Steering Actuator for Autonomous Driving and Platooning[*1]

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The New Energy and Industrial Technology Development Organization (NEDO) is running a "Development of Energy-saving ITS Technologies" project for the development of future technology meeting energy conservation needs. JTEKT has manufactured and supplied a steering actuator for the "R&D of autonomous driving and platooning" element of this project. This actuator is designed to maintain steering function even in the case that single-failure should occur on the ECU or motor. This report describes the results of steering performance evaluations both with and without single-failure.

***Key Words**: steering system, automatic driving system, Energy ITS, platooning*

1. Introduction

Approximately 20% of Japan's CO_2 emissions are generated from vehicles, making energy conservation in vehicle transportation an issue of increasing importance.

In 2008, NEDO implemented a five-year project called the "Development of Energy-saving ITS (Intelligent Transport System) Technologies." NEDO proposes that by introducing ITS, unnecessary acceleration/deceleration will be reduced, as will traffic congestion, etc., thereby alleviating fuel consumption. As one element of this project, research and development activities are being conducted for autonomous driving and platooning. This R&D is being carried out as a joint effort by the Japan Automobile Research Institute (JARI) and various industries, administrations and academic institutions, which are developing sophisticated element technology and test vehicles for substantiation.

Until now there have been many examples of autonomous driving and platooning using infrastructure[1), 2)] although only at a demonstrational level with nothing ever progressing to practical application. This project involves image processing using camera information, GPS, etc. and does not require any special road infrastructure. The aim is to develop a platooning technology which can be put to practical use, thereby improving mainstream logistics and conserving energy.

This report discusses steering actuator for autonomous driving and platooning that has been manufactured and supplied to the experimental vehicles for this project.

2. System Outline

Figure 1 is an outline of the autonomous driving and platooning project systems. The vehicle controller adjusts vehicle speed, direction, etc. based on information such as yaw rate and actual vehicle speed. In the steering system that JTEKT has designed and manufactured, steering angle is controlled in accordance with target values from the vehicle controller. The yaw rate, etc. generated in the vehicle is then fed back to the vehicle controller.

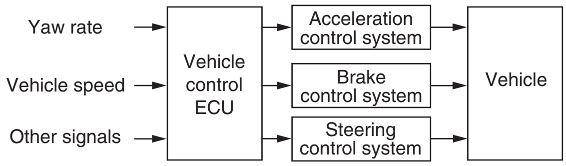

Fig. 1 Outline of autonomous driving system

Figure 2 gives the steering system of this vehicle. The experimental vehicle requires a large amount of torque to turn the wheels due to a large front wheel axial load. Consequently, this system requires not only a function to control steering angle but also a mechanism to assist steering torque. Hence, the existing hydraulic power steering has been used and an electronic actuator for controlling steering angle has been installed to the column.

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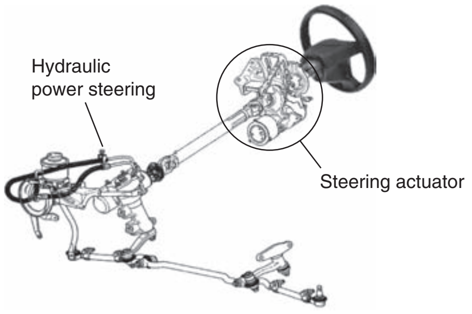

Fig. 2 Steering system

3. Actuator Performance Aims

The steering actuator for this vehicle requires the following performance.

(1) Steering performance

Steering angle control response and accuracy are important in achieving lateral displacement targets during platooning. **Table 1** shows the responses and resolution that would be required of the steering actuator. Target values were set with the cooperation of JARI, based on the steering angle target value data of the autonomous driving & platooning bus system[3] exhibited at Expo 2005 Aichi, Japan.

(2) Fault-tolerance

One of the aims of this research is verification of fault-tolerance assuming unmanned or hands-free vehicle travel. A redundant system was also studied in the name of securing vehicle safety in the case that faults occurred. This report discusses the results of the studies/verifications made on maintaining steering performance in the case of single-failure occurrence in the components of the developed steering system.

