Automated Driving System Architecture to Ensure Safe Delegation of Driving Authority

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Abstract. In this paper, the architecture of an automated driving system (ADS) is proposed to ensure safe delegation of driving authority between the ADS and a driver. Limitations of the ADS functions may activate delegation of driving authority to a driver. However, it leads to severe consequences in emergency situations where a driver may be drowsy or distracted. To address these issues, first, the concept model for the ADS in the situation for delegation of driving authority is described taking the driver’s behaviour and state into account. Second, the behaviour / state of a driver and functional flow / state of ADS and the interactions between them are modelled to understand the context where the ADS requests to delegate the driving authority to a driver. Finally, the proposed architecture of the ADS is verified under the simulations based on the emergency braking scenarios. In the verification process using simulation, we have derived the necessary condition for safe delegation of driving authority is that the ADS should assist the driver even after delegating driving authority to a driver who has not enough capability to regain control of the driving task.

1. Introduction

Recently, Advanced Driver Assistance Systems (ADAS) are already common technology and widely adopted in automobiles [1]. The tendency of automated driving from driving with ADAS has been accelerated and technology for realizing automated driving is being developed [2]. Automated driving improves road safety and traffic efficiency, but also changes the role of the driver and requests new tasks depending on the traffic situation and the automation level [3]. For example, according to the SAE international specifications [4], at automation level 3, the longitudinal and lateral driving of the ego vehicle are controlled by the automated driving system (ADS) instead of the ego-vehicle driver. However, the ego-vehicle driver has responsibilities for automated driving of the ego vehicle at any time. Here, an ego vehicle is a vehicle equipped with an ADS and an ego-vehicle driver is a person who operates the ego vehicle. The ego-vehicle driver does not need to continuously monitor the ego vehicle but should be required to regain control of the driving task from the ADS (called delegation of driving authority), especially due to the limitations of the ADS functions [5]. Previous research on the delegation of driving authority from automated to manual driving and vice versa shows that safety can be highly dependent on the driver state/behaviour [6-7]. Delegation of driving authority will lead to severe consequences in emergency situations where the ego-vehicle driver may be drowsy or

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distracted. Therefore, for automated driving safety, issues related to the delegation of driving authority must be resolved.

In this paper, architecture of the ADS is proposed to ensure safe delegation of driving authority between the ADS and the ego-vehicle driver. First, the concept model for the ADS in the situation for delegation of driving authority is described taking the ego-vehicle driver’s behaviour and state into account. Second, behaviour / state of the ego-vehicle driver and functional behaviour / state of ADS and interactions between them are modelled to understand the context where the ADS requests to delegate the driving authority to the ego-vehicle driver. Finally, the proposed architecture of the ADS is verified under the simulations based on the emergency braking scenarios. In the verification process using simulation, we have derived the necessary condition for safe delegation of driving authority that the ADS should assist the ego-vehicle driver even after delegating driving authority to the ego-vehicle driver if her / his capability is not enough to regain control of the driving task. The behaviour / state of ADS and ego-vehicle driver are described using the System Modeling Language (SysML) [8]

2. Automated driving system

2.1. Concept model of automated driving system

The concept model of ADS in the situation for delegation of driving authority is presented in Figure 1. In the automated driving mode, the ADS controls the vehicle and provides information related to the surrounding environment or the intent of the ADS operation. The ego-vehicle driver also monitors the ADS operation, the surrounding environment’s state and the ego vehicle’s state. When the ego-vehicle driver is requested to regain control of the driving task from the ADS due to the limitations of the ADS functions, the ADS should determine whom to delegate the driving authority to considering the ego-vehicle driver’s behaviour / state, the surrounding environment’s state and the ego vehicle’s state. When the ability of the ego-vehicle driver to regain control of the driving task from the ADS turns out to be appropriate, the ADS delegates driving authority to ego-vehicle driver and provides information about the high priority of the current traffic situation and the most suitable decision. Even though the ego-vehicle driver takes back control of vehicle, the ADS should intervene immediately and execute an emergency stop if the driver’s behaviour such as braking, accelerating and steering manoeuvre is not determined to be safe for delegation of driving authority. Additionally if the ego-vehicle driver is unprepared to take back control of the ego vehicle, the ADS assists the ego-vehicle driver so that she / he could control the ego vehicle within the allowed time before a traffic accident occurs. However, if the ego-vehicle driver cannot regain control of the driving task within the allowed time before a traffic accident occurs or there is no time to delegate driving authority to the ego-vehicle driver safely, the ADS takes safe action not to delegate driving authority to the ego-vehicle driver.

