Development of Steer-by-Wire System (J-EPICS) with No Mechanical Link*1

K. NISHIMURA I. NAMIKAWA K. ABE Y. KAJISAWA R. YAMAZAKI

Future steering systems need to not only be compatible with automated driving systems, but also allow for improved driving space flexibility. To address these needs, we are currently developing a Steer-by-Wire system with no mechanical link. This document provides an explanation of the advantages of this new steering system, its concept of safety, and new technologies such as system redundancy and control based on the concept of safety.

Key Words: *steer-by-wire, ADAS, SBW, EPS, EE, BPS, J-EPICS*

1. Introduction

Recent years have seen a progression in the spread of Advanced Driver Assistance Systems (hereinafter, "ADAS") and their practical application for automated driving[1), 2)]. An example of this progression can be seen in Fig. 1, which shows a roadmap for the introduction of ADAS and automated driving systems in Japan[3)]. In Japan, vehicles compatible with Level 3 automation (Conditional Driving Automation)[4)] defined by the Society of Automotive Engineers of America (SAE) are currently being sold, and it is expected that automated driving technology equivalent to Level 4 (conditional automation of driver response when it is difficult to continue driving) will have become widespread by around 2030.

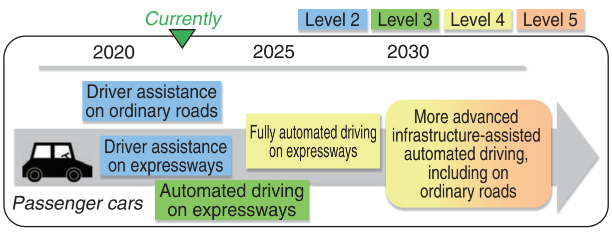

Fig. 1 Roadmap of introduction of ADAS and automated driving in Japan[3)]

Considering these developments, we assume that it will be necessary for steering systems to not only be compatible with ADAS and AD but also provide comfort and convenience during manual driving. Furthermore, in order to improve driving space flexibility, we can assume that the preferred layout for steering systems will feature two separate structures: Human Machine Interface (hereinafter, "HMI") unit for detecting hand wheel operation by the driver and Steering unit for controlling the road wheel angle based on the level of driver operation.

To address these needs, we are currently developing a Steer-by-Wire system with no mechanical link (hereinafter, "SBW"). This paper describes our development results of the system that can be mounted on a vehicle by implementing both system redundancy based on our concept of safety and new control technology. This system is the first implement example of J-EPICS (JTEKT Electronics Performed Intelligent Control Steering), which we define as the steering system that controls road wheel operation by electrical signals.

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2. Development Objectives and Issues

2. 1 Development Objectives

SBW uses electrical signals in place of mechanical parts to connect HMI unit and Steering unit, and has the following main features:

(1) Hand wheel operation and road wheel operation can be controlled independently.

(2) There is no mechanically connected structure between HMI unit and Steering unit.

(1) above is advantageous because it prevents interference between the road wheel angle and hand wheel operation during automated driving performed via ADAS-controlled driver assistance and vehicle system commands. This, in turn, improves compatibility between ADAS, automated driving, and steering functions. During manual driving, the amount of hand wheel operation relative to the wheel turning angle can be minimized

through adjustments made by controlling the angle ratio (gear ratio) of the road wheel angle (wheel turning angle) to the hand wheel angle. This makes it possible to improve comfort and convenience during hand wheel operation. Also, (2) above enhances the system mounting flexibility on vehicle. Furthermore, (1) and (2) above block unnecessary road vibrations during manual driving while enabling the transmission of necessary road surface information, making it possible to reduce driver fatigue while ensuring safety and security.

As described above, because SBW optimally combines manual driving with ADAS/automated driving, we expect that its application will increase in the future with the spread of automated driving.

2. 2 Development Issues

When developing SBW, the main thing one notices about its system configuration is that it differs from conventional electric power steering (hereinafter, "EPS") in that HMI unit and Steering unit are connected electronically instead of mechanically. This difference gives rise to two main issues:

(1) Ensuring safety in the event of system failure

(2) Basic function establishment when the system operates normally

In regard to (1), conventional EPS enables the driver to perform road wheel operation using hand wheel operation in the event of an electrical/electronic (hereinafter, "EE") system failure, by increasing manual steering torque due to the loss of assist torque. On the other hand, because SBW does not have a mechanically connected structure, the driver will not be able to perform road wheel operation using hand wheel operation in the event of EE system failure. For this reason, SBW must have a mechanism for ensuring the continuation of system operability in the event of a failure.