Table 1 Actuator specifications

Steering angle resolution		0.1 deg
Max. steering torque		10 N·m
Rated steering angular speed		310 deg/sec
Max. steering angle		±700 deg
Frequency response	Gain	0.9 Min. (at 3 Hz)
	Phase delay	45 deg Max. (at 2 Hz)
		90 deg Max. (at 3 Hz)
Step response	Angular speed	200 deg/s Min.
	Dead time	20 msec Max.
Ramp response	Delay time	80 msec Max.
	MAX deviation	10 deg

(3) Driver intervention requirement

It is assumed that during autonomous driving, intentional driver intervention (override) will be necessary at times to avoid danger, etc. In such cases the steering control must be stopped in order to prioritize driver operation.

4. Overview of System Design

4. 1 Overview of Control System Configuration

Figure 3 is an overview of the control system configuration. It is a parallel redundant system with CAN signal transmitting/receiving cables, power cables, motors and ECUs. An active redundant system is used for the drive of the two subsystems. This structure is also adopted in the steer-by-wire[4] fault tolerant systems currently in development. Compared to the back-up redundant system in which one subsystem is in a standby state, before the failure state duration without the failure judgment can be minimized. Also, because there is no changing over to the standby side, steering angle control can be continued without dead time or response delays.

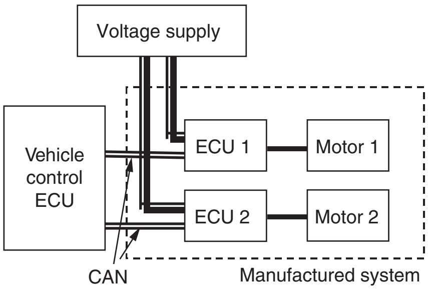

Fig. 3 Redundant system

4. 2 Mechanical Elements

Figure 4 shows the actuator appearance. The two previously mentioned motors are connected to the steering shaft through the reduction gear. Design of the main mechanical elements is as follows:

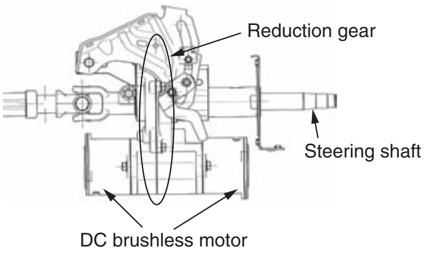

Fig. 4 Actuator appearance

Reduction gear: To achieve the necessary reduction ratio within limited space, a double reduction gear comprising steel helical gears was used (**Fig. 5**). The parallel arrangement of the motor shaft and the steering shaft satisfied the modification requirements of the column area on the test vehicle. Furthermore, the helical gears aim to reduce friction and provide high transmission efficiency and control performance. The stable strength characteristic of steel gears also contributes high reliability.

Motor: A synchronous DC brushless motor was adopted to achieve high control performance and maintainability. A resolver with superior durability and reliability was installed inside the motor as a rotating angle detection sensor.

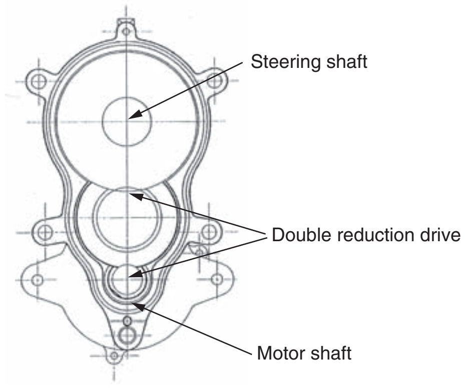

Fig. 5 Reduction gear

5. Actuator Control

5. 1 Steering Angle Control

Figure 6 is a control block diagram of a motor/ECU parallel redundant system control. Steering angle target identical values θ_1^*, θ_2^* are sent from the vehicle controller via the independent CAN network bus of the parallel system, to each steering controller. The two independent steering controllers calculate the motor current target values of i_{m1}^*, i_{m2}^* based on the deviation between θ_1^*, θ_2^* and the actual steering angles θ_1, θ_2. PWM control is also performed on the motor based on the deviation between i_{m1}^*, i_{m2}^* and actual current values i_{m1}, i_{m2}. θ_1, θ_2 are calculated from the motor rotating angle and reduction gear ratio K_G.

