Shared Control Framework and Application for European Research Projects

Mauricio Marcano[1,2], Sergio Diaz[1], Myriam Vaca[1,2], Joshué Pérez[1], and Eloy Irigoyen[2]

[1] TECNALIA, Basque Research and Technology Alliance (BRTA), Derio, 48160, Spain {`mauricio.marcano, sergio.diaz, myriam.vaca, joshue.perez`}`@tecnalia.com`
[2] University of the Basque Country, Bilbao, 48013 Spain `eloy.irigoyen@ehu.eus`

Abstract. Current commercial Advanced Driver Assistance Systems (ADAS) assist the driver indirectly through warning signals. However, a new generation of ADAS and Automated Driving applications, known as Shared Control, where driver and automation control the vehicle together, have the potential to influence upcoming functionalities, improving the driving performance and reducing the driver's physical and mental workload. The development of such a system has the attention of the European Commission, and different Research Innovation Actions (RIA) are developing new technologies for the human-centered design of partially and highly-automated vehicles. In particular, the PRYSTINE and HADRIAN projects are facing the challenge of sharing the authority of the dynamic driving task between driver and automation. In this sense, a common approach is shared between these projects to combine the necessary systems for a complete collaborative driver-automation framework. The integration of a Driver Monitoring System, a cooperative HMI, and a Shared Control System is part of their goals. In particular, the control system in charge of changing the control authority will be presented in this article for a collaborative overtaking scenario, analyzing two modalities: a collision-avoidance system, and a control transition system. Results, discussion, and future challenges are presented.

Keywords: Shared control, autonomous vehicles, driver-automation cooperation, arbitration, partially automated vehicles

1 Introduction

Automated Driving (AD) applications have increased in impact and maturity in the last years, due to the technological advances in perception sensors, processing hardware capabilities, artificial intelligent techniques, and new legal concessions to test automated vehicles on public roads [1]. However, despite the impressive demonstrators of automated driving functionalities, including commercial vehicles with partially automated driving features, the realization of such technology at a greater scale in our society is still a challenge [2], which could take decades to be achieved, while facing the technological, legal, and social barriers.

In parallel, the relevant advances achieved up to know can contribute to the development of human-centered vehicles that offer continuous control support during the driving task, reducing mental and physical workload, and ensuring a safer, more comfortable, and less demanding experience [3]. This collaborative driving strategy is suitable for inclusion as an especial mode of operation in partially automated vehicles (SAE Level 2 (L2) [4]). In these vehicles, automation has control over steering and pedals, but the driver has to monitor the environment and be ready to take full control in critical scenarios.

Nonetheless, current L2 vehicles, work under the on/off standard, with almost any cooperative control interaction with the driver. Furthermore, when the driver is out of the control loop, it leads to over-trust in automation, and consequently, increases the chance of a late take-over maneuver [5]. In this sense, ADAS with control cooperative components (or shared control ADAS) is a topic of interest in the AD research community. In these systems, the driver and the automation are guiding the vehicle together, with the proper authority that corresponds to the situation (e.g., driver distraction increases the authority of automation).

Shared control in the context of automated driving, is defined using the terminology presented by Abbink [6] as: "driver and automation interacting congruently in a perception-action cycle to perform a dynamic driving task that either the driver or the system could execute individually under ideal circumstances". Also, a joint effort with Flemisch [7] has included shared control in a cooperative framework at different task support levels: 1) operational, related to the control task, 2) tactical, for the maneuvers and decisions, and 3) strategical, which refers to the planning strategy of going from A to B.

The study of shared control systems has particular interest in steering applications, which is the most critical control interface in the driving task. Therefore, many European projects, as part of the mobility needs for a more safe and comfortable driving, have faced the challenge of human-machine cooperation in automated vehicles, aiming for a collaborative system that: 1) increase safety in dangerous maneuvers, such as lane change with a blind spot, 2) assist driver in authority transitions to ensure a smooth, progressive, fluid and safe control resuming, and 3) make the driving task comfortable and less demanding. These ADAS for partially automated vehicles have been studied in different EU research projects such as HAVEit [8], DESERVE [9], and the ABV Project [3].

