Development and evaluation of a general-purpose electric off-road robot based on agricultural navigation

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Abstract: The aim of this study was to develop a general-purpose electric off-road robot vehicle by using automatic control technologies. The vehicle prototype used in this study was a commercially-purchased electricity utility vehicle that was designed originally for manual operations. A manipulating unit, an automatic steering system and a speed control system were developed and integrated into a CAN-bus network for operating on functions (forward, reverse, park or stop), realizing desired steering angles and maintaining a constant speed, respectively, in the mode of automation. An autonomous navigation system based on RTK-GPS and IMU was used to evaluate the performance of the newly developed off-road robot. Field tests showed that the maximum error in speed control was 0.29 m/s and 0.22 m/s for speed tests and autonomous runs, respectively. The lateral offset was less than 10 cm in terms of straight paths, indicating that the automatic steering control system was of good performance.

Keywords: electric off-road robot, automatic control, automatic steering, speed control, autonomous navigation system, field test

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1 Introduction

With the rapid development of modern technologies and economy, agricultural machines are supposed to be highly efficient and labor-saving. With this trend acknowledged by researchers, agricultural vehicles capable of automatic agricultural operations emerge fast and tend to gradually replace conventional vehicles. The concept of GPS-based global navigation has attracted much research efforts in related fields[1-4]. Noguchi et al. developed a robot tractor based on the sensor fusion of an RTK-GPS and an inertial measurement unit (IMU)[1]. The completed robot tractor was capable of following pre-planned paths, either straight or curving, by a lateral offset of less than 5 cm when speeding up to 2.5 m/s. To achieve higher efficiency for autonomous operations, Noguchi et al. developed a master-slave multi-robot system that integrated two robot vehicles for collaborative work on the farm using two control algorithms, named GOTO algorithm and FOLLOW algorithm, respectively, to guide the slave to achieve a specific place away from its current position or to follow the master at a predetermined relative distance and angle[5]. In terms of local navigation, a number of researchers made great efforts to develop low-cost automatic systems by using machine vision[6-8], ultrasonic sensors[9], stereo vision[10-12] and omni-cameras[13] to sense unstructured field environments. Besides, direct acquisition of 3D data showed a great potential in agricultural navigation and obstacle detection with

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attempts in use of 3D cameras[14] and laser range finders[15-17]. Some researchers have also been concentrating on driving assistant systems to improve working conditions and alleviate labor intensity[18-20].

Those studies mentioned above focused on explanation of navigation systems and evaluation of their guidance performance in farm operations while few of them presented the platform hardware and automation realization of agricultural robots. As the most fundamental elements of an off-road robot platform, automatic mechanisms are involved in automatic steering, speed control and automatic operation of implementations. Therefore, it is necessary to demonstrate effective solutions to automatic operations on agricultural vehicles. Zhang et al. utilized an adaptive PD controller to realize automatic steering of the Kubota SPU-60 rice transplanter according to the running speed[21]. The finished system proved to be of adequate accuracy in guiding the vehicle for orientation tracking through simulations and field tests[21]. For data exchange between sub-systems, the CAN bus network was always adopted in the establishment of vehicle hardware systems because of its communication stability and structure simplicity[22, 23].

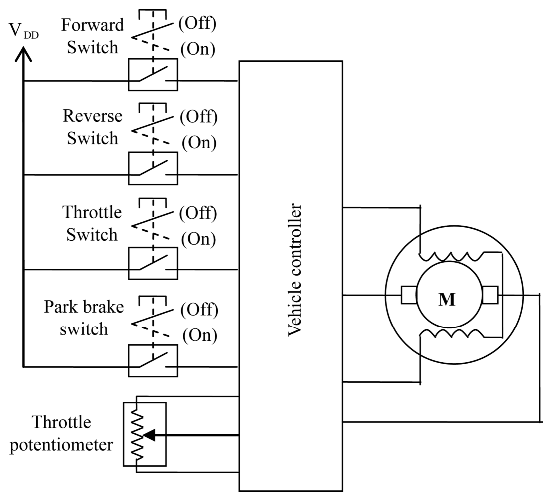
The objective of this research was to demonstrate technical details in modifying a manually-operated vehicle into an automatic one. This research dealt with the modification of vehicle hardware including the vehicle electrical system, the steering system and the vehicle controller, as well as performance evaluation of autonomous navigation that used RTK-GPS and IMU as navigation sensors to guide the off-road robot along predetermined trajectories during farm operations. Each system had an electronic control unit (ECU) for both execution of control algorithms and signal processing. For information exchange among ECUs, a CAN-bus network was established based on the "ISO 11783" standard. Two proportional-integral-derivative (PID) controllers were integrated into ECUs for automatic steering and speed control, respectively.

