Pairdriver™
Steering Collaborative Control for Automated Driving[*1]

N. SHOJI T. NAKADE T. TAMURA R. FUCHS

Safety and comfort in automated vehicles are related to how the driver and the automation system cooperate during the driving task. We propose a control framework for electric power steering (EPS) where both manual and automated driving can coexist, and which enables cooperative driving. Sharing manual and automated lateral control provides a new driving experience, where the driver can steer the vehicle over the automation system without deactivation. Manual intervention is intuitive, as the driver only needs to hold, steer, and release the steering wheel. Furthermore, this control provides haptic information about where the automation system is heading when manually steering.

***Key Words**: shared control, human machine interaction, electric power steering, automated driving, ADAS*

---

1. Introduction

Safety in automated vehicles is related to how the driver and the automation system collaborate in the driving task[1)]. Intuitive and consistent operation of the vehicle up to SAE (Society of Automotive Engineers) automation level 4 through elaborated human-machine interaction is a key enabler for safety, comfort, and market acceptance of driving automation[2)]. This paper presents the control framework Pairdriver™[*2] for electric power steering (EPS), which enables manual and automated driving to coexist in order to achieve collaborative driving.

An overview of the prior art and of the proposed control is presented following the division of the driving tasks in **Chapter 2**. Issues related to control are defined in **Chapter 3**. **Chapter 4** provides details on the proposed control, and **Chapter 5** presents the results of verifications performed on an actual test vehicle. In **Chapter 6**, the extension of the proposed control is discussed and application examples are introduced in **Chapter 7**. Finally, the paper is concluded in **Chapter 8**.

2. Sharing the Driving Task

Driving collaboration is often simplified to the authority transfer between manual and automated driving at a low level of automation (SAE level 1 and 2). Override or takeover when using lane centering assistance (LCA) is straightforward as long as the level of intrusion remains low. Typically, if the driver opposes the LCA torque above a certain threshold, the function is automatically disengaged. Because of the low level of intrusion of such ADAS, the torque threshold is set to a relatively low value and a seamless transfer of authority is achieved. When the level of intrusion increases, or at higher level of automation (SAE level 3 and 4), higher performance of the angle control of the EPS is achieved, improving the capability of the vehicle in tracking the lane center[3)]. The angle control in automated driving mode and the assist control in manual driving mode oppose each other. A manual input is seen as a disturbance and is rejected by the angle control. Previous experiences have demonstrated that seamless and robust authority transfer is obtained by a weighted shared control mode during the transition[4)]. The proposed approach aims to combine automated and manual operations into a single, non-exclusive control mode using a weighting function during the transition triggered by the manually induced angle error. While authority transfers are well performed, the full potential of driver–automation shared steering control is not exploited.

The literature shows that the concept of shared control and, more generally, of mixing EPS assistance with angle

---

*[*1] This paper is a revised version of the paper published in the proceedings of technical paper presentations at the 2019 JSAE Annual Autumn Congress.*

*[*2] Pairdriver™ is a registered trademark of JTEKT Corporation.*

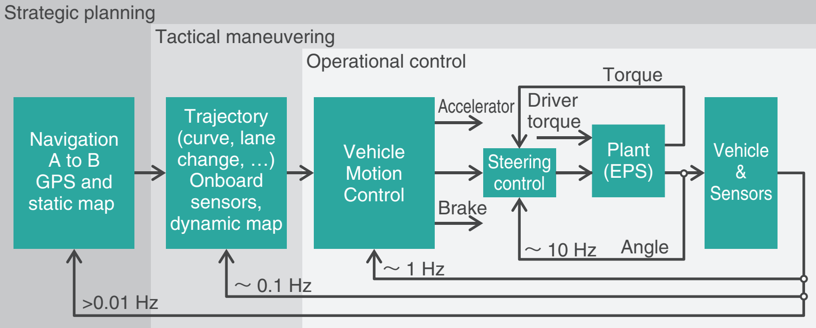

Fig. 1 Schematic structure of the automated driving control. Accelerator and brake controls are not illustrated for the sake of clarity

control has been addressed in various ways. The levels of implementation in the automated system (**Fig. 1**) and the variety of control objectives demonstrate the wide scope of applications and implication of this concept. However, many publications focus on how to prioritize the driver or the automation system and how to manage conflict, providing limited answers to the technical challenge of developing a control framework enabling both agents to coexist.

