Development of the electric automatic steering system for agricultural vehicles

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Abstract: Automatic guidance of agricultural vehicles requires automatic execution of operation commands received from the navigation controller by using electronically controlled mechanisms for wheel steering, speed changing and work implementing. Automatic steering contributes as a prerequisite technique in automatic and semi-automatic agricultural navigation. This research aimed to develop an electric automatic steering system that was compact in its structure and integrated into original steering mechanism in a simply and convenient way for aftermarket modification. A brushless motor and reducer assembly was utilized to provide an adequate steering torque instead of manual maneuver. A rapid assembling approach was proposed by passing the steering shaft through the hollow output shaft. A digital proportional-integral-differential (PID) algorithm was implemented to calculate the rotation speeds and directions by comparing the desired angle and the actual angle, which was implemented in a printed circuit board with a microcontroller unit (MCU) and interface chips. An unmanned wheeled tractor was applied as test platform to integrate the newly developed electric automatic steering system. Tests were conducted to evaluate its performance in terms of stability and responsiveness. An autonomous navigation system guided the tractor along target paths in the field by sending steering commands to the electric automatic steering system. The results show that the steering angle error was less than 0.81° when desired steering angle was less than 10°. The lateral error difference was no more than 4.76 cm when repeating following the same target path, which indicated that the electric automatic steering system responded accurately and robustly to steering commands.

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1 Introduction

In agricultural production, off-road vehicles as important participants have been expected to be more efficient in cost reduction and more precise during farm work including sowing, harvesting and spraying[1-3]. Various technologies are increasingly applied to realize automatic and real-time control for all working parts by considering limitation of operators in manipulation experience and insufficiency in perception, which include hydro-static transmission, mechatronics, electro-hydraulic control, Geographic Information System (GIS), and Global Navigation Satellite System (GNSS), machine vision and automatic navigation[4-6]. Among those techniques, automatic navigation comes as the priority to guide off-road vehicles accurately along straight or zigzag paths, which is difficult for most operators, especially on a large-scale farm without referred markers.

A number of researchers make great efforts in fabricating automatic systems for operation of off-road vehicles featured hydraulic power assisted steering (HPAS) systems. The automatic steering system contributes as the actuator for executing commands generated by the navigation system, which intrinsically determines the navigation performance[7-10]. For aftermarket applications, solutions to automatic steering by using hydraulic power were adopted by some researchers and manufacturers with consideration that the hydraulic power could be bypassed from original pipelines to through the electro-magnetic hydraulic servo valves that automatically alter the hydraulic oil flow by receiving electrical signals[11-13]. Tayea and Zhang developed mathematical models for the electro-hydraulic (EH) steering mechanism to improve the dynamic performance of EH steering system for off-road vehicles. Steering controllers were designed to improve the dynamic performance in steering on different soil conditions[14,15]

Steering powered by electricity was commonly used for electric power assisted steering (EPAS) systems, which were mostly applied to automobiles[16-18]. Electric motors were integrated to generate robust and optimized steering torque for reduction of steering torque exerted by a driver and realize various steering functions. EPAS was increasingly adopted due to its advantages over traditional hydraulic power steering systems in efficiency and compatibility[19]. Inspired by use of EPAS and HPAS in automobiles and agricultural vehicles, this research proposed an integration of those two steering systems to realize automatic steering for agricultural vehicles by utilization of adequacy of hydraulic power and responsiveness and robustness of the electric motor. Such a proposal allowed a relatively low cost in modification of both hydraulic and mechanical

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systems, which would be preferred for aftermarket installation of agricultural navigation.

In this research, an electric automatic steering system was developed for agricultural vehicles with HPAS, which could automatically rotate the directional wheel to a target angle according to steering commands. The newly developed electric automatic steering system includes a brushless motor and reducer assembly to generate the steering torque to rotate the steering shaft without manual intervention. A compact mechanical structure was designed for users to conveniently install the assembly with reservation of manual operation. A digital PID controller was designed to calculate the rotating speeds and directions of the brushless motor and send control signals to the motor driver. To evaluate the stability and accuracy of the newly developed system, field tests were conducted by integrating the system into a wheel-type tractor as test platform, which was electronically automated in terms of transmission, clutching, travel direction and power take off (PTO) control based on the controller area network (CAN).