2 Materials and methods

2.1 Vehicle prototype

The vehicle prototype used in this research was a 48VDC battery-operated electric vehicle, the E-Gator, by Deere & Company. It was originally designed for manual operations. Figure 1 shows the original appearance of the E-Gator and the diagram of its electrical system. The electrical system is centered with a vehicle controller and an electric motor and also is composed of operation units including a throttle pedal, a park brake lever and a forward/reverse/neutral lever. Each of the operation units interrelates with a corresponding switch that conveys manual operations to the vehicle controller. The vehicle controller is used to detect status of all switched circuits, and based on the position of the throttle pedal as well, to control the vehicle electric motor in terms of its rotating direction and speed.

a. Original appearance of the E-Gator



b. Schematic diagram of the electrical system

Figure 1 Vehicle prototype

2.2 Vehicle automation

In developing agricultural robots, it is a prerequisite to establish automatically-operated vehicles as their platforms. For general-purpose uses, this section is intended to introduce necessary solutions of vehicle automation to automatic manipulation, automatic steering and automatic speed control in the following three subsections, respectively. The manipulation system was dedicated to switching functions between forward, neutral and reverse. The steering system was used to realize a desired turning through a rack and pinion mechanism. The speed control system determined the throttle depth to maintain a desired speed during operation even in uneven fields. Those three systems had their own ECUs for execution of control algorithms, each of which was connected as a node to the vehicle communication network based on the CAN-bus protocol.

2.2.1 Automatic manipulation

When performing a forward command, throttle switch, park brake switch, forward switch and key switch are activated at the same time. When performing a reverse command, throttle switch, park brake switch, reverse switch and key switch are activated at the same time. When the park brake switch is released, the motor controller will receive a voltage input through the park brake switch and allows the vehicle to operate normally. If the park brake is engaged, there will be no input to the motor controller from the park brake switch and the drive motor will be shut down.

For automatic realization of those functions mentioned above, each of related switched circuits was by-passed through a corresponding relay (such as R1, R2, R3 and R4 shown in Figure 2) that was controlled on or off by the Function ECU that was centered with a microcontroller. K1, K2, K3 and K4 were gang switches and selected by users between manual and automatic modes. The Function ECU was also used to exchange information with other nodes on the CAN-bus network. All by-passing circuits, relays and the Function ECU made up the automatic manipulation system. Its performance was verified during evaluation experiments in the field as presented in section 3.

2.2.2 Automatic steering

Figure 3 depicts the left half of the E-Gator steering system from a front view. The E-Gator features a rack and pinion steering system. The steering wheel connects to the rack and pinion assembly through U-Joint assembly. In the manual mode, operators could drive the vehicle along desired paths only by manipulating the steering wheel with their hands.