5. 2 Failsafe Control

This section explains the failsafe control of the steering system components. The two motors are constantly driven by independent steering controllers as explained in **Section 5. 1**. Each controller monitors faults in the power cable, sensor signal cable, etc. based on voltage and current values. If a fault is detected, the relays installed on the power cable and the motor cable will isolate the circuit. Thus, the steering function is maintained by the other controller in the case of single-failure. **Table 2** shows the main parameters for failsafe control.

Table 2 Failsafe specifications

Element in failure	Failure modes
Power supply	Wiring harness shorting
	Wiring harness earthing
	Low and high voltage
Motor	Wiring harness shorting
	Wiring harness earthing
	FET shorting
Motor rotor angle sensor	Wiring harness shorting
	Wiring harness earthing
CAN	Fault of bus line
Control unit	Sticking of relay contact
	Fault of micro processor
	RAM error

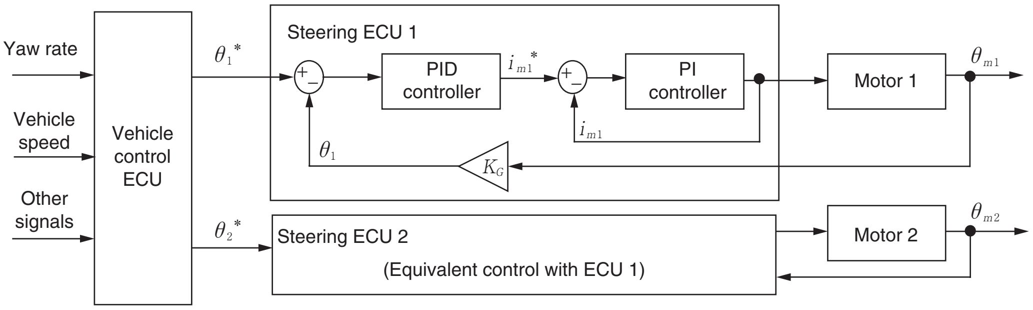

Fig. 6 Control block diagram

5. 3 Override Control

A function to stop the steering control and prioritize driver operation upon override has been introduced. The judgment criteria for override are given below.

Formula (1) shows the motion equation for the king pin perimeter of the wheels.

$$T_h + T_m + T_{assist} - T_{self} = I\ddot{\theta} + C\dot{\theta} + K\theta \tag{1}$$

T_h, T_m, T_{assist} indicate the conversion value for the torque at the king pin perimeter caused by the driver's steering, the steering actuator and the power steering assist. T_{self} is self-aligning torque. Here, the change of motor torque due to driver steering intervention is considered. Formula (1) can also be expressed as formula (2) below.

$$T_m + T_h = (I\ddot{\theta} + C\dot{\theta} + K\theta) - (T_{assist} - T_{self}) \tag{2}$$

For short durations of the steering control, the right side of formula (2) will be a constant value. Consequently, motor torque T_m will increase or decrease in response to steering torque of driver's override. Meanwhile, the maximum motor torque required for the steering control T_{mMAX} can be obtained from actual vehicle measurement. If the absolute value of motor torque T_m is sufficiently greater than T_{mMAX}, then the condition will be determined as override. It is possible to judge an override condition without any additional elements such as torque sensors, etc.

6. Actual Unit Performance Test

6. 1 Frequency Characteristic

This actuator has been installed on the test vehicle and the frequency characteristic has been measured. **Table 3** shows the measurement conditions, and **Fig. 7** shows the results.

