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COOPERATIVE CONTROL AND ACTIVE INTERFACES FOR VEHICLE ASSISTANCE AND AUTOMATION

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ABSTRACT – Enabled by scientific, technological and societal progress, and pulled by human demands, more and more aspects of our life can be assisted or automated by technical artefacts. One example is the transportation domain, where in the sky commercial aircraft are flying highly automated most of the times and where on the roads a gradual revolution takes place towards assisted, highly automated or even fully automated cars and trucks. Automobiles and mobility are changing gradually towards intelligent vehicles embedded in an integrated, intelligent transportation system.

On the one hand, assistance and automation can have benefits like higher safety, lower workload, or a special fascination of use. On the other hand, assistance and automation come with a couple of challenges especially regarding the interplay between the driver and the assistance/automation.

Some of these challenges can be addressed with a close coupling of assistance/automation and the driver, which leads to a shared or cooperative control of the vehicle. An early example of cooperative control in a car is the Lane Keeping Assistant System LKAS, where the automation delivers about 80% of the force required to keep the vehicle on the road, while the driver has to provide the missing 20% and therefore stays in the loop. A combination of LKAS and ACC (Adaptive Cruise Control) leads to highly automated driving, one level of automation on the automation spectrum between manual and fully automated driving.

A close coupling between automation and driver can be achieved with active interfaces, e.g. force feedback steering wheels like in the LKAS or active sidesticks. After a brief overview on active interface technology, a prototype system developed in the H-Mode project by NASA, DLR and TU-Munich, and first data gained in driving simulators will be described.

FROM VEHICLE ASSISTANCE TO HIGHLY AUTOMATED VEHICLES

Assistant systems like Adaptive Cruise Control (ACC) or Lane Keeping Assistant Systems (LKAS), and automation developments like the robotic cars of the Grand Challenges, e.g. (1), can be seen as part of a general development towards a better support of humans by technical artefacts. Especially when the degree or level of automation is varying, the concept of automation spectrum can support to structure the scientific and technical discussion. Based on fundamental work by (2), Flemisch et al. (3) describe an automation spectrum from fully manual to fully automated, with intermediate levels of “assisted” (e.g. Lane Departure Warning Systems), “semi-automated” (e.g. ACC or LKAS) and “highly automated” level of automation (Figure 1). The spectrum also indicates a future direction of research and development: Highly Automated Vehicles have automation capabilities up to fully automated driving, but the driver is usually, meaningfully involved in the control of the vehicle. A recent example for highly automated driving is the combination of LKAS and ACC, which in 2008 is available in a number of cars already. Examples for research projects that address highly automated vehicles are the recently started EU-Integrated Project HAVEit, approaches like Conduct-by-Wire (4), and the H-Mode project described below.