2 Materials and methods

The agricultural vehicle platform in this research was a wheeled tractor T954 by ISEKI, commercially available on the market as shown in Figure 1. This platform featured power steering, hydrostatic transmission (HST) and an electronically controlled wet-clutch system, which allowed operator to change travel directions by simply shifting a hydraulic shuttle lever. A dual-antenna RTK-GNSS receiver was adopted as the rover station for centimeter level high-accuracy positioning by using Trimble RTX service. A position antenna of the rover station was fixed on the left of the vector antenna by a base line of 1.4 m as shown in Figure 1, which was applied to acquire positioning in real-time and heading measurement by errors of less than 0.2°. An autonomous navigation system was developed[20] by the Shandong Laboratory of Dry Farming Machinery and Informatization at Shandong University of Technology (SDUT) in China, which has been integrated into the vehicle communication network. Operation commands were generated and distributed from navigation controller to automatic executing mechanisms including the newly developed automatic steering system during field tests.

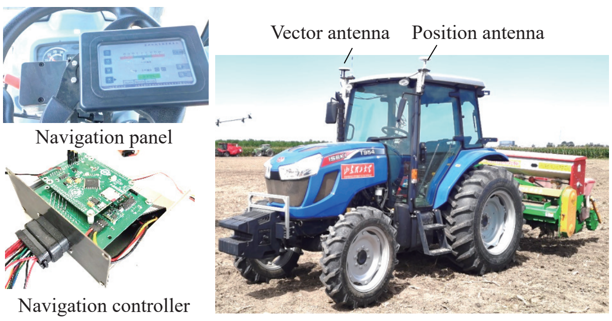


Figure 1 The wheeled tractor with the navigation system

2.1 Automatic steering mechanism

The steering wheel was originally handled by operators and the steering torque was conveyed to the hydraulic unit through the upper shaft and the gimbal. The required steering torque was relatively small with a maximum value of around 7.6 N·m since the hydraulic unit augmented the manual steering effort by regulating hydraulic energy, which made it possible that a relatively small torque generator was adequate for automatic steering.

A motor and reducer assembly was utilized as the torque generator, as shown in Figure 2. It featured a hollow output shaft that allowed the upper steering shaft to pass through by using the reserved keyed joint. The motor was a brushless one working at 12VDC with a nominal power of 100 W. The output torque generated by the motor was amplified to a nominal value of 12 N·m with a gear box as the reducer of ratio 50:1. Such an assembly had no static or holding torque when the automatic system was not at work. The steering wheel can be manually handled without removing the mechanical connection between the motor and the shaft. For compactness in mechanical structure and convenience in installation, a coupler and a metal frame were designed to connect the motor output shaft with the upper steering shaft, which has been applied to restrict rotation of the assembly by fixing it on the steering column.

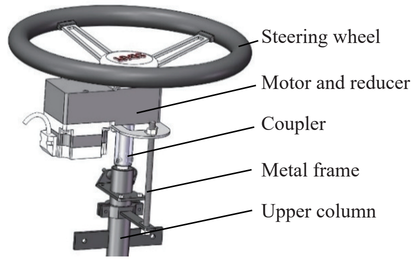
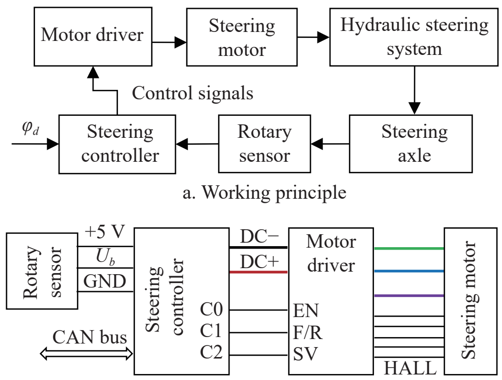