The specific issues presented by (2) are: providing a method of transmitting torque and steering angle information between units, synchronizing the operation of both units, and responding to phase shifts between the hand wheel angle and the road wheel angle.

We have remained focused on solving these issues over the course of our development.

3. Development Concept

The issue to which we give the highest level of priority during our development is ensuring the safety of the steering system. During our development, in addition to utilizing two independent EE systems for the purpose of ensuring operability in the event of a failure, we developed a configuration which uses the main battery for both systems when the power supply configuration is normal and which switches to a system-dedicated backup power supply (hereinafter, "BPS") in the event of a failure. This enables steering functionality to be maintained during any primary failure of EE system while allowing for subsequent evasive action. The power supply capacity of BPS is designed to enable the vehicle to be stopped safely on the road shoulder in most driving scenarios.

Figure 2 shows our concept of safety.

① The minimum level of steering functionality when one of EE systems fails is maintained by utilizing the one system that remains operable.

② The minimum level of steering functionality when the main battery fails is maintained by switching the power supply to BPS and utilizing one system within the range of BPS power supply capacity.

③ The vehicle is stopped in the vehicle lane when both systems fail.

Additionally, our development aims to achieve a level of performance equal to or higher than EPS during manual driving, while also providing high value-added performance that utilizes compatibility with ADAS and AD. In particular, as an approach to realizing performance

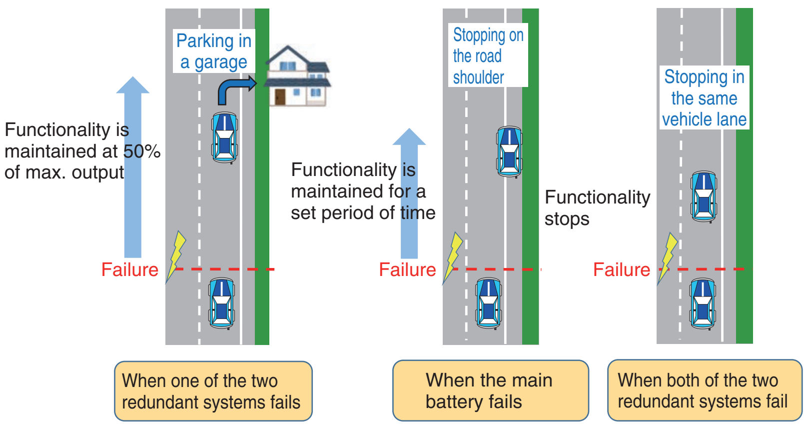

Fig. 2 Safety concept

during manual driving, this system is equipped with functions for adjusting the angle ratio between the hand wheel angle and the road wheel angle based on the steering angle, for appropriately transmitting road surface information to the driver, and for aligning the phases of the hand wheel angle and the road wheel angle.

4. Outline of the System Configuration

Figure 3 shows an outline of this system's configuration. The system is comprised mainly of HMI unit, Steering unit, BPS, and the power and signal harnesses that connect these components.

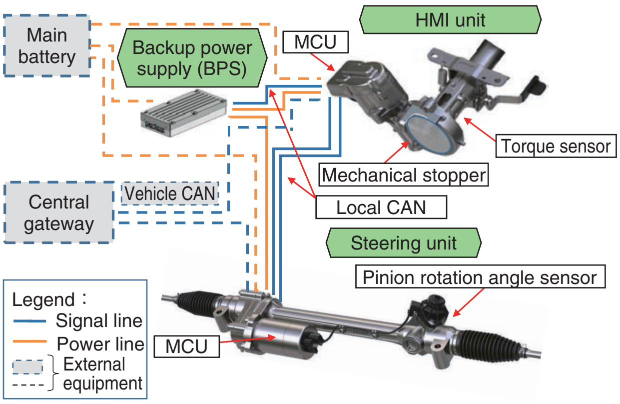

Fig. 3 SBW system configuration

HMI unit operates by detecting the level of hand wheel operation by the driver, after which it instructs Steering unit to turn the road wheel angle, and generates a reaction force appropriate for the hand wheel operation. Steering unit operates by controlling the road wheel angle and detecting information such as reaction force that is fed back from the road surface, which it then transmits to HMI unit. Both units are cooperatively controlled by their respective control software.