For example, Benloucif *et al*. propose a control that enables driver input by modifying the trajectory of the automated system accordingly5). This implies regular rerouting of the trajectory whose response is not likely to be optimal (slow bandwidth as indicated in **Fig. 1**). Cerone *et al*. introduce a combined automatic lane-keeping and driver steering with a 2-dof control at the lower level of vehicle motion control6). This has the benefit of offering faster response, although the goal is to enable an exclusive manual or automated control mode. Abbink *et al*. address the problem of shared control at the actuator level optimizing the response time7). The control is based on knowledge of neuromuscular control, which limits its market acceptance due to low robustness. More recently, Klesing *et. al*. presented a work on operating a steering system in a dual-model vehicle8). A shared control scheme is proposed for a steer-by-wire system where the two driving modes coexist only electronically. At first, the driver's performance in following the trajectory of the automated system is evaluated prior to enabling driver input as a command of the wheel angle control.

This paper presents a control framework for EPS where both manual and automated driving can coexist to enable collaborative steering. Shared control is implemented at the operational level1) (**Fig. 1**). Technically, the classical assist control of EPS active in manual driving and the angle control used for lane centering are mixed without internal modification in a two degree-of-freedom control architecture. It is a cost-effective solution because it relies solely upon the sensors available in mass-produced EPS. From an operational point of view, any manual intervention is intuitive as the driver only needs to hold, steer and release the steering wheel. No switch or button activation is required, reducing driver workload while improving comfort and safety. The driver naturally steers the vehicle over the automated actuation. Furthermore, this control provides haptic information regarding where the automation system is heading when manually steering.

3. Control Problem Formulation

The definitions of shared and collaborative controls used in this paper are first stated before formulating the considered problem. From a system (automated driving) perspective, the operational or actuator control receives a command from the higher tactical (guidance) and strategical (navigation) levels (**Fig. 1**). Shared control is implemented at the operational level or in the EPS. Human-machine collaboration is considered at the tactical or strategical level1).

The following specifications must be satisfied concerning the shared control problem under consideration:

- Prior to any driver steering action, the vehicle tracks the trajectory planned by the automated system in a continuous manner (no signal interruption).
- When the driver initiates a manoeuvre, the angle control remains active, but the vehicle trajectory is modified seamlessly (no external steering wheel jerk, i.e., a jerk that is caused by other sources than the driver).
- While steering, the driver feels a torque indicating, for example, where the AD is heading (haptic feedback for safety).
- If the driver releases his hands from the steering wheel when the vehicle is on the AD trajectory (i.e., the error of the angle control is null), the vehicle lateral motion is smooth (no external steering wheel jerk).
- If the driver releases his hands from the wheel when the vehicle deviates from the AD trajectory, the vehicle automatically returns to that trajectory (safe vehicle

return should be considered at tactical and strategical levels).

4. Haptic Shared Control of EPS

This section first describes the proposed haptic shared control of EPS. Afterward, its performance and haptic feedback are discussed along with test data.

4. 1 Control Structure

The structure of haptic shared control is illustrated in **Fig. 2**. $\theta_{\mathrm{m,\ ad,\ cmd}}$ is the automated driving (AD) angle command, $\theta_{\mathrm{m,\ md,\ cmd}}$ is the manual driving (MD) angle command, $\theta_{\mathrm{m,\ ma,\ cmd}}$ is the steering angle command, and θ_{m} is the actual steering angle. T_{d} is the driver torque, T_{tb} is the torsion bar torque, T_{m} is the motor torque, and T_{assist} is the assistance torque.