Recently, two European projects continue this research line, looking for the implementation of collaborative human-centered vehicles using the shared control concept. First, PRYSTINE (Programmable Systems for Intelligence in Automobiles) project [2, 10], studies shared control under the framework of fail-operational systems. Secondly, HADRIAN (Holistic Approach for Driver Role Integration and Automation Allocation for European Mobility Needs), makes emphasis on the dynamic adjustment of (fluid) human-machine interfaces (HMI) that take environmental, vehicle and driver conditions into account to provide adaptive signals and information, transfer control authority, and lead to safe transition between automated driving levels. These two projects have similarities and differences that will be highlighted in this article. Additionally, a common design framework will be presented, with an emphasis on the shared control system design that will be part of both approaches.

This article is structured as follows: Section II presents the description and objectives of the projects, together with the common framework, Section III describes the design of the shared control system. Section IV analyzes the results of the system in an overtaking maneuver. Lastly, Section V closes with conclusions and future works.

2 Driver-Automation framework for PRYSTINE and HADRIAN

The European Commission has granted funding for the development of Research Innovation Actions (RIA) in the context of automated driving. In this sense, PRYSTINE and HADRIAN are part of the ongoing projects that evaluate, design, and implement the human-centered concept in vehicles SAE Level 2, 3, and 4. PRYSTINE focuses the attention in fail-operational systems with an emphasis on the perception of the external environment using cameras, radar, and LiDAR, but also, considering in-cabin sensor fusion to detect the driver state. On the other hand, HADRIAN evaluates the human-centered design implementing fluid interfaces to improve driver automation-interaction not only at the operational level, but also from the human-acceptance perspective.

On the one hand, PRYSTINE intends to increase the Technology Readiness Level (TRL) to TRL 3-4, with validation in a Hardware and Driver in the Loop (HDiL) simulator. Conversely, HADRIAN push to take this technology to implementation in real vehicles and achieve demonstrations in relevant environments, increasing the TRL index to 5-6, with more emphasis on driver acceptance tests. A more detailed comparison between these two projects is given in Table 1.

Table 1. Comparison of scopes of PRYSTINE and HADRIAN

	PRYSTINE	**HADRIAN**
Period	2018-2021	2020-2023
Objective	Fail-Operational System	Fluid Interfaces
Test Platform	HWiL/DiL Simulator	Experimental vehicle
DMS	Fusion of audio and vision-based sensor for driver distraction and drowsiness	Multisensor platform with driver model and RT-learning process
HMI	Visual HMI	Multi-sensory HMI Haptic, auditory, and visual
Scenario	Distraction in urban environment Authority transition in overtaking	Elderly driver assistance system
Acceptance	One cycle testing	Two iteration cycles

Additionally, in the context of these projects, a common control framework is proposed to integrate the driver and the automation in the collaborative and dynamic driving task. This integration requires interactions between different systems related to automated driving functionalities. Previously, a general architecture has been proposed for fully automated vehicles by Gonzalez et. al. [9], with six high-level modules: acquisition, perception, communication, decision, control, and actuation. However, there are additional necessary modules to be included if the driver is sharing the authority of the vehicle with the automation: 1) a Driver Monitoring System (DMS), 2) a set of Human-Machine Interfaces (HMI), and 3) a Shared Control System (SCS). These systems are integrated into the original framework, and highlighted in green in Figure 2, to indicate an addition to the original architecture.

Driver Monitoring System: It evaluates the driver's capability to execute the driving task by his/her own, and indicates the degree of assistance needed. According to the World Health Organization, most of the road traffic deaths are due to driver recognition errors, such as distraction or inattention [11]. That is the reason for the importance of taking into account the driver state as a variable of primary importance for decision making. The factors that can affect the driver's behavior can be assigned to a specific group taking into account outer (i.e. surrounding cars and vehicle density) and inner factors (i.e. distraction, drowsiness(fatigue), and medical conditions) [12]. Other measures indicating physical and mental workload are relevant in this module.

Human-Machine-Interfaces They help the driver to understand the automation intention, state, and actions, increasing situation awareness and trust in the automated vehicle. In this sense, the system can communicate information to the driver by 1) a visual screen, through text or images, for example showing the representation of the environment with nearby vehicles, 2) haptic interfaces, using vibration in the pilot seat, at the steering wheel, or any other surface in contact with the driver, and 3) audio warnings, either by sound alerts or tutoring voice. The design of such strategies should follow the principles of comfort, usability, and avoid excessive information to not overwhelm the driver.