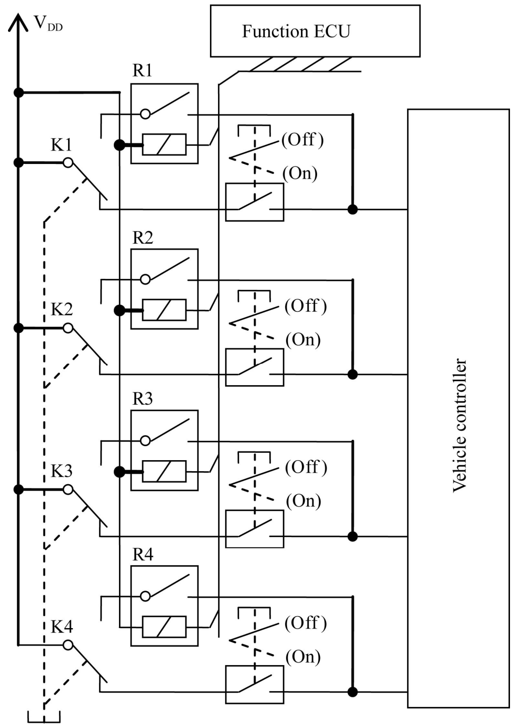


Figure 2 Modification of switched circuits

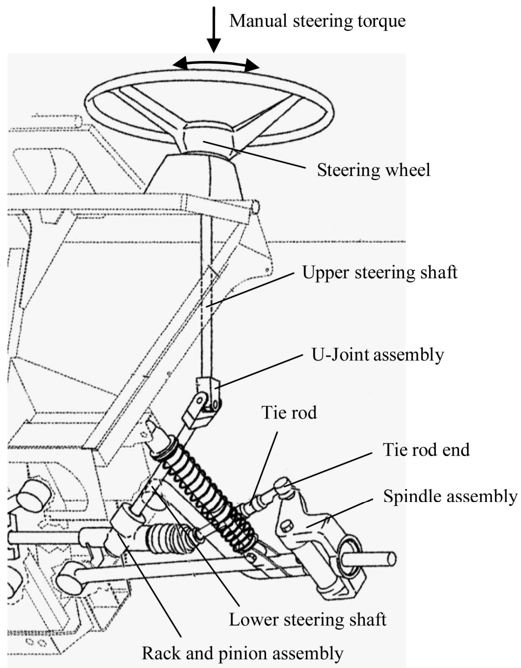


Figure 3 The E-Gator steering system.

With consideration of realizing automatic steering in an efficient and effective way and also retaining the original steering mechanisms as most as possible, this study proposed an automatic steering system composed mainly of a steering motor and its driver, a PID (Proportional-Integral-Derivative) controller, a potentiometer and a steering ECU as shown in Figure 4. The steering ECU receives the steering command through the CAN bus network in the form of a desired steering angle φ_d in digital and then translates it into an analog signal ranging from 0 to 5 V as one of inputs to the PID controller. The potentiometer is of high linearity and elastically ganged upwards with the kingpin of the front-left wheel to measure and feedback the actual rotating angle φ_a of the wheel. The electric motor is used to produce the torque force that is conveyed to the upper steering shaft through a chain and sprocket mechanism and then to the rack and pinion assembly through the U-Joint assembly for implementation of steering the front wheels as illustrated in Figure 5. The PID controller takes both φ_d and φ_a as two analog inputs and comparing them to calculate out a voltage signal V_C, ranging from -10 to 10 V, which determines the desired rotating speed and direction of the steering motor that is driven directly by the motor driver that amplifies V_C as its input signal up to V_D varying roughly from -23 to +23 V.

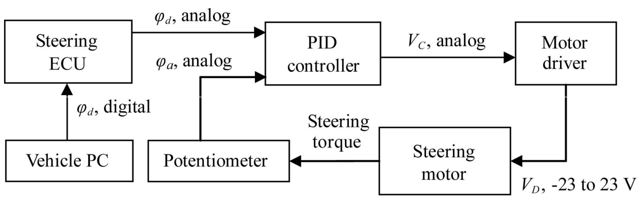


Figure 4 Diagram of the automatic steering system

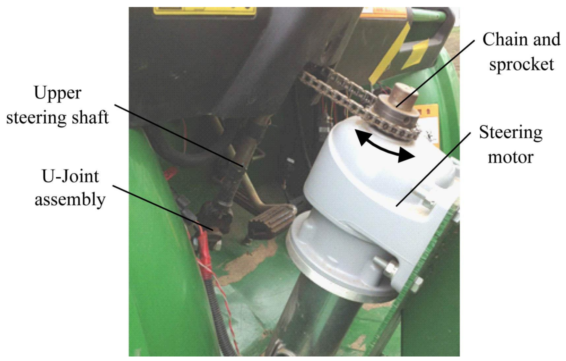


Figure 5 Installation of the automatic steering mechanism

The steering torque acting on the steering wheel is the most important parameter in selecting the motor type. It was determined by attaching strain gauges onto the upper steering shaft. Related experiments were conducted under different conditions including off-road, on-road, right-turn and left-turn as introduced by Oscar et al.[24] Results showed that the maximum torque value was 24 N·m. Finally, the steering motor with a maximal torque of 49 N·m was used for safety. The newly developed automatic steering system was evaluated during autonomous navigation in terms of the lateral error as introduced in section 3.2.