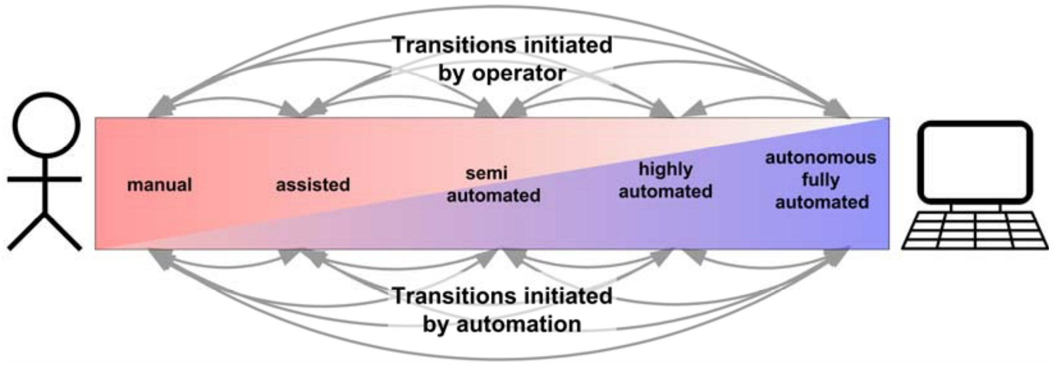

Figure 1: Simplified automation spectrum, levels of automation and transitions

ACTIVE INTERFACES FOR VEHICLE ASSISTANCE AND AUTOMATION

The different levels of automation described above need consistent and easy to understand interaction between driver and vehicle automation. The use of haptic feedback might be a solution for this, which in today's cars is underutilized. Most of the communication and warning signals are presented visually or acoustically. Nevertheless, haptic feedback enters modern vehicles in form of some lane departure warnings using vibrations as warnings or lane keeping assistant systems using forces as a display function of the automation actions. Several research studies have shown the advantages of haptic feedback in the car domain. In summary, haptic feedback can lead to a better driving performance, reduced driver workload and high acceptance (5–10).

Especially for designing a consistent driver-vehicle interaction for different automation levels haptic interaction offers some advantages over other feedback channels:

a) Haptic feedback can be directly linked to the actuator on which a reaction of the driver is required. For example, a lane departure warning can signal the lane departure of the vehicle by a vibration of the steering wheel.

b) In addition, the feedback can not only be linked to the actuator but can also be used to show the kind of reaction that is needed, e.g., the steering wheel can be turned into the correct direction by the automation to trigger a steering reaction of the driver.

c) Like spoken language haptic interaction is bidirectional. That means that continuous communication between the driver and the vehicle can be established which is especially important for higher automated driving. For example, the driver can oversteer a specific force threshold on the steering wheel to signalize that he intentionally leaves the lane.

Haptically active controls

A comfortable way to provide haptic feedback to the driver is the use of haptically active controls in the vehicle. Active controls are characterized by their capacity to generate forces and discrete haptic signals. This makes it possible to establish a haptic driver-vehicle interaction. From a technological point of view, the development of drive-by-wire technology in the car domain makes the use of active controls and with it a haptic feedback easy. Drive-by-wire means that all mechanical links between control devices and the vehicle, e.g., wheels, are replaced by electronic links. This allows different kind of haptic feedback, e.g. vibrations for warnings, steering advices for lane keeping or discrete signals for direct communication with the driver. For displaying dynamic system behaviour two concepts of feedback can be distinguished in general: force feedback and position feedback. Further information can be found in e.g. in Schieben et al. (11).

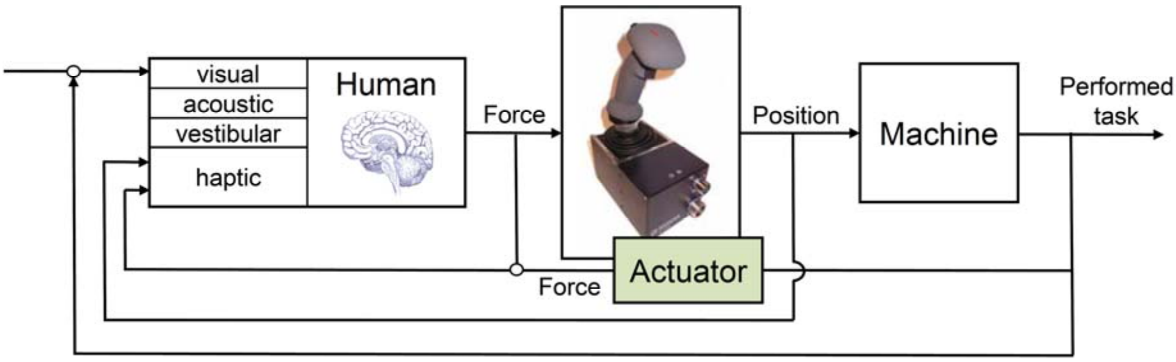

Figure 2: Active side stick with force feedback control loop

H-METAPHOR AND H-MODE

Metaphors can be useful especially for the design of active interfaces. The starting point for the design metaphor "H-Metaphor" and the interaction language "H-Mode" were a couple simple question: If there are more and more assistant systems in vehicles, if automation gets more complex, if we allow different levels of automation, how can this be understood in non-technical terms as one integrated system, also for the driver? What is it that we might be driving in the future? What is the basic way of driving such highly automated vehicles? As in the 1970 with the desktop metaphor for computers, a design metaphor might provide an easy to understand answere: Flemisch et al. (12) describe a H(orse)-Metaphor, the relationship of horse and human in horse back riding or horse cart driving as a natural example for highly automated means of transportation.