As a result of tuning each control parameter, the target shown in **Table 1** (less than 90 degrees of phase delay at 3 Hz) was achieved. In high-speed travel situation, a highly stable robust system will be required for strong external disturbance such as side winds, etc. For this reason, the frequency characteristic was measured at the presumed speed of autonomous driving/platooning of 0 to 80 km/h, it has been confirmed that the characteristic was sufficient and not dependent on vehicle speed.

Table 3 Frequency response test conditions

Vehicle speed	10 km/h
Input steering angle	±5 deg
Frequency	0 – 10 Hz

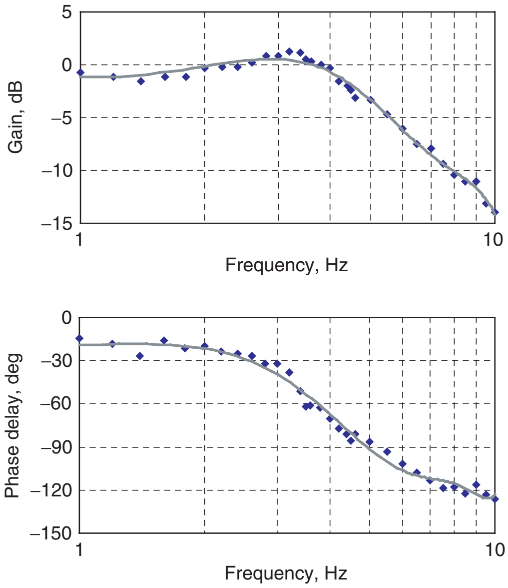

Fig. 7 Frequency response characteristics

6. 2 Steering Performance at Single-Failure

Steering performance at single-failure occurrence has been measured. **Table 4** shows the measurement conditions, and **Fig. 8** shows the results.

Table 4 Single-failure test condition

Input steering angle	Sine wave (±30 deg/1 Hz)
Failure mode	Motor angle sensor harness shorting
Output load	5 N·m (Powder brake)

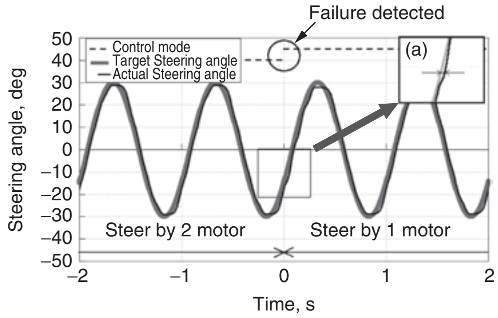

Fig. 8 Steering angle response at single-failure occurrence

The broken line in **Fig. 8** is the control mode within the ECU1 and shows that a failure judgment signal was artificially sent to ECU1 at 0 seconds. After a failure condition was judged, the steering function was continued by ECU2 and motor2. The actual steering angle is slightly fluctuated against the target steering angle (**Fig. 8**(a)) when a failure condition was judged. However, the fluctuation to the vehicle behavior has been minimized due to the function of the active redundant system. Also, around failure judgment, the deviation between the target steering angle and actual steering angle has been minimized, and it has been proven that the steering performance is maintained.

6. 3 Override Judgment

It has been confirmed that the steering can be released by driver intervention based on the above-mentioned override judgment. The detail is omitted the details from this report due to space restrictions.

7. Conclusion

A steering actuator has been manufactured and supplied for autonomous driving and platooning as a part of the "Energy ITS" project.

(1) This actuator has been designed using electric power steering and steer-by-wire development know-how against the steering performance targets required for autonomous driving and platooning, and it has been proven on the actual unit that performance targets are satisfied.

(2) This actuator is configured from a motor/ECU parallel redundant system in order to have sufficient reliability in the event of failure occurrence. Regarding a single-failure, experiments conducted on the actual unit proved that steering performance can be maintained.

(3) A function to judge intentional steering intervention by the driver during autonomous driving and stop the steering control has been introduced. This allows the driver's operations to be prioritized and aims to avoid hazardous situations.

It has been confirmed that the experimental vehicle equipped with this actuator satisfied the predetermined target performance (lateral deviation fluctuation amount with the lane) in platooning tests.

8. Acknowledgements

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