2.2.3 Automatic speed control

The off-road robot developed in this research was intended to be utilized in general fields for agricultural work like automatic transportation of materials and supplies if equipped with an autonomous navigation system. Since the field ground and roads were always uneven and sometimes slopes existed in the field, the robot vehicle had to continuously adjust its throttle depth in order to run smoothly at a desired speed, which made it highly necessary to develop an automatic speed control system for the agricultural robot.

As introduced in section 2.1, the driving force of the E-Gator was generated by the vehicle electric motor controlled by the vehicle controller according to the throttle position. Through investigation on the acceleration process of the E-Gator in the manual mode, it was found that the output of the throttle circuit varied continuously from 0 to 5 V as an analog signal when it was pushed from its default position to the deepest, motivated by which, this research proposed to generate a separate voltage signal instead of the throttle output by the by-passing method.

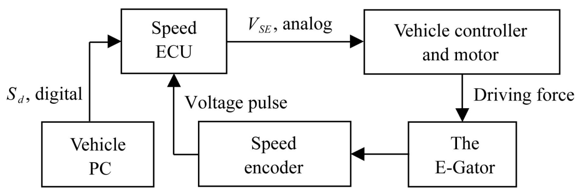


Figure 6 Automatic speed control system

Figure 6 shows the closed-loop automatic speed control system. The speed PID controller was implemented in digital with the microcontroller of the Speed ECU. A speed encoder attached directly to the rear left wheel with its shaft synchronized with the wheel rotation was used to detect the actual vehicle speed S_a. In the automatic mode, the speed PID controller took the desired speed S_d from the vehicle PC through the CAN-bus network and S_a calculated by using a counter to record the number of voltage pulses within a certain period as two input parameters to calculate an appropriate voltage signal V_{SE} as the throttle input to the vehicle controller. Gains in the speed PID controller were tuned in evaluation of the automatic speed control system in the field mentioned in section 3.1.

2.2.4 CAN bus-based communication network

As mentioned in subsections above, each of automatic systems was equipped with a separate ECU for its high ability in response and execution of commands. All the ECUs were integrated into a CAN-bus communication network as shown in Figure 7. The vehicle PC was included as one node for processing large data information from RTK-GPS, IMU and vision sensors. For general-purpose applications, the CAN-bus network was designed open for users to control the off-road robot with their own devices connected to reserved nodes.

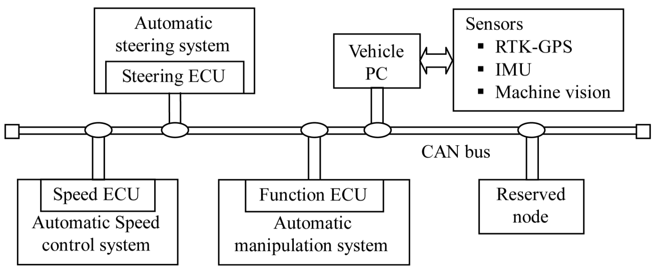


Figure 7 CAN-bus network of the off-road robot

3 Results and discussion

Through automation modifications in the hardware of the E-Gator, the newly-developed off-road robot platform appeared as Figure 8, contrasting to the vehicle prototype shown in Figure 1a. A black metal frame was attached for mounting devices, sensors and wires.

Figure 8 The completed off-road robot

For verifying basic functions of the off-road robot and evaluating its performances in speed maintaining and automatic steering, field experiments were conducted on the farm of Hokkaido University, Sapporo, Japan. The RTK-GPS and IMU were used in the map navigation method in section 3.2 to test the accuracy of the automatic steering system.

3.1 Evaluation of speed control system

Experiments for evaluating the developed speed control system were designed with the vehicle PC sending a series of desired speed values to the speed ECU via the CAN-bus network. For safety, the off-road robot was manually operated except the throttle pedal that was bypassed through the circuit of the speed PID controller. During experiments, the robot vehicle was steered along straight lines with its desired speed set to 0.25, 0.4, 0.75, 1.0, 1.4, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, and 3.5 m/s, respectively, for each run. The actual vehicle speed was measured using the speed encoder that also constituted as the feedback element in the closed-loop system in section 2.2.3.

Figure 9 shows the results in three runs, for example, with the desired speed of 0.25, 1.5 and 3.0 m/s, respectively. According to S_a measured during the stable process of each run, the RMS error and maximum deviation $D_{\max}$ were acquired for all runs as shown in Table 1.

