less than rear distance (A).

After the toe-in adjustment, steering calibration was made. To measure the actual turning of the wheels (both left and right wheels), they were removed and rods were attached directly to the kingpin of the wheels, and a plumb was attached at the end of the rods. A semi-circle which resembles a protractor with measurement in degrees was made and was used to measure the tip of the plumb in each rotation. Output data from the potentiometer was recorded using a data encoder while the angle rotation of the wheels was measured manually using the measurement scale. Figure 8 shows the method to calibrate the steering system. The input angle to the computer was then compared to the output angle measured from the measurement scale.

5. Algorithm to control the steering angle of the robot tractor

To obtain the steering angle (δ) that will be sent to the steering system of the robot vehicle, a function of lateral error (ε) and heading error (Δφ) are needed. In this research, ε and Δφ were calculated using the RTK-GPS and the IMU. Lateral error can be calculated using Eqn (3).

$$
ε = \frac{αE_{GPS} + βN_{GPS} + C}{\sqrt{α^2 + β^2}}
$$

(3)

Where α, β and C are the constant coefficients in a line equation, and $E_{GPS}$ and $N_{GPS}$ are the current location of the vehicle in UTM (Universal Transverse Mercator) coordinates obtained from the RTK-GPS. For the heading error (Δφ) is computed by Eqn (4);

$$
Δφ = \arctan\left(\frac{L}{T}\right) + θ
$$

(4)

where $L$ is the look-ahead-distance of the vehicle and $θ$ is the relative angle of the vehicle obtained from the IMU. The heading angle is the actual heading direction of the vehicle with respect to the north UTM coordinates. Finally, to calculate the steering angle ($δ$), an algorithm developed by Kise et al., 2001 was adapted.
Where $GainA$ is the lateral gain and $GainB$ is the heading gain. To determine the correct parameters for $GainA$ and $GainB$, different test runs were conducted by trial-and-error which was also discussed in the previous paper. Figure 9 shows the outline on how to obtain the steering angle of the vehicle.

A preliminary autonomous test run of the electronic robot vehicle was conducted inside Hokkaido University campus. The vehicle was run in a straight-line path with different speeds (0.86, 1.52, 1.61 m/s) in a 50-m distance. The robot vehicle could follow the path with minimum errors both in lateral and heading.

### III Results and discussion

1. Steering calibration results

Figure 10 shows the data obtained from the actual measurement of the steering angle rotation both on right and left direction. Figure 10 (a) shows the actual right and left steering angle rotations measured in the measurement scale. The $x$-axis and $y$-axis are the steering angle rotations and input voltage in the controller, respectively. The $x$-axis with ($-$) negative voltage value means right steering angle rotation and ($+$) positive voltage value means left steering angle rotation. The data obtained from the right and left steering angle rotation were different because of the effect of wheels toe-in. The $X$ symbol is the steering angle rotation of the right-side wheel and $\Delta$ is the steering angle rotation of the left-side wheel, both in degrees. To get the correct vehicle steering angle rotation, the average of the left and right steering angle rotations was obtained and became the vehicle's actual heading angle shown in Figure 10 (b).

A calibration was made by comparing the input steering angle to the ECU and output angle from the measured actual steering angle of the vehicle. Figure 11 shows the comparison of the measured and input angles. The difference of these two angles will be the offset angle that will be sent to the ECU.

The electronic vehicle was properly adjusted following the procedure stated above. To see if the vehicle wheels were properly aligned, a manual run was conducted in an almost flat surface with 150-m distance. The vehicle was run in 0 deg steering angle. In this run, the vehicle should run in a straight line because the surface was flat. The vehicle could run in a straight line almost accurately. It means that the vehicle is ready to test for an autonomous run.

2. Preliminary testing of the robot vehicle

Before the autonomous run test, a hardware and software tests were conducted to check if each hardware of the robot vehicle such as the ECU, the motor and the motor driver, the emergency stop, the vehicle movement (forward, backward, neutral), the steering system and the vehicle software is properly working. The software used in this research was Microsoft
Visual studio 2008. The tests were done by hanging the vehicle wheels (front and back), to avoid vehicle movement and accidents, running the vehicle (forward and backward) and checking all the components of the vehicle to see if all are working properly.

After the hardware test, preliminary autonomous test runs were conducted to follow a straight-line path. The robot vehicle was run in different speeds (0.86, 1.52, 1.61 m/s) in an approximately 50-m distance. To evaluate the accuracy of the trajectory of the vehicle, the RTK-GPS and the IMU were used as the navigation sensors. Table 3 shows the RMS (root mean square) errors in lateral, heading and steering in different speeds. The results showed that while the speed was increasing, the lateral and heading errors were also increasing.

The speed 0.86 m/s has the minimum RMS errors. In the figures, the x and y axes correspond to the RMS error and distance, respectively. These results were compared with the accuracy results of the one of the developed robot tractors (KUBOTA MD77) in an autonomous orchard run (Barawid et al., 2006). The evaluated accuracy results comparison was shown in Table 4. The accuracy results of the electronic robot vehicle showed that it was adequate enough to run the electronic robot vehicle in an autonomous run. The future works include conduct experiments in a map path planning and in orchard navigation, and turning algorithm in an orchard application using the electronic robot vehicle.

### IV Conclusion

An electronic robot vehicle was developed in this research using electronic utility vehicle (E-GATOR) manufactured by Deere and Company. This electronic vehicle is powered by 48-VDC (voltage direct current)
with 266.5 × 152.5 × 113 cm (length × width × height) dimensions. The developed robot vehicle will be used in an orchard application particularly in citrus and coconut orchard. The research used the PID and the PWM to control the steering system of the vehicle. A potentiometer was used to get feedback of the actual steering angle and used to have the steering offset. The Microsoft Visual Studio 2008 was used to make GUI (graphical user interface) to be able to test the different functions of the robot vehicle. After testing the different functions of the robot vehicle, autonomous test runs were conducted. To evaluate the accuracy of the vehicle, the RTK-GPS and the IMU were used as the navigation sensors. The lateral, heading, and steering errors were 0.08 m, 1.20 deg, and 1.73 deg, respectively. The robot vehicle is enough to use in vehicle’s autonomous run because of its minimum errors.

References


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要 旨
本研究の目的は果樹園作業用低コスト小型ロボット車両の開発である。ロボットプラットホームとして（株）Deere and company 社製電気ユニティリティビーキルを採用した。この電動車両に操舵、進行方向（前進、後退、停止）及び非常停止などの機能を制御することができるように改造した。航法センサとして RTK-GPS と IMU を使用して、直線経路において自律走行試験を行った。実験の結果、直線経路で 0.079 m の横方向偏位と 1.2 deg の方位偏位を達成し、ロボットとして十分な性能と判断した。

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