Figure 2 Installation of steering mechanism

2.2 Steering controller

Figure 3 depicts the electric automatic steering system with respect to its operational principle. A rotary position sensor based on touchless magnetic sensing technology with its transducer were mounted on the front axle. A magnet was fixed on the top of the kingpin of the front left wheel and rotated together with the front wheels, as shown in Figure 4. The rotary angle was output in the form of an analog voltage from 0.5 to 4.5 V, which indicated the steering angle value from –60° to 60°. The motor driver was of a common type available on the market. Necessary functions of the motor were realized by sending control signals to the driver including both rotary speeds and directions.



a. Working principle

b. Main components

Figure 3 Steering control system

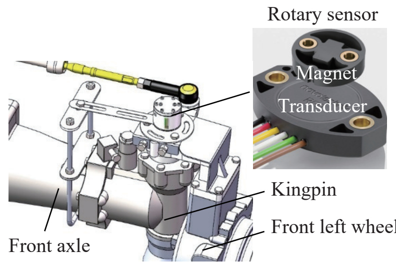
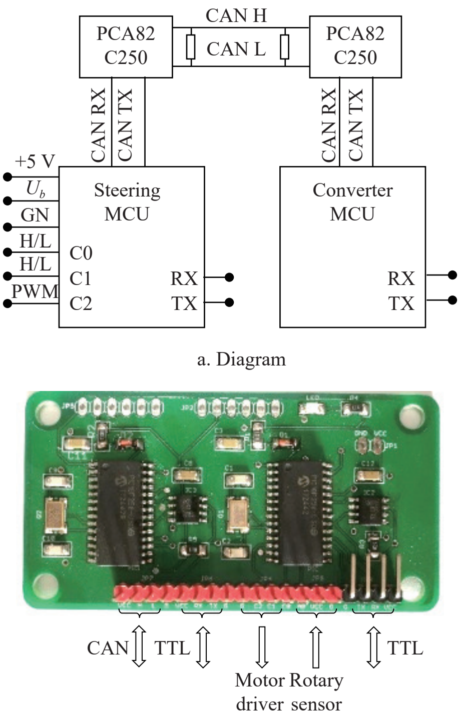


Figure 4 Installation of the rotary sensor

According to working requirements, the steering controller centered with an MCU of PIC18F258 by Microchip Technology Inc. was designed and manufactured, as shown in Figure 5. A pulse width modulation (PWM) signal was produced by this controller and output from pin C2 to the SV port of the motor driver at a frequency of 3 kHz. Its duty circle determined the motor rotary speeds, which needed to be calculated and configured in real-time by using the steering control algorithm introduced in Section 2.3. The function of the F/R port was to alter the motor rotary directions by receiving a digital signal in high/low voltage levels generated from the MCU digital pin C0. The EN port of the motor driver was connected to the MCU digital pin C1 for configuring the motor driver enable or disable. A CAN-bus controller chip PCA82C250 by Philips Semiconductors was applied as the interface between the CAN protocol controller embedded in the MCU and the physical bus, which was used for information exchange between the steering controller and other devices including the navigation controller. In this way, the MCU was committed to execute steering algorithm while reading steering commands from devices with the CAN interface. Another PIC18F258 MCU was used as a converter to receive data including steering commands from TTL serial port and distribute it onto the CAN bus.



a. Diagram

b. PCB board

Figure 5 Steering controller

2.3 Steering algorithm and its optimization

As illustrated in Figure 3, the analog voltage signal U_b from the rotary position sensor was collected and converted to a corresponding digital steering angle value φ_a by the MCU A/D converter module, which would be used together with the target steering angle φ_d to calculate the motor rotating speeds and directions.

According to the principles of kinematics and dynamics in the mechanical system, the motor rotor would experience a process from stop, acceleration, stabilization, deceleration to stop during the entire working path. This indicates that achieving automatic steering control needs to follow such a motion law. In this research, a digital PID algorithm was implemented as the steering control algorithm to determine the rotary directions and speeds according to Equations (1) and (2).

$$e(i) = \varphi_d - \varphi_a \tag{1}$$

$$S_i = K_P e(i) + K_I[e(i) - 2e(i-1) + e(i-2)] + K_D[e(i) - e(i-1)] \tag{2}$$

where, $e(i)$ is the difference between φ_d and φ_a, K_P, K_I and K_D are PID parameters.