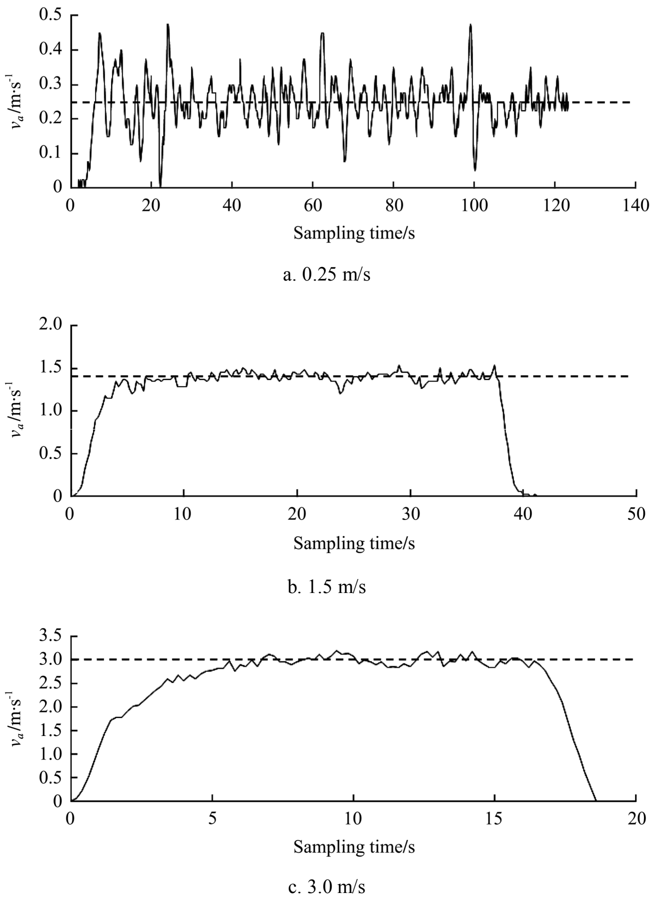


Figure 9 Variations of S_a under different settings of S_d

Table 1 Evaluation of the automatic speed control system

v_d /m·s^{-1}	RMS error /m·s^{-1}	D_{max} /m·s^{-1}	v_d /m·s^{-1}	RMS error /m·s^{-1}	D_{max} /m·s^{-1}
0.25	0.07	0.25	2.25	0.08	0.29
0.40	0.04	0.14	2.50	0.09	0.19
0.75	0.04	0.13	2.75	0.09	0.22
1.00	0.04	0.13	3.00	0.12	0.24
1.40	0.06	0.20	3.25	0.13	0.28
1.75	0.08	0.24	3.50	0.11	0.29
2.00	0.07	0.14			

From Table 1 it could be noticed that larger RMS errors occurred when the vehicle moved faster, with largest error values at 3.1, 3.25 and 3.5 m/s of v_d. $D_{\max}$ followed almost the same rule. And its largest values were found at 2.25, 3.25 and 3.5 m/s of v_d. One reason for such results was that PID parameters of the speed controller kept constant all through the experiments after being determined by optimizing the running performance at around 1 m/s. For lower or higher running speeds, adaptive PID controllers could be an effective solution to achievement of high accuracy. Another reason was that the speed measurement interval was fixed at 200 ms, which resulted in a relatively large delay in appropriate outputs of the controller. Since the electric off-road vehicle was developed mainly for agricultural navigation at a low speed of around 1 m/s, its running accuracy could meet the system requirements.

3.2 Evaluation of the off-road robot in autonomous map navigation

One of potential applications of the newly developed off-road robot was to use it to autonomously transport agricultural materials from the fuelling station to a target location around the field. With such autonomous runs, the multi-respect performances of the field robot in maintaining speed, operating switched circuit and especially automatically steering the vehicle could be evaluated at the same time. An autonomous navigation system already developed using RTK-GPS and IMU by the Laboratory of Vehicle Robotics at Hokkaido University was integrated into the vehicle network.

During field experiments, the navigation system determined and sent commands of φ_d and S_d on the network and also recorded the actual trajectory with the RTK-GPS. A navigation map was first generated according to the transportation task with the start point A and the target point E on the field road as shown in Figure 10. And three turns existed at B, C and D. Locations of five key points including A, B, C, D and E were measured using the vehicle RTK-GPS. Then navigation points were interpolated between A and B, B and C, C and D, D and E, respectively, to create the navigation map.