![Figure 1. Concept model of the automated driving system](image-url)
2.2. Functions of automated driving system

The concept model of the ADS in the situation for delegation of driving authority in section 2.1 shows that it is closely related with the ego-vehicle driver’s behaviour and state. Therefore, the ADS functions responsible for enabling the delegation of driving authority should be derived by considering the ego-vehicle driver’s behaviour and state. Figure 2 shows the use case of the ADS. The use cases describe the functionality of the ADS in terms of how it is used to achieve the safe delegation of driving authority of its various users. The users of the ADS are described by actors, which represent the ego-vehicle driver and external systems such as the ego vehicle and the surrounding environment that interacts with the ADS. The functions of the ADS described in Fig. 2 are as follows.

- Execute Automated Driving (EAD): This is the base function of the ADS which controls longitudinal and lateral driving using brake, steering, and acceleration control. For the control of the ego vehicle, the ADS monitors the surrounding environment and provides an estimation about the state of the entities in the surrounding environment. And also, the ADS monitors the ego vehicle and provides information about the ego vehicle’s state such as position and velocity. Furthermore, in order to guarantee appropriate selections about the safe delegation of driving authority considering the driver’s behaviour and state, the ADS monitors the ego-vehicle driver’s state and provides estimations about the state of the ego-vehicle driver.

- Select Delegation of Driving Authority (SDA): The ADS determines whom to delegate the driving authority to considering the ego-vehicle driver’s behaviour / state, the surrounding environment’s state and the ego vehicle’s state when the ego-vehicle driver is requested to regain control of the driving task from the ADS due to the limitations of the ADS functions.

- Assist Delegation of Driving Authority (ADA): The ADS provides information about the high priority of the current traffic situation using a sensor or a camera and also, the most suitable decision is provided to the current state of the ego-vehicle driver when the ego-vehicle driver regains the normal state from the distracted or drowsy state in a situation of delegation of driving authority.

- Bring Back Driver in Normal State (BBDNS): The ADS helps the driver to regain the normal state when the driver becomes distracted or drowsy in a situation for delegation of driving authority in the allowed time before a traffic accident occurs.

- Execute Emergency Braking (EEB): If the ego-vehicle driver cannot regain control of the driving task when the ADS requests to delegate the driving authority to the driver, the ADS executes emergency manoeuvres to stop at a safe place while blocking the ego-vehicle driver’s manoeuvre input if the ego-vehicle driver intervenes with the ADS operation.

![Automated Driving System Functions Diagram]

Figure 2. Functions of the automated driving system
2.3. Functional architecture of the automated driving system

The functional flow of the ADS and the ego-vehicle driver, and interactions between them in the delegation of driving authority are described by the activity diagram of Figure 3. The activity starts execution at the initial node (i.e., filled in circle) from the action of “execute automated driving” that is performed by the ADS. The output of the action “put position and orientation of sensory receptors” performed by the ego vehicle driver is sensory receptor movement (SRM), surrounding environment’s state and ego-vehicle’s state, which are the inputs to the action “execute automated driving”. The output of the action “execute automated driving” is the ADS cmd to the ego vehicle. When it turns out that the ADS has functional limitation, the action “select delegation of driving authority” is performed by the ADS. The action “select delegation of driving authority” receives the output of the action “execute automated driving” by the information of delegation (IoD). Thus, if it is determined that the ego-vehicle driver could take back control of the ego vehicle, the action “assist delegation of driving authority” is performed by the ADS and produces the output, assist of delegation (AoD). If not, the action “bring back driver in normal state” is executed when there is enough time to recover the ego-vehicle’s state before emergency situation occurs. If there is no time, the ADS makes a decision to perform the action “execute emergency braking” to avoid resulting in an emergency situation.

The output of the action “bring back driver in normal state” which is the information of recover (IoR), assist of delegation (AoD), the surrounding environment’s state and the ego-vehicle’s state, which are a input to the action of “put position and orientation of sensory receptors”. The action of “perceive ADS delegation request” and the action of “perceive surrounding environment / vehicle’s state” is performed then the action of “decide to operation” and the action of “operate manoeuvre” is performed sequentially by the ego-vehicle driver.

Figure 3. Functional flow of the automated driving system and behaviour of the ego-vehicle driver
State transitions of the ego-vehicle driver and the ADS are described by the state machine diagram in Figure 4. As can be seen in Fig. 4, the ego-vehicle driver is in the Normal state at first but then may become Distracted by performing a sub-task such as watching the navigation display or may become Drowsy because of monotonous driving as estimated from the dispersion of the driver’s gaze direction or low rate of eye blink. The ADS executes BBDNS function in order to recover the ego-vehicle driver’s state when the ADS requires ego-vehicle driver to regain control of the driving task. The state of the ego-vehicle driver is transitioned from Distracted / Drowsy to Normal if there is a proper response from the ego-vehicle driver within the allowed time (AT) before a traffic accident occurs. However, if the state of the ego-vehicle driver is not restored to the Normal state within AT, the ADS executes the EEB function immediately.