The steering algorithm was embedded and implemented in the steering controller program, which was applied to determine output signals for pins of the steering controller connected to the motor driver. The proportional component $K_P e(i)$ determined the response rotational speeds to the steering command while the derivative component $K_D[e(i)–e(i–1)]$ made the steering controller react more strongly to the angle difference in a more stable approach. Since agricultural vehicles worked in fields with different soil conditions, the steering system was subject to different reacting forces generating from the interaction between wheels and soil. Besides, the steering power transmission process varied depending on agricultural vehicles. Consequently, the response time of the directional wheels during automatic steering was different, which required the PID parameters to be tuned in real-time to achieve adequate accuracy and responsiveness while working in the field.

3 Results and discussion

A series of field tests were conducted in the unmanned farm of Shandong University of Technology, locating at (36.8058°N, 117.9924°E) in Zibo, China. Accuracy and stability of the newly developed automatic steering system were evaluated by using the autonomous navigation system of the tractor, which was applied to send steering commands for map-based automatic guidance tasks.

3.1 Evaluation of steering stability

During farm working, the tractor needs to continuously keep its front wheels at a target steering angle in consideration that the field ground applies reaction forces to wheels and that directional wheels tend to restore straight due to intended design in the vehicle chassis. Consequently, the control stability contributes to as one of important evaluation indicators for the automatic steering system. During tests, the autonomous navigation system kept sending the same steering commands for each running at a frequency of 20 Hz to the steering controller. The tractor moved around in a circle with a certain radius. Figure 6 shows the trajectories of the tractor for seven typical runs by different steering angles.

The turning trajectory was recorded by reading positioning information from the RTK-GNSS receiver under the UTM coordinate system. Target steering angle φ_d of the front left wheel was calculated according to the desired steering angle φ_c of the front tread center by using the kinematic model of the tractor chassis. The actual steering angle φ_a of the front left wheel was recorded by reading measurement of the rotary sensor. Table 1 lists details for evaluation of steering stability when giving a constant value of φ_d that was plus when turning to the left and minus to the right. The maximum steering angle error was 2.35° on the right and 1.35° on the left. The RMS errors were less than 0.1°, which indicated adequate stability of the steering control. When the desired steering angle φ_c was less than 10°, the errors were no more than 0.81°. This revealed that the electric automatic steering system could ensure high accuracy in tracking straight paths since the tractor covered the field in straight target line and the desired steering angle fluctuated around 0° at most working times.