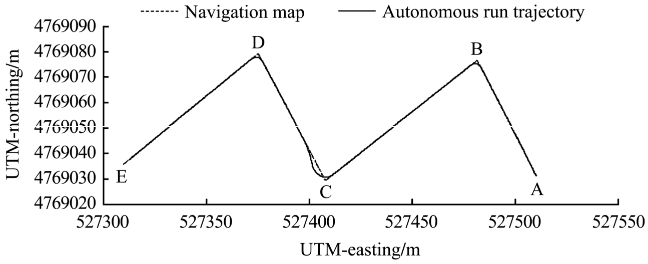
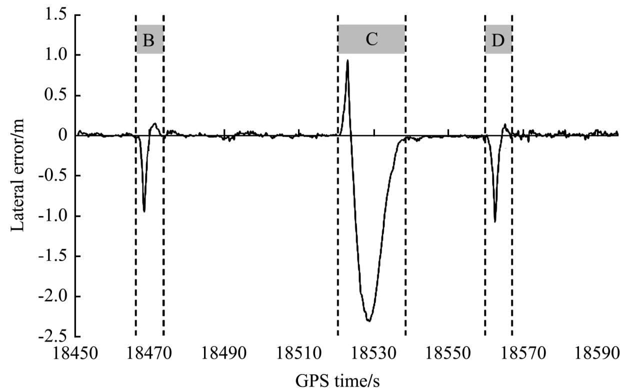
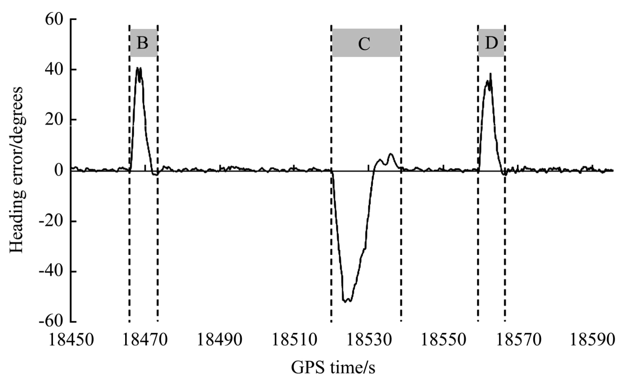


Figure 10 Autonomous run in the field

In the autonomous run, the robot vehicle started at A and turned at three corners with a right turn at C and two left turns at B and D. In Figure 10 it is obvious that the field robot deviated a lot from the desired trajectory because the maximum steering angle of the front wheels was 21 degrees for right turning, resulting in a larger turning radius than that when turning left. Both lateral and heading errors are shown in Figure 11.



a. Lateral error



b. Heading error

Figure 11 Performance evaluation of the steering system

From Figure 11 it could be seen that both lateral and heading errors were significantly large when turning around corners. This could be attributed to the kinematic characteristics of wheel-type vehicles in turning. On the other hand, results along straight lines shows high-accuracy path following with lateral error and heading error less than 10 cm and 1.5 degrees, respectively, which indicates that the automatic steering system is of fast responsibility and good accuracy in realizing desired steering angles.

4 Conclusions

In this research, the realization process of an electric off-road robot was introduced in technical details with respect to the development of an automatic steering system, a speed control system and a CAN bus-based communication network. Experiments were conducted in the field to verify its performances in controlling speed and following path. Results showed that the agricultural robot had a maximum RMS error of 0.13 m/s and a maximum deviation of 0.29 m/s when the vehicle moved up to 3.25 and 3.50 m/s, respectively. The lateral and heading errors were less than 10 cm and 1.5 degrees, respectively. Data listed above indicated that the newly developed off-road robot could meet requirements of most agricultural operations in terms of accuracy. For general purposes, this research was intended to illustrate a successful example in exploring the possibility of an agricultural robot from a view of feasibility and practicability. Therefore, it was possible for most researchers involved in agricultural engineering to establish a low-cost and versatile robot platform with functions like automatic steering and speed controlling by following the modification methods depicted in section 2. In the future, a machine vision-based navigation system would be integrated as one node into the CAN-bus network to guide the agricultural robot in performing variable applications like spraying and fertilizing in row-planted crops.

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