Shared Control System: It is the critical module of a human-centered vehicle framework where the decision and control actions are implemented. In the decision block, an arbitration sub-module is in charge of distributing the authority between the driver and the automation. This module calculates two relevant values: 1) the Level of Haptic Authority (LoHA), that represents the strength of intervention of the system when safety is compromised, (it is the stiffness of the controller around the optimal command [13]), and 2) the Level of Shared Authority (LoSA), a continuous value which indicates the mode of automation, either fully automated or manual, to allow smooth, progressive, and comfortable transitions. This shared control system is explained in detail in the next section.

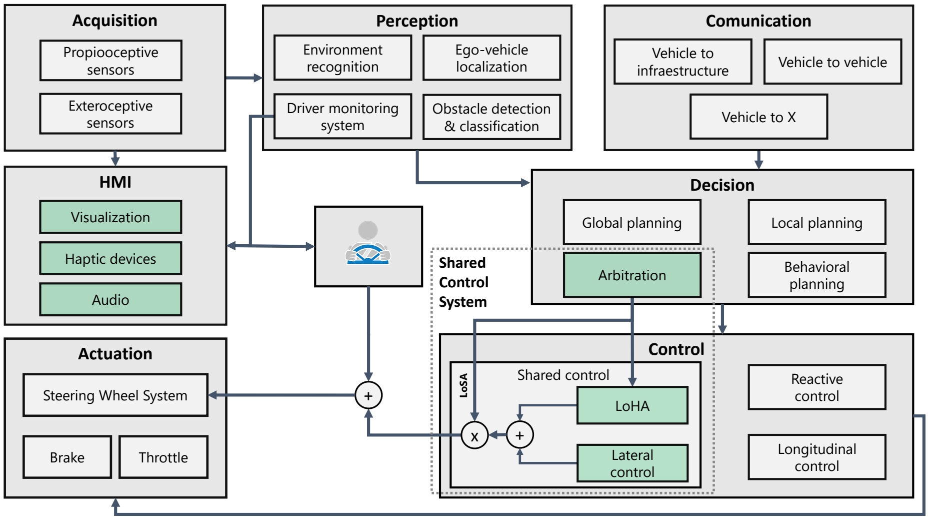

Fig. 1. Driver-Automation Framework

3 Shared Control System

The shared control system architecture is comprised of two subsystems. First, the lateral shared controller that assists the driver in the lane keeping task. Secondly, an arbitration system calculates the two levels of authority. On the one hand, the Level of Haptic Authority (LoHA) increases the default authority of the steering controller to avoid hazardous situations. On the other hand, the Level of Shared Authority (LoSA) manages the transitions of control from manual-to-automated and automated-to-manual, as a continuous value.

3.1 Lane-keeping controller

The lane-keeping system for shared control applications makes use of the optimization framework of Model Predictive Control (MPC) as in previous works [14, 15], considering the torque at the steering wheel as the control input, to facilitate the driver-automation cooperation. The design of the controller has two considerations: 1) the representation of the system model through differential equations, and 2) the configuration of the optimization problem.

The system model It comprehends three sub-systems: the vehicle, the lane-keeping model, and the steering mechanism. This combination represents the road-vehicle model. The *vehicle* model uses dynamic bicycle system equations for a front steered vehicle. The *lane-keeping* model includes two differential equation respective to the lateral error (e_y) and angular error (e_Ψ). The *steering model* uses the inertia (J) and damping (B) model, which relates the steering wheel angle with the steering torque. It also considers an approximation of the self-aligning torque proportional to the lateral force of the front tire and includes the torque of control (T) as part of the model. For more information on the complete road-vehicle model, refer to [15].

The optimization problem: It considers three different optimization functions: 1) the tracking performance, to follow the reference trajectory ($\boldsymbol{z_{tra}} = [e_y, e_\Psi]$), 2) the driving comfort, minimizing speeds ($\boldsymbol{z_{com}} = [v_y, \psi, w]$), and 3) the control conflicts, optimizing the driver control effort ($\boldsymbol{z_{tor}} = [T, \Delta T]$). The reference of the controller comes from an offline trajectory with information of curvature and tracking errors. The solution is obtained with the use of ACADO toolkit, an online optimization problem solver [16].