Angle and torque information required for control is calculated based on the detected values from the torque sensor of HMI unit, the pinion rotation angle sensor of Steering unit, and the motor rotation angle sensors of both units, which are then transmitted between both units. Local CAN is used to communicate information between the units and between HMI unit and BPS, while vehicle CAN is used to communicate information between vehicle systems.

This system is equipped with safety mechanisms in the form of two EE systems centered on a Motor Control Unit (hereinafter, "MCU") with an integrated motor and ECU, as well as BPS and prevention of hand wheel over-rotation (described later in **section 5. 3**).

Furthermore, in order to ensure reliability, HMI unit and Steering unit utilize technology from both column type EPS and rack parallel type EPS, which have a proven track record in mass production.

5. Safety

5. 1 Ensuring Safety in the Event of EE System Failure

Figure 4 shows an outline of EE system configuration. Both HMI MCU and Steering MCU feature configurations in which all EE components are redundant, including the control calculation units (hereinafter, "micro controllers"), motor drive units, motor coils, and sensors (torque sensor/motor rotation angle sensor). Each EE component is also arranged independently by being separated into those for system 1 and those for system 2. The motor drives one rotor based on the magnetomotive force generated by each of the motor coils of both systems. Furthermore, by establishing separate lines of communication between HMI MCU and Steering MCU for each system, the configuration is one in which the systems can operate independently of each other. Such a configuration enables system operation to continue even when any of EE components fail by using the normal system that has not suffered a failure.

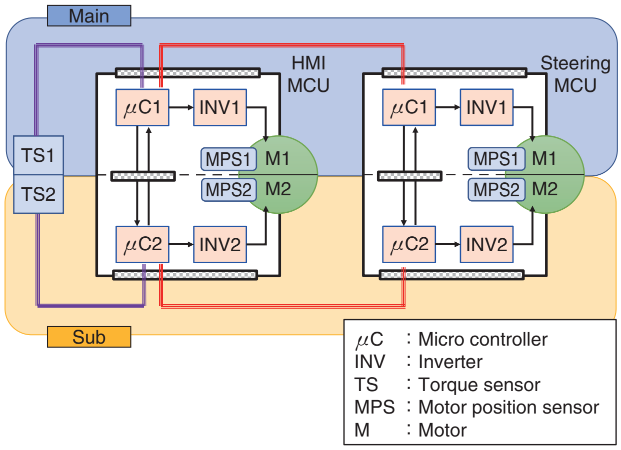

Fig. 4 EE system configuration

Figure 5 shows the system operation modes during an assumed failure. During normal operation, both systems cooperate in operating the system (SBW_Mode1: Cooperative drive). At this time, with system 1 acting as the main system and system 2 acting as the subsystem, information from other systems required for mode switching when a malfunction occurs is shared through information exchanges between both systems via communication between the micro controllers. Commands calculated by system 1 are then also shared and the motor of system 2 is driven based on those commands. If communication between the micro controllers fails, each system changes to a mode in