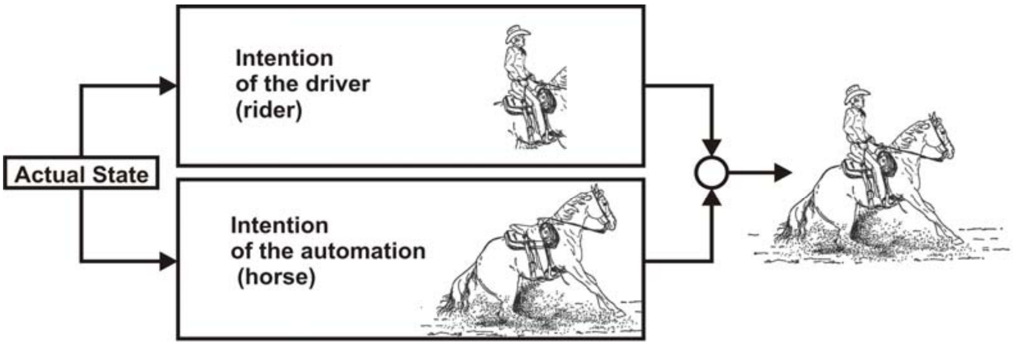

Figure 3: Arbitration of intentions and cooperative control between rider/driver and horse/automation

Essential features are a multi-modal combination of the driver input with the automations intent via an active interface, and a fluid transition especially between two levels of automation, assisted (Tight rein) and highly automated (Loose rein). The following chapter gives a short glance into the activities at DLR and Technical University of Munich, especially of first experiments related to highly automated driving with the H-Mode. Besides ground vehicles, the H-Metaphor and the H-Mode was applied to airplanes (13) and uninhabited helicopters (14).

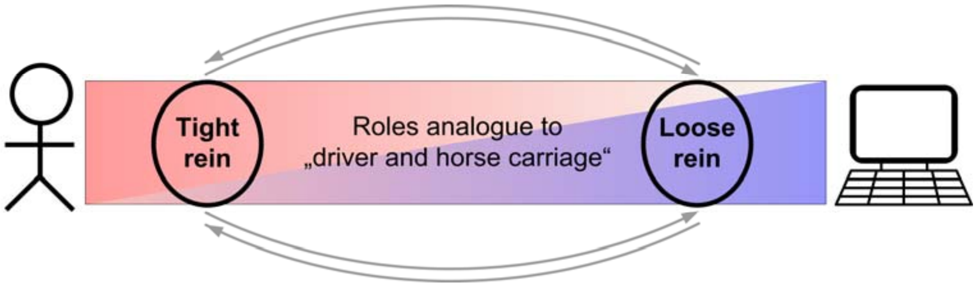

Figure 4: Levels of automation, roles and transitions in a H-Mode control of highly automated vehicles

A GLANCE INTO AN EXPERIMENT WITH VARIING LEVELS OF AUTOMATION

In the context of the H-Mode project an exploration and usability study was performed in a generic usability laboratory (SMPLab, 15), followed by an experiment in the dynamic simulator (Figure 5, see also 16 in this issue).