3.2 The LoHA controller

Additionally to the lane-keeping controller, the shared control system needs a sub-module to increase the intervention of the controller to override the driver's intention in situations when safety is compromised. In this sense, a LoHA controller is added in cascade to the lane-keeping controller. The LoHA is the stiffness around the optimal steering angle. The higher the LoHA, the harder for the driver to override automation. This controller is defined as a proportional term to the difference between driver and automation command $T_{LoHA} = K_{LoHA}(\theta - \theta_d)$. It changes the original stiffness of the system K, to a new equivalent value $K_{eq} = K + K_{LoHA}$. Therefore, to keep the system stable, a new equivalent damping is found using the damping ratio formula $B_{eq} = B\sqrt{(K + K_{LoHA})/K}$ resulting in the following LoHA controller:

$$T_{LoHA} = K_{LoHA}(\theta - \theta_d) + (B_{eq} - B)w \tag{1}$$

3.3 The arbitration system

The arbitration system is based in a Fuzzy Inference System, a powerful soft computing technique that allows to include human knowledge into the design of control and decision algorithms [17]. The fuzzy scheme comprehends four inputs and two outputs. The representative inputs are: 1) the driver's intention, considering the lateral error and its derivative, 2) the driver effort, measured as the equivalent torque at the steering wheel, and 3) the risk of collision, calculated as the time-to-collision with the vehicle in the left lane. These three variables allow us to calculate the following outputs: 1) the LoHA, which represents the need for a greater intervention of the system to avoid collisions, and 2) the LoSA, which is the variable authority for a progressive transition from automated-to-manual and manual-to-automation. The design rules are shown in Tables 2 and 3 for the conditions of a low and high risk of collision respectively.

Table 2. Rules for low collision risk

	e_y	Low			Med			High			
	de_y/dt	↓	–	↑	↓	–	↑	↓	–	↑	
T	$= 0$	A	A	A	A	T	M	M	M	M	LoSA
	> 0	T	T	T	T	M	M	M	M	M	
	$= 0$	LOW									LoHA
	> 0										

Manual (M) - Transition (T) - Auto(A)

Table 3. Rules for high collision risk

	e_y	Low			Med			High			
	de_y/dt	↓	–	↑	↓	–	↑	↓	–	↑	
T	$= 0$	AUTOMATED									LoSA
	> 0										
	$= 0$	L	L	L	L	M	H	H	H	H	LoHA
	> 0	L	M	M	M	M	H	H	H	H	

Low (L) - Medium (M) - High (H)

4 Use case and Results

This section presents the tests of the shared control system in a collaborative overtaking maneuver, where the system assists the driver in three scenarios. First, if the driver plans to do a lane change, but there is a high risk of collision with the side vehicle, the system increases the LoHA to guarantee the safety and guides the vehicle towards the main lane, as shown in the top of Figure 2. Secondly, when there is low collision risk, the system decreases the LoSA conceding the transition from automated-to-manual (see bottom of Figure 2). Lastly, once the driver has passed the front vehicle and returns to the main lane, the system increases the LoSA to allow the transition from manual-to-automated and continue with the lane-keeping assistance.

The implementation of this maneuver is performed by one real driver in the HiL Automated Driving Simulator shown in Figure 3. It is comprised of a high-performance computer, running Matlab/Simulink, and communicates with a steering wheel capable of a maximum torque of 15 N.m. The automated driving software simulator is based on Dynacar [18], a vehicle dynamic software based on a multi-body formulation.