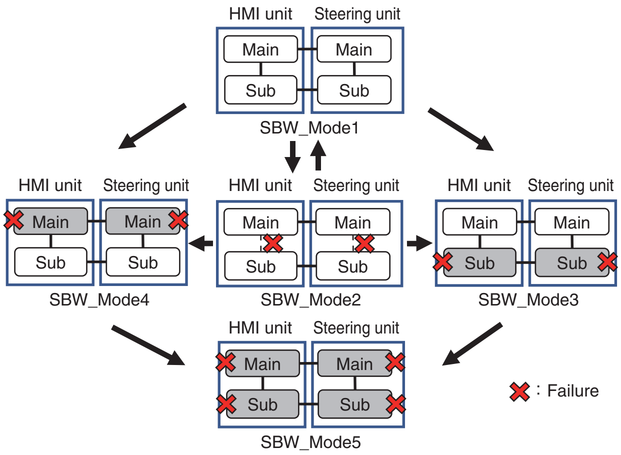

Fig. 5 System operation mode

which the motor is driven based on commands calculated by its own system (SBW_Mode2: Independent drive). Once it has been confirmed that system 1 is normal, the mode switches to one in which the motor is driven based on command values obtained by doubling the values calculated by system 1 (SBW_Mode3: One system drive). If a failure occurs in either system, the operation of the faulty system is stopped while communication between the micro controllers and between the units is continued. At this time, the mode switches to one in which operation is performed only on the side of the normal system (SBW_Mode3 / SBW_Mode4: One system drive). If a failure (secondary failure) then occurs on the side of the normal system as well, both systems are stopped (SBW_Mode5: Both systems stopped).

5. 2 Ensuring Safety in the Event of a Main Battery Failure

By using BPS in the power supply system, steering functionality can be maintained even if the main battery fails. **Figure 6** shows a power supply diagram. Normally, power is supplied from the main battery to system 1 via BPS. When the main battery fails, steering functionality can be maintained by having BPS supply power to system 1. At that time, because power stops being supplied to system 2, the mode switches to one system drive (SBW_Mode3) using system 1.

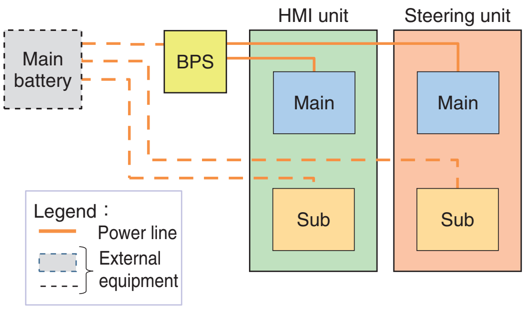

Fig. 6 Power supply diagram

5. 3 Safety Functions for Hand Wheel Usage

The fact that there is no mechanical connection between HMI unit and Steering unit (road wheels) may result in the failure of components such as spiral cables due to over-rotation of the hand wheel, and may cause drivers to feel inconvenienced because the hand wheel moves when they place their hand on it as they attempt to get in and out of the vehicle.

As a means of preventing over-rotation of the hand wheel, during system is power-on status, SBW system electrically generates a response (steering reaction torque) to contact with the rack end (hereinafter, “the virtual rack end reaction torque”) (**Fig. 7**) and communicates to the driver the fact that the rack bar of Steering unit is about to make contact with the rack end. Also, a mechanical stopper is used to prevent over-rotation when SBW system power is off and when the driver attempts to turn the hand wheel with a steering effort that exceeds the virtual rack end reaction force (**Fig. 8**).

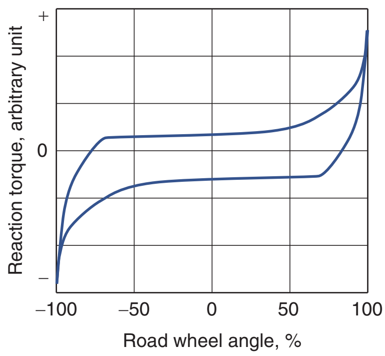

Fig. 7 Example of virtual rack end reaction torque

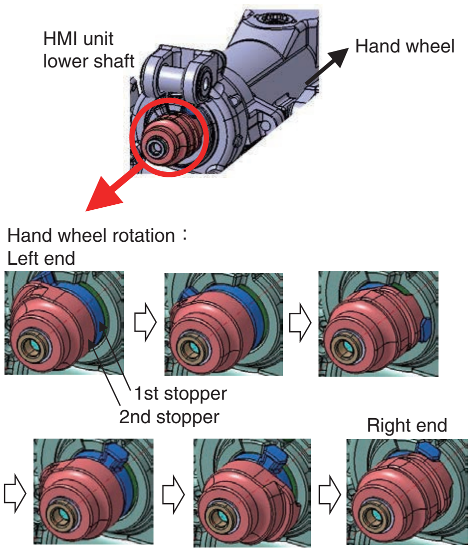

Fig. 8 Example of mechanical stopper

Because it is assumed that drivers may place their hands on the hand wheel when attempting to get in and out of the vehicle, the hand wheel has also been provided with a mechanical locking mechanism that activates when SBW system power is off.