Figure 5: Experimental setup in the DLR dynamic driving simulator

10 participants (5 men + 5 women, 18-59 years old, average age of 32.7 years, wide variety of professional background and driving experience) drove in the dynamic simulator on the right lane of a two-way curvy track of 3.5 km length, with a speed limit of 50 km/h, steering the vehicle with an active sidestick. The study was designed as a within-subject design so that each subject was exposed to each of the variations described below. The variation of the task (independent variables) included:

- The presence of a secondary, visual search task that was displayed on the lower right side of the driver on a monitor.
- Different levels of automation, covering the automation spectrum from
    - Manual
    - Assisted / Tight rein
    - Highly automated / Loose rein
    - Fully automated.
- The reliability of the automation, by introducing one situation with an automation failure at the end of the very last run of each participant (5 participants in the condition Highly automated, 5 participants in the condition Fully automated)

The automation level Assisted/Tight rein offered low assistance with combined lateral and longitudinal vehicle control. The vehicle was slightly kept on the lane and there was a slight haptic force on the sidestick in case the driver exceeded the speed limit.
For the automation level Highly automated/ Loose rein we used the concept of combined lateral and longitudinal vehicle guidance described above, but with much stronger forces on the stick. In this condition, the driver was freed from most of the driving task and had to guide the vehicle only slightly by adding some force in curves and for accelerating the vehicle.
In both automation levels a lane departure warning and intervention feature helped the driver to stay on the road in case he left the lane. This “virtual gravel pit” consisted of a escalating sequence of haptic interactions starting with a tic for information, followed by a warning vibration and a force steering the vehicle back to the lane.
The automation level Fully automated was defined by a complete lateral and longitudinal automated vehicle control. The driver was completely freed from the driving task and was allowed to take his hands off the stick.

In addition, an automation failure was introduced at the end of the study to check driver’s reactions for different automation levels. The automation failure occurred in a curve and the driver had to react with a manual takeover of control. 5 subjects were exposed to this failure in the condition Highly automated driving, 5 subjects in the condition Fully automated driving.

Every different condition was performed after a sufficient training. In order to minimize sequence effects, the presentation of conditions were varied amongst participant. The dependent variables evaluated for this paper were

- Subjective acceptance in a variety of questions and subjective workload (NASA-TLX)
- Objective performance: speed, deviation from the center of the lane, the number of solved secondary tasks.

The preliminary results show that the haptic design of the prototype is overall well accepted as useful, easy to understand, safe and pleasant, compared to the manual driving with stick (Figure 6). Remarkable is the high acceptance of the fully automated condition. This was assessed in the simulator and before the automation failure, the acceptance of full automation in real vehicles, especially after failure events, should be subject to future research.