The states of the ADS are Automated Driving, Manual Driving and Emergency States. The state of the ADS is changed from Automated Driving to Manual Driving if the ego-vehicle driver is in the Normal state when the ego-vehicle driver is required to regain control of the driving task. However, the state of the ADS is transitioned from Automated Driving to the Emergency State if there is not enough time to recover the Normal state of the ego-vehicle driver or if there is no response when the ADS executes the BBDNS function. Furthermore, the state of the ADS is transitioned from Manual Driving to the Emergency State if the driver’s operation is not determined to be safe for the delegation of driving authority.
3. Simulation and results

3.1. Simulation model and parameter calibration method
Rear-end collisions against a preceding vehicle cover a high quantity of accidents with casualties. In this situation, unsafe delegation of driving authority will lead to severe consequences in emergency situations. Thus, in order to calibrate the key parameters and verify the proposed architecture of ADS for safe delegation of driving authority, simulations were carried out in the emergency braking scenarios related to rear-end collisions.

Figure 5 shows the simulation model provided from benchmark problems No.3 from the Society of Automotive Engineers in Japan and the Society of Instrument and Control Engineers [9]. The simulation model is constructed by simulation software based on the Modelica modelling language [10]. The simulation model consists of a vehicle model and a driver model primarily. The vehicle model consists of the sub-models of the chassis, the power train and the brake. The driver model is made up of a perception block, a planning block and a tracking block. The perception block calculates the current vehicle state that the driver recognizes and the planning block settles target points on the path to be followed on the road from the information of the perception block. Target points are settled on the road respectively according to the desired road shape and the vehicle speed profile for each task. The tracking block calculates the driving operation command of front steering angle, acceleration pedal angle and braking force, respectively, using the information from the planning block and the perception block.

![Figure 5. Simulation model](image)

![Figure 6. Logical diagram of the driving authority delegation of the automated driving system](image)
A situation of emergency braking scenarios is assumed, where another vehicle at the velocity of 60 km/h (16.7 m/s) cuts in to the ego vehicle (initial velocity 60 km/h) at 1 s and decelerates at a rate of 0.46 g to stop at 4.7 s. It is assumed that the ego-vehicle driver is required to regain control of the driving task due to functional limitation of the ADS at 2 s and the ego-vehicle driver is in normal state in the situation of emergency braking scenarios. In these scenarios, the ego-vehicle driver brakes her/his vehicle fully within 0.5 s (full brake) or slowly for 8 s (slow brake). In each case, execution of the ADS emergency braking is considered selectively for safe delegation of driving authority. Figure 6 shows the logical diagram of the driving authority delegation in the ADS. The ADS determines activation timing of emergency braking based on the braking distance, the distance to the preceding vehicle from the ego vehicle and the ego-vehicle driver’s state. To avoid rear-end collision to the preceding vehicle, braking distance should be smaller than the distance to the preceding vehicle from the ego vehicle. Here, the braking distance is the distance taken to stop once the vehicle’s brakes are fully applied at a certain velocity. It is affected by the ego vehicle velocity and the coefficient of friction between the tires and the road surface primarily.

3.2. Verified Results from Simulation

Figure 7 shows three cases; case1: full braking by the ego-vehicle driver, case 2: slow braking by the ego-vehicle driver with ADS emergency braking and case 3: slow braking by ego-vehicle driver without ADS emergency braking. In the case 1 where the ego-vehicle driver may have enough capability to regain control of the driving task, she / he can retrieve the control of the driving tasks at 4.7 s and the ego vehicle is stopped safely before 8.8 m in front of preceding vehicle without intervention of ADS emergency braking. In the case 2 where the ego-vehicle driver may not have the capability to regain control of the driving task, she / he starts slowly braking at 4.7 s but the ADS intervenes and executes emergency braking while excluding the ego-vehicle driver’s braking at 5.4 s to avoid collision with the preceding vehicle. In the case 3 of the ego-vehicle driver braking slowly without ADS emergency braking, collision with preceding vehicle occurred at 7.1 s due to no emergency braking of the ADS without regaining control of the ego-vehicle driver.

Figure 7. The simulation results in the situation of emergency braking scenarios
4. Conclusions
This paper has proposed the architecture of an ADS to ensure safe delegation of driving authority between the ADS and the ego-vehicle driver. First, the concept model for the ADS in the situation for delegation of driving authority is described taking the ego-vehicle driver’s behaviour and state into account. Second, behaviour / state of the ego-vehicle driver and functional flow / state of the ADS and interactions between them are modelled to understand the context where the ADS requests to delegate the driving authority to the ego-vehicle driver. Finally, the proposed architecture of the ADS is verified under the simulations based on emergency braking scenarios. In the verification process using simulation, we have derived the necessary condition for safe delegation of driving authority that the ADS should assist the ego-vehicle driver even after delegating driving authority to the ego-vehicle driver if her / his capability is not enough to regain control of the driving task.

5. References
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