The manual reference controller (MRC) is used to enable the two agents to work together on the plant. Basically, it is composed of a model of the EPS (**Fig. 3**), which computes the angular displacement generated manually from the measured driver input. This angular component or MD command is then added to the AD command as input to be tracked by the angle controller. In this way, both AD and MD commands are tracked together by the EPS.

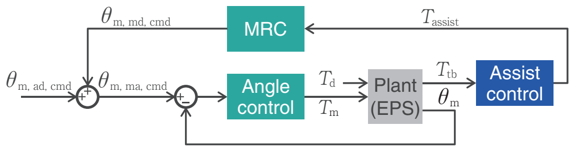

Fig. 2 Structure of haptic shared control

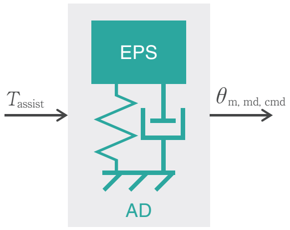

Fig. 3 Example of structure of MRC

4. 2 Haptic Feedback

One objective of haptic shared control is to provide haptic feedback to the driver while maneuvering. This function is realized with the load applied to the EPS model of MRC (**Fig. 3**). This load can be designed and tuned according to the steering feel, safety, and any other objectives. In its simplest form, this load is represented by a spring and a damper connecting the EPS inertia to the ground. Instead of using an absolute ground, a relative reference corresponding to the AD command is preferred. With this, the reaction torque felt by the driver is related to the manually induced deviation away from the AD trajectory. The content of this feedback can be designed, for example, to indicate the automation system heading direction. Furthermore, because of the spring effect, if the driver releases their hands, the steering wheel automatically returns to the AD trajectory. This provides significant benefits in terms of safety, firstly for the driver, as the haptic feedback informs them on where the AD is heading, and secondly for the vehicle, in case of driver misuse (e.g., the driver suddenly removing their hands from the steering wheel).

5. Actual Vehicle Verification

Figure 4 gives an example of shared control data measured on a vehicle equipped with an EPS. The AD trajectory follows the path of a winding road. Between about eight and fourteen seconds of the simulation, the driver steers the vehicle away from the roadwork. The steering angular displacement shows that the AD trajectory command is accurately tracked before and after the driver maneuver. During the driver intervention, the manual action is superimposed on the AD trajectory according to the stated objective. Furthermore, the EPS applies a small torque directed toward the AD trajectory as haptic information.

6. Function Extension

This chapter describes function extensions for the basic control structure described in **Chapter 4**.

6. 1 Extending Haptic Feedback

Section 4. 2 provided an explanation regarding haptic feedback as defined by springs and dampers. In this case, the characteristics of the reaction force felt by the driver remain constant regardless of driving conditions. Here, using a variable load according to driver and vehicle conditions is expected to improve the steering feel during manual intervention. For example, changing the characteristics of the springs and dampers according to the vehicle speed, or measuring the reaction torque from the actual road surface and setting the load accordingly are available options. Furthermore, using sensors such as cameras to recognize traffic environments would enable the provision of haptic feedback based on the position of the vehicle in the driving lane and its distance from obstacles. This would enable the driver to intuitively feel conditions around the vehicle via the steering wheel. In other words, because driving can be performed as collaboration between automated and manual steering, driving safety would be improved.