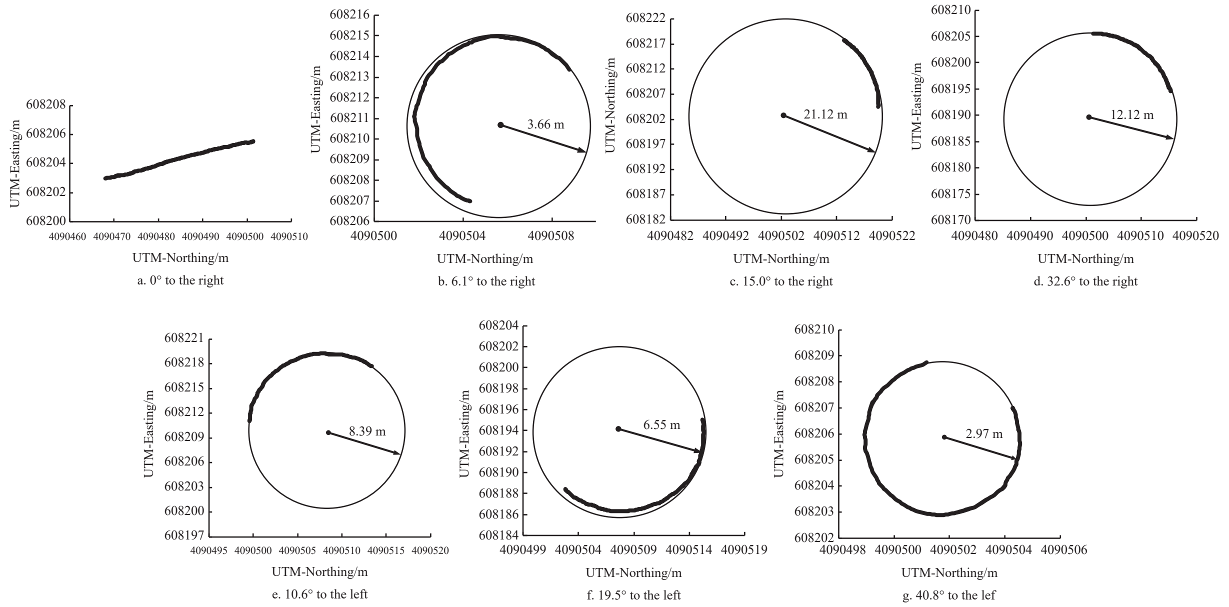


Figure 6 Turning by a target steering angle φ_d

Table 1 Evaluation of steering stability

Desired steering angle φ_c/(°)	Target steering angle φ_d/(°)	Average of φ_a/(°)	Turning radius R_A/m	Maximum error E_{max}/(°)	RMS error E_{RMS}/(°)
–39.5	–32.6	–30.85	3.65	**2.35**	0.01
–35.5	–29.7	–29.40	4.05	2.04	0.04
–27.5	–23.8	–23.70	5.18	0.84	0.02
–16.5	–15.0	–14.94	8.39	1.02	0.02
–6.3	–6.1	–6.40	21.12	0.74	0.03
0	0	–0.05	/	0.80	0.02
+10.0	+10.6	+10.71	12.12	**0.81**	0.03
+17.5	+19.5	+19.52	6.55	1.12	0.01
+31.5	+38.0	+32.73	3.22	1.02	0.02
+33.5	+40.8	+40.90	2.97	**1.35**	0.09

3.2 Evaluation of automatic steering in autonomous navigation

The autonomous navigation system developed by SDUT was adopted to send steering commands to the newly developed electric automatic steering system in automatic guidance for evaluation of the steering responsiveness by verifying its performance during path tracking. The target path was defined by navigation points, as shown in Figure 7. The desired steering angle was calculated by the autonomous navigation system[21] and executed by the newly developed electric automatic steering system.

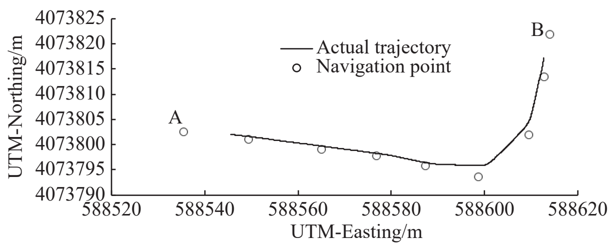


Figure 7 Autonomous navigation along the target path defined by navigation points

The tractor started around from the first navigation point A (588 535.620, 4 073 802.508) to cover each navigation point on the target path in turn and stop at point B (588 614.089, 4 073 821.883), which was repeated three times further for verification of replicability in following the same target path. Figure 8 shows variations of the lateral error, heading error and actual steering angle during run 1 along the target path. Those values during run 2 and run 3 presented a similar fluctuation by a small difference with respect to the lateral error, the heading error and the actual steering angle.