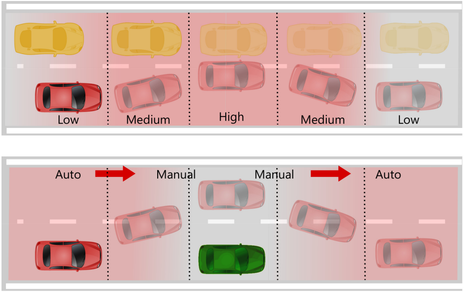

Fig. 2. Collaborative Overtaking

Fig. 3. HDiL Simulator Platform

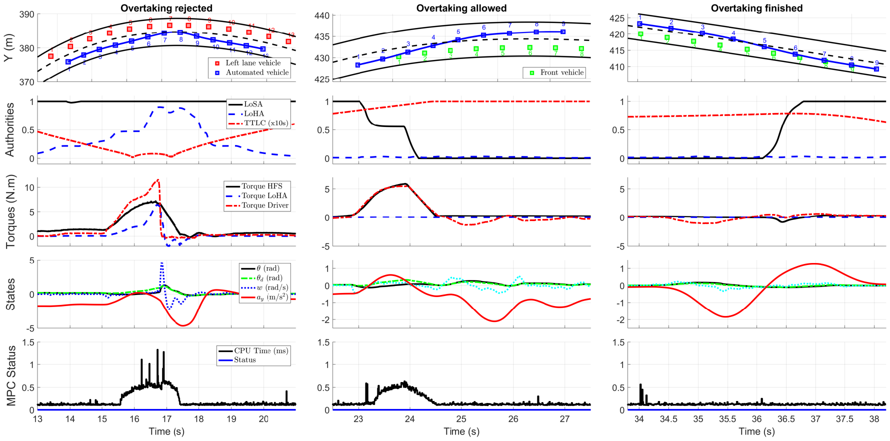

Fig. 4. Shared control system results in three scenarios

The results of the three scenarios are shown in Figure 4. First, the collision avoidance system is tested with the vehicle starting in a fully automated mode. Initially, the LoHA is very low as there is no risk of collision. Then, in the second 16, the driver intends to make a lane change, but the system detects a low time-to-collision with the left lane vehicle. The arbitration system maintains the automated mode and increases the LoHA to strengthen the intervention of the system ensuring safety. The system achieves an assistance torque of 10 N.m, and the driver releases the steering wheel. In this case, the system can return to the lane without losing stability. On the one hand, safety was the priority, but also, the comfort was compromised with a lateral acceleration close to -5 m/s^2. The results also show that the MPC solver always found a feasible solution calculated in less than 1.5 ms.

In the second scenario, the driver intends to do a lane change again, but in this case, the system does not detect any collision risk and allows the transition from automated-to-manual. It is shown in the second column of Figure 4, that the LoSA is changed smoothly and progressively, making the transition comfortable and understandable for the driver, with a maximum effort of 5 N.m in a short period. The maximum lateral acceleration was kept close to 2 m/s^2. Also, it is observed that the variation of authorities, does not affect the calculation of a feasible solution of the optimization problem.

Lastly, when the driver wants to return to the original lane after surpassing the front vehicle, the system changes from manual-to-automated and keeps assisting the driver in the lane-keeping task. In this case, the LoHA is low and the LoSA changes progressively to 1 (fully automated mode). It is important to mention that the behavior of the LoSA departing the lane and returning the lane is different. In the first, an intermediate step is observed which is, in fact, helpful for the driver to confirm the lane change intention. In the second one, the transition is performed without medium steps, allowing activation of the lane-keeping that is barely notable to the driver, as shown by the low lateral acceleration and steering wheel angular velocity.

5 Conclusions and future works

This article presents a shared control framework for implementations in two European RIA projects, PRYSTINE and HADRIAN, to improve the development of advanced control techniques for human-centered vehicles SAE Level 2, 3 and 4. The shared control system is comprised of an arbitration function that calculates the appropriate control authorities, based on fuzzy logic, a well-known soft computing technique, and a cascade architecture controller including an MPC and a PD controller for the lane-keeping task.

Results show the effectiveness of the system in a collaborative overtaking maneuver. When the risk of lateral collision is high, the automation overrides the driver's intention increasing the level of intervention (LoHA). Conversely, when there is no risk, and a lane change intention is recognized a transition of authority takes place in a fluid, progressive, and comfortable manner by changing the LoSA. The system is also able to reactivate the automated mode when returning to the lane.

In future works, the integration of the shared control system with other complementary modules such as the DMS and the cooperative HMI is necessary to prove the feasibility of the complete collaborative framework. The implementation of this approach will be tested with different drivers for a complete driver acceptance test and evaluates the utility of this cooperative control system in passenger vehicles.

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Disclaimer

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