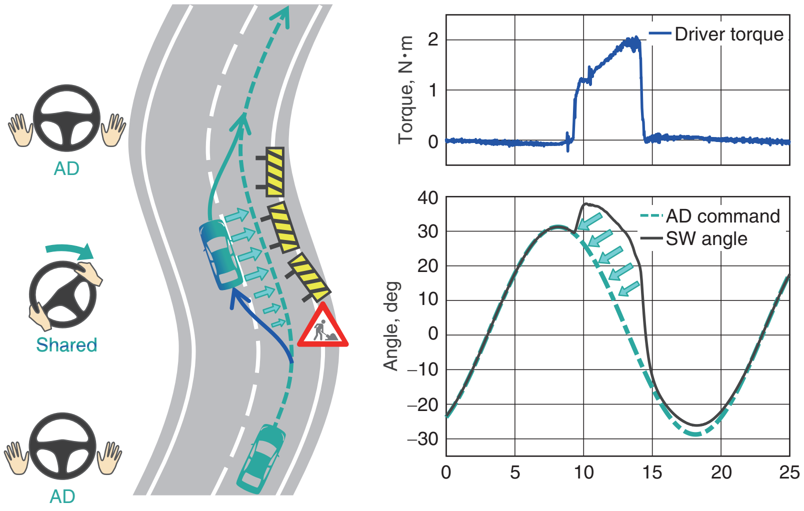

Fig. 4 Concept validation made on a vehicle equipped with an EPS. The AD trajectory follows the path of a winding road. At the location of the roadwork, the driver adjusts the position of the vehicle. During this manual intervention, he feels a small torque in the direction of the AD trajectory.

6. 2 Shift to Manual or Automated Control

The previous section presented haptic shared control that enables AD and MD to coexist. There is no switch or weighting function for setting the steering mode. However, a means to allocate the steering control authority is still required for safety reasons. This will allow prioritization of manual, automated, or shared mode according to higher-level instruction. The tactical and strategical controls are responsible for evaluating the traffic context as well as the driver awareness and readiness necessary for the priority decision process.

One way to extend the proposed configurations is by adding a control authority selector after the AD and MD commands (**Fig. 5**). Continuous and smooth fade-in/out functions are preferred to ensure seamless prioritization. For example, when driving in shared mode, if a transition to manual is required, selector weighting over a certain period of time will gradually shift the control authority. However, this would require the characteristics of the control authority selector to be appropriately set depending on the conditions. For example, it would also be necessary to have a setting for giving priority to automation during emergency avoidance by immediately switching to automated mode.

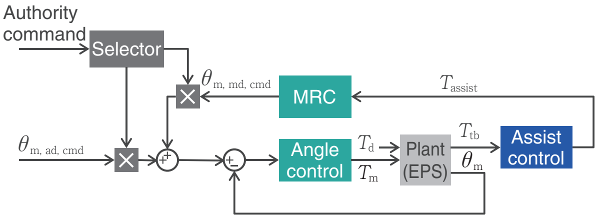

Fig. 5 Haptic shared control framework. The selector function enable an external input to allocate the steering mode to manual, shared and automated steering.

7. Examples of Applications

This chapter introduces examples of applications for the proposed shared control. It shows that well-known steering functions required in automated vehicles do not require separate development. The proposed shared controls enable most of these issues to be addressed within a single and generic framework.

7. 1 Lane Centering Assistance and Lane Keeping Assistance

Level 1 and 2 vehicles, in which the driver is the main operator, are equipped with functions that assist the driver in keeping the vehicle at the center of the lane and in the lane. Shared control can be applied because it enables guidance towards the lane center by superimposing assistance torque on the manual steering. Typically, the assistance function is deactivated when a large amount of driver steering torque is applied. Applying the configuration shown in **Fig. 5** enables smooth shifts between manual mode and shared mode, depending on the steering torque. However, override free assistance is possible because of the absence of conflict in shared control even when high manual torque is applied.

Furthermore, shared control can be used for lane keeping assistance. This function generally alerts the driver by adding guidance torque for returning the vehicle to the lane center when the distance between the vehicle and lane markings falls below a certain threshold. Shared control is expected to improve safety because it enables the virtual load of MRC to be adjusted based on the distance to the lane edge, thereby enabling enhanced control of the reaction torque to the driver operation.

7. 2 Road Narrowing

Drivers often encounter road narrowing, for example, at locations where roadwork is taking place. Intuitively, they adjust the vehicle position between the lanes and sometimes cross a lane in order to feel safe in the changing road condition. For a driver in an automated driving vehicle, such a situation might be uncomfortable if enough space remains within the lane but the safety margin of the vehicle position becomes narrower. Moreover, if a lane has to be temporarily crossed, the automation system might face limitations. In both cases, shared control enables the driver to momentarily adjust the vehicle position manually without deactivating the automated driving system (**Fig. 6**).