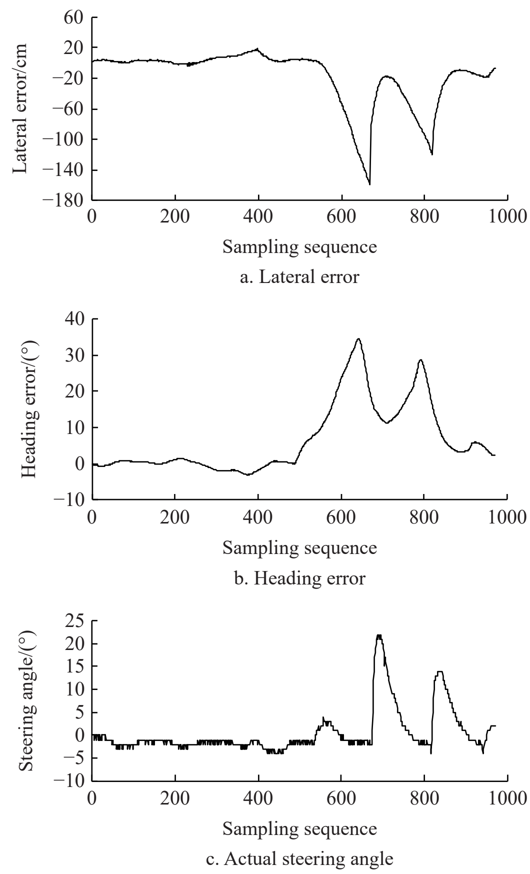


Figure 8 Performance of automatic steering in autonomous navigation

Variation of the lateral error difference between two runs at the same position was shown in Figure 9. The average of the lateral error difference D_{12}, D_{13}, and D_{23} between run 1 and run 2, run 1 and run 3, and between run 2 and run 3 was 0.17 cm, 0.40 cm and 0.24 cm, respectively. The maximum absolute value of D_{12}, D_{13}, and D_{23} was 4.64 cm, 4.76 cm, and 4.47 cm, respectively. And the RMS value was 1.19 cm, 1.07 cm, and 0.97 cm, respectively. It was indicated that the proposed electric automatic steering system could execute steering commands correctly and accurately.

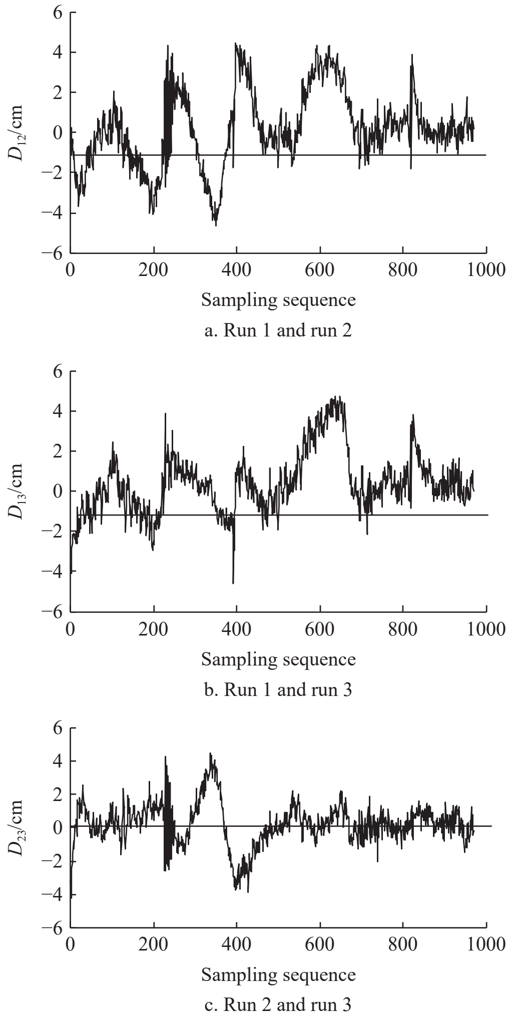


Figure 9 Variation of difference of lateral error between different runs

4 Conclusions

An electric automatic steering system was developed for agricultural vehicles, which could receive steering commands and rotate directional wheels of the agricultural vehicle to the desired angle. A ISEKI tractor commercially available was utilized as test platform to integrate the newly developed automatic electric steering system with the autonomous navigation system. During path following, the autonomous navigation system calculated the desired steering angle and sent commands to the electric automatic steering system so that the tractor was able to cover navigation points on the target path.

Turning tests resulting showed that the maximum steering angle error was 2.35° when the target steering angle was –32.6°. The steering angle error was less than 0.81° when desired steering angle φ_c was less than 10°, which illustrated that the newly developed electric automatic steering system could realize accurate and stable steering control in straight movement. Working performance was further evaluated with respect to responsiveness and replicability by using the autonomous navigation system to send steering commands for the automatic steering system to repeat following the target path by three times. The lateral error difference between two of three runs was no more than 4.76 cm and its maximum RMS value was 1.19 cm. That implicated the electric automatic steering system could respond accurately and robustly to steering commands distributed from the autonomous navigation system in practical applications. For general purposes, future work will focus on more validation experiments for applications on various agricultural vehicles.

Acknowledgements

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