The timing at which each of the above functions activate, as well as relationships between system modes, are shown in **Fig. 9**.

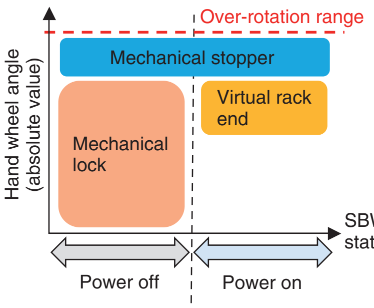

Fig. 9 Countermeasure concept for wheel over-rotation

6. System Control

6. 1 System Startup/End Sequence

Figure 10 shows a timing chart indicating the system startup and end sequence. The system starts up when the vehicle ignition is turned on, after which it performs an initial check. The steering lock then unlocks and the phases of HMI unit and Steering unit are then aligned. This alignment is performed because there is no mechanical connection between these units, which may result in the hand wheel angle and the road wheel angle being misaligned before system startup. Once the phase alignment is complete, the engine (READY) is turned on and BPS is activated, after which system control starts.

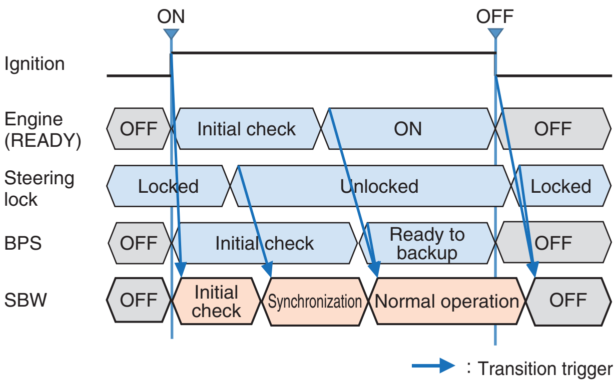

Fig. 10 Timing chart of SBW system

At system end, system control ends once the vehicle ignition has been turned off and the steering lock engages. This sequence prevents the hand wheel from freely turning when the system is stopped.

6. 2 Mode Switching in the Event of EE System Failure

We will now explain the mode switching described in **section 5. 1** using a specific example in which mode switching occurs in the event of failure. **Figure 11** shows an example in which a failure has occurred in the micro controller on the system 1 side of HMI MCU. In this case, HMI MCU immediately stops operation of system 1 and switches to one system drive (SBW_Mode4) using system 2. Although Steering MCU of system 1 is capable of operating normally, because its continued operation would complicate control being performed, all operation of system 1 is stopped in order to ensure reliability.

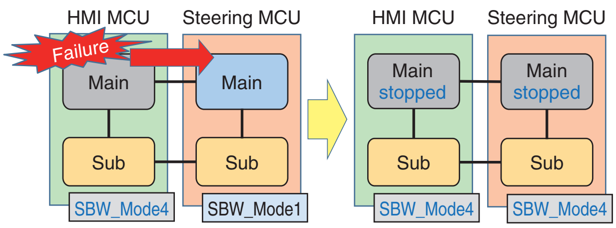

Fig. 11 Transition of SBW_Mode

6. 3 Switching in the Event of Main Battery Failure

In the power supply system described in **section 5. 2**, BPS detects the main battery failure and switches the power supply source for system 1 from the main battery to BPS internal power supply in order to continue supplying power to MCU.

7. Steering Control

7. 1 Control Outline

Figure 12 shows a control outline. HMI unit detects the hand wheel angle and sends that information to Steering unit. Steering unit calculates the target road wheel angle by taking into account factors such as the gear ratio based on the hand wheel angle, and performs angle feedback control based on the target road wheel angle and actual road wheel angle. Conversely, Steering unit detects things such as the motor current and the road wheel angle and sends that information to HMI unit. HMI unit then generates reaction torque based on the road wheel motor current, the road wheel angle, and the hand wheel angle.