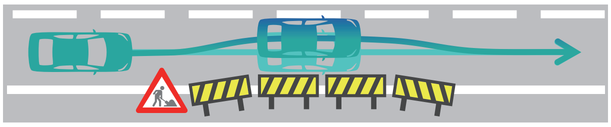

Fig. 6 Example of adjustment of vehicle positioning using shared control. During the driver intervention, the AD remains active.

7. 3 Evasive Steering Assist and Automated Emergency Steering (AES)

Evasive steering assist and automated emergency steering are technologies that are recently gaining particular attention because of their potential in providing additional contributions to vehicle and road safety[9]. The former technology assists the driver after detecting their intention in initiating an evasive maneuver. A small torque is added to that of the driver for facilitating collision avoidance. The responsibility remains that of the driver as the function is active only while manually steering. Similarly to the application of guidance, shared control can be applied to superimpose the evasive assist torque.

AES is more complicated as the driver is no longer responsible. Technically, such a function has at least two additional constraints. The first is to avoid causing another accident during the emergency maneuver, especially if it is necessary to cross lanes. The second is to ensure no harm to the driver when the steering wheel is subjected to an abrupt and large angular displacement. The SBW system and angle overlay device offer hardware solutions to this second issue but at a cost that is not acceptable for all vehicles. Shared control provides a partial but cost-competitive solution because of the compliance with driver input. Indeed, if one of the driver's arms is placed inside the steering wheel, the force felt by the driver will be that generated by the spring in the sharing controller (**Fig. 3**) rather than that developed from the maximum torque of the assist motor. Driver injury is prevented at the cost of a deviation from the AD trajectory.

7. 4 Take Over Request (TOR)

TOR is a demand sent by the vehicle to the driver asking to regain manual control in the case of an anticipated limitation of the automation system (**Fig. 7**). Safe operation of the TOR has generated significant attention due to the complexity of setting a reasonable timeframe for the driver to recover their awareness of the traffic situation. Shared control offers a partial solution to the problem of authority transfer by avoiding an exclusive interpretation. It can be activated instantly when the TOR is released, enabling manual steering without immediate disengagement of the AD mode. When the driver feels confident in regaining control of the vehicle, they can turn off the shared mode. Even in a worst-case scenario in which the driver fails to manually take control of the vehicle, a minimum-risk maneuver can be launched without any particular setting of the EPS control. This illustrates the consistent operation of the proposed framework.

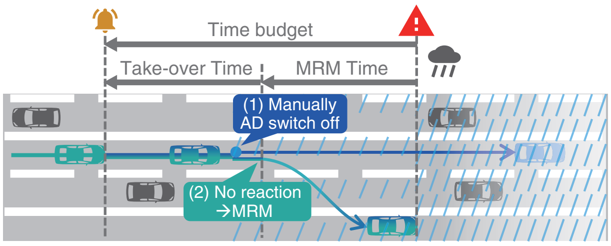

Fig. 7 Application to a TOR. Shared control is set immediately after the release of the TOR enabling the driver to steer at any time. Only confirmed operation of the driver can turn-off the AD mode. Furthermore, shared control can remain active when launching the minimum risk manoeuvre in case of no reaction from the driver.

7. 5 Override Function for SBW Systems

In terms of driver comfort, one of the benefits of the SBW system in automated driving vehicles is that it enables the steering wheel position to be locked. Conversely, a drawback of a fixed steering wheel arises during a driver takeover operation when the steering wheel is not aligned with the wheels. If an angular synchronization is required, robot-like control (e.g., position control) is performed initially to cancel the angular offset. The time allotted for the angular synchronization should be short enough so as not to constrain the driver in his maneuver but long enough to prevent discomfort caused by too fast motion of the steering wheel. Shared control provides a solution to these issues.