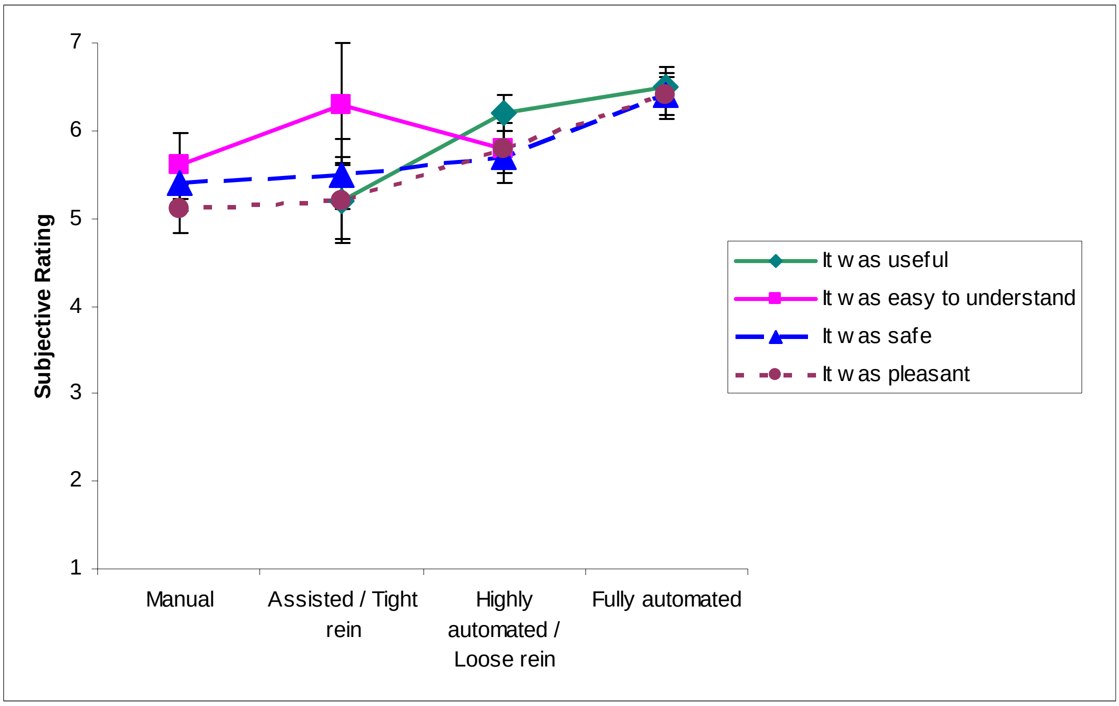

Figure 6: Subjective acceptance of different levels of automation

Figure 7 shows the secondary task performance and the workload ratings on three dimensions of the NASA-TLX for the driving with a secondary task. The mean number of secondary tasks performed during driving increases clearly with higher automation levels. While in manual driving condition the participants finished an average of 6,6 tasks, they solved 35,2 tasks in the fully automated driving condition. That means that the growing involvement of automaton in vehicle control by increasing level of automation creates additional resources for secondary tasks processing.

In general, workload decreases with higher automation. The effort that participants reported decreases with higher automation levels. For mental demand, the results show that in conditions of manual and assisted driving the mental demand of the driving task in combination with the secondary tasks is relatively high. In contrast, when freeing the driver nearly or completely from the driving task the mental workload decreases. Overall, the frustration level of the participants is low. The lowest frustration was reported for fully automated driving. For highly automated driving/Loose rein there is a peak that can be ascribed to one participant who had specific problems with the automation authority in the highly automated/Loose rein condition.

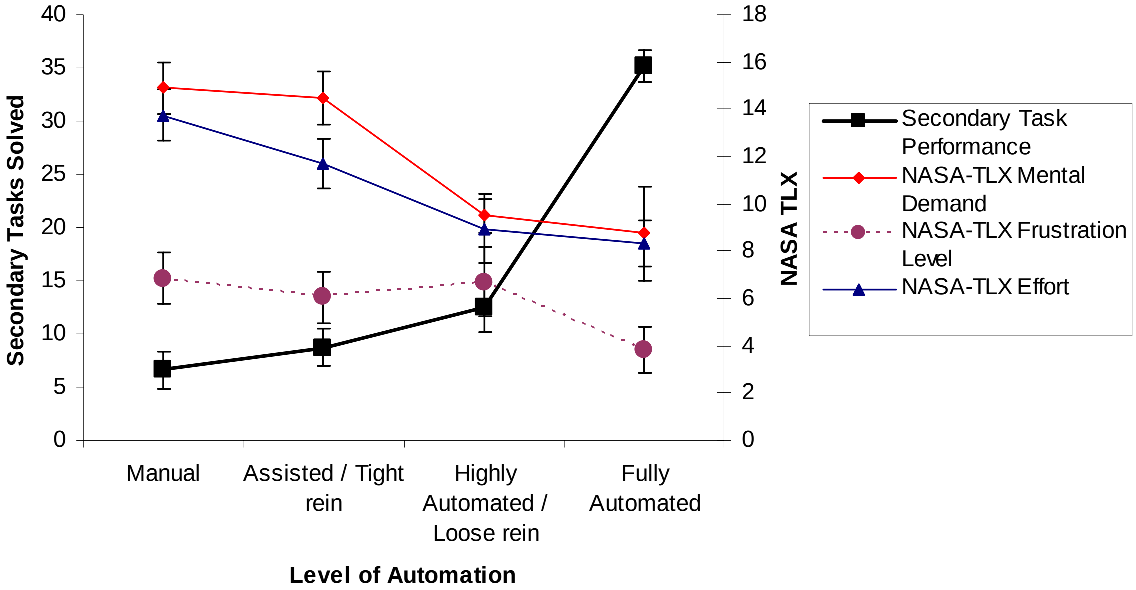

Figure 7: Subjective acceptance and Secondary Task Performance for different levels of automation