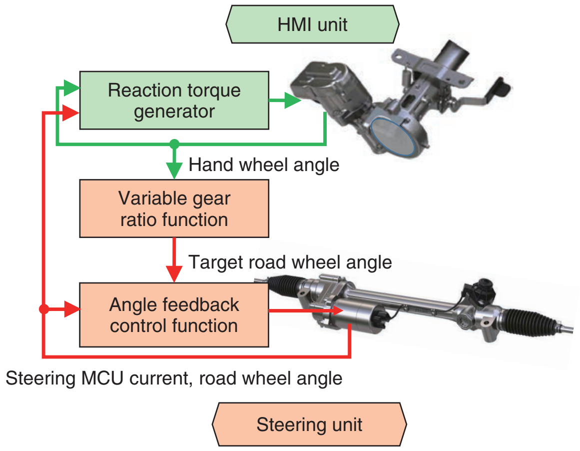

Fig. 12 Control outline

7. 2 Transmission of Road Surface Information to the Driver

Because there is no mechanical connection between HMI unit and Steering unit, a function is necessary for informing the driver of road surface conditions while driving. However, because there are certain types of information that should not be provided to the driver, such as brake vibration and kick-back on bad road surfaces, the driver is only provided with the necessary information. As shown in **Fig. 13**, HMI unit generates reaction torque based on the motor current of Steering unit. Because the current contains other information such as on the vehicle behavior and road surface, the driver can perform hand wheel operation based on that information, providing them with the same sense of security as a conventional steering system. Furthermore, if information transmission is unnecessary, HMI unit generates reaction torque based on the target road wheel angle obtained from the hand wheel angle. This reduces the driver's burden provided with unnecessary information.

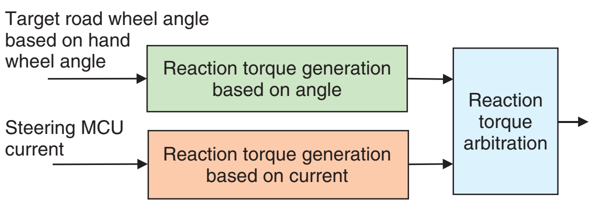

Fig. 13 Block diagram of reaction torque generators

7. 3 Transmission of System Status to the Driver

Because there is no mechanical connection between HMI unit and Steering unit, there may be instances in which the driver feels a sense of discomfort, such as when the hand wheel angle and the road wheel angle become deviate from each other due to the tires coming in contact with an obstacle on the road surface. For this reason, the system includes a function for notifying the driver when the deviation between the hand wheel angle and the road wheel angle exceeds a constant value. As shown in **Fig. 14**, when the angle deviation between the hand wheel angle and the road wheel angle exceeds a constant value, reaction torque is increased to both notify the driver that amount of road wheel operation is unable to keep up and to suppress road wheel operation by the driver in order to prevent angle deviation from exceeding the current amount.

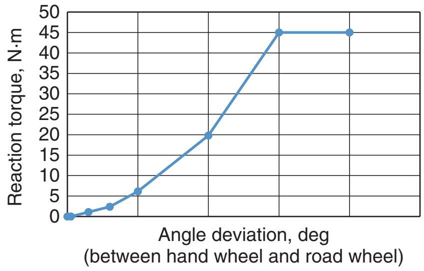

Fig. 14 Reaction torque against angle deviation

8. Conclusion

We have worked to develop SBW system that features excellent compatibility with ADAS and AD and that improves comfort and convenience during manual driving. Because we made ensuring system safety our number one priority during this development, we equipped the system with redundant EE systems and BPS to respond to EE system and power supply failures. Additionally, we have succeeded in developing a system that ensures safety by incorporating a function that limits the rotation angle to prevent hand wheel over-rotation. Furthermore, we have worked to ensure system reliability by employing technology established for EPS. On top of that, we have established basic SBW technology for achieving performance equal to or higher than EPS, such as phase alignment of the hand wheel angle and the road wheel angle.

In the future, we will continue to promote development with the aims of providing comfort and convenience during manual driving by taking advantage of SBW and realizing high added value by leveraging compatibility with ADAS and AD.

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K. NISHIMURA[*]


I. NAMIKAWA[**]


K. ABE[*]


Y. KAJISAWA[*]


R. YAMAZAKI[***]

* *Advanced System Development Dept., Automotive Business Unit*
** *Function and Software Engineering Dept., Automotive Business Unit*
*** *Engineering Planning Dept., Automotive Business Unit*