As shown in **Fig. 8**, implementation is possible in a two-stage form with the first stage applied to the rack (gear) and the second to the steering wheel with the reaction force unit (column). In this implementation, the angular synchronization is triggered by the detection of the driver's hands on the steering wheel (e.g., using a hands-on detection function). The first advantage of applying the proposed control is that driver intervention is enabled at any time throughout the synchronization. The second advantage comes from the steering wheel compliance that guarantees no harm to the driver during sudden motions. In practice, the following two extreme patterns are possible. Firstly, the driver holds the steering wheel without applying much torque. In this case, the steering wheel aligns with the wheels. Secondly, the driver firmly holds the steering wheel. Here, the wheels align with the steering wheel.

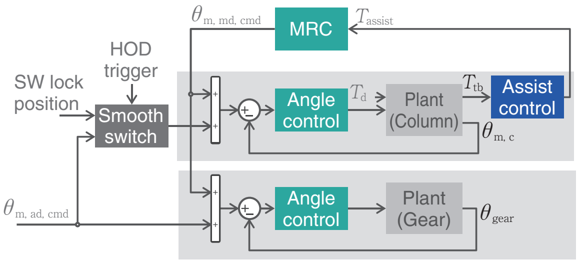

Fig. 8 Example of haptic shared control applied to a SBW system. The selector function for the driver input is replaced by a smooth switch function triggered by the detected hands state. For the sake of clarity, the selector functions for the steering authority allocation are not shown.

8. Conclusion

The proposed haptic shared control has been presented as a generic control architecture for EPS where both manual and automated steering can coexist. During shared steering mode, the collaborative characteristics can be tuned in a flexible manner by controlling haptic feedback via the manual reference controller. Moreover, shifting between manual, shared, and automated steering modes is possible by applying a smooth control mode selector. Haptic shared control provides solutions to various functional requirements of EPS in highly automated vehicles within a single, computationally efficient, and consistent framework.

Technically, the concept is cost-efficient and has good adaptability based on the existing hardware. The mature technologies of steering assistance and angle control can be implemented in their original form and can still be independently improved. Only an additional controller of limited computational load is required to blend the two controls.

From a driver perspective, haptic shared control enables AD and MD to be active at the same time without the need for manual switching. Naturally, the driver can steer over the AD operation. Conversely, they feel the AD heading direction through haptic feedback.

References

1) F. Flemisch, D. Abbink, M. Itoh, M-P. Pacaux-Lemoine, G. Webel: Shared Control is the Sharp End of Cooperation: Toward a Common Framework of Joint Action, Shared Control and Human Machine Cooperation, IFAC PapersOnLine, Vol. 49, No. 19 (2016) 72-77.
2) Surface Vehicle Recommended Practice – Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, J3016, SAE International (2014).
3) A. Seeck: Automated Driving: German Status and Euro NCAP's Approach, NCAP & Car Safety Forum, Tokyo (2018).
4) M. Moreillon, T. Tamura, R. Fuchs: Transfer of Lateral Control Authority for Automated Vehicles, JSAE Congress (Autumn), Nagoya (2018).
5) M. A. Benloucif, A. T. Nguyen, C. Sentouh: A New Scheme for Haptic Shared Lateral Control in Highway Driving Using Trajectory Planning, 20th IFAC World Congress, Toulouse (2017).
6) V. Cerone, M. Milanese, D. Regruto: Combined Automatic Lane-Keeping and Driver's Steering Through a 2-DOF Control Strategy, IEEE Trans. On Control Systems Technology, Vol. 17.1 (2008) 135-142.

7) D. A. Abbink, M. Mulder, E. R. Boer.: Haptic Shared Control: Smoothly Shifting Control Authority, Cognition, Technology & Work, Vol. 14.1 (2012) 19-28.
8) J. Klessing, J. Zuraski, A. Rezaeian: Steering on Demand for Dual-Mode Vehicles, 9th International Munich Chassis Symposium 2018, Springer Vieweg, Wiesbaden (2019) 539-549.
9) Euro 2025 Roadmap, In Pursuit of Vision Zero, Euro NCAP, (2017).

N. SHOJI[*] T. NAKADE[**] T. TAMURA[**]

R. FUCHS[**]

* *Advanced System Development Dept., Automotive Business Unit*
** *Systems Innovation R&D Dept., Research & Development Division*