Figure 8 shows the overall performance of the participants for each driving condition in which the participants had to perform the secondary task in addition. The mean speed is nearly stable over the three driving conditions that the driver could influence by his driving behaviour (Manual, assisted, highly automated). The mean speed of the fully automated driving is lower because of a conservative controller for vehicle guidance. With increasing automation (force that keeps the vehicle on the lane) the average standard deviation of lateral position decreases, driving becomes more precise. The difference between Highly automated/Loose rein driving and Fully automated driving in mean speed and mean standard deviation of lateral position occurs because the driver still has some influence on the vehicle control in Highly automated/Loose rein driving.

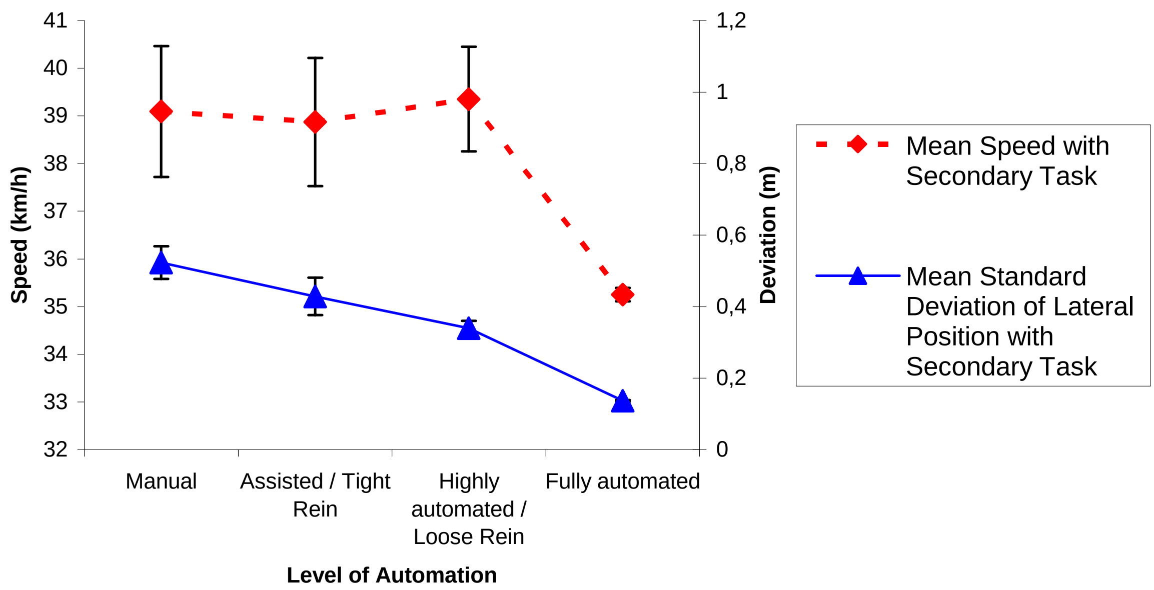

Figure 8: Means of Speed and Standard Deviation

As seen above, the overall workload decreases while the driving and secondary task performance increases with an increasing level of automation. Nevertheless, some of these benefits are compensated, especially for full automation, with a decrease in the ability of the drivers to cope with automation failures. Figure 9 shows the driving path of each driver (based on the vehicle center) shortly after an automation failure which was indicated by an acoustic warning signal. 5 out of 5 participants in fully automated mode left the road (Figure 9, red dotted line), 5 of 5 participants in highly automated mode were able to take over control in time, and, even if some of them drove briefly on the opposite lane, all of them were able to recover and to stay on the road (Figure 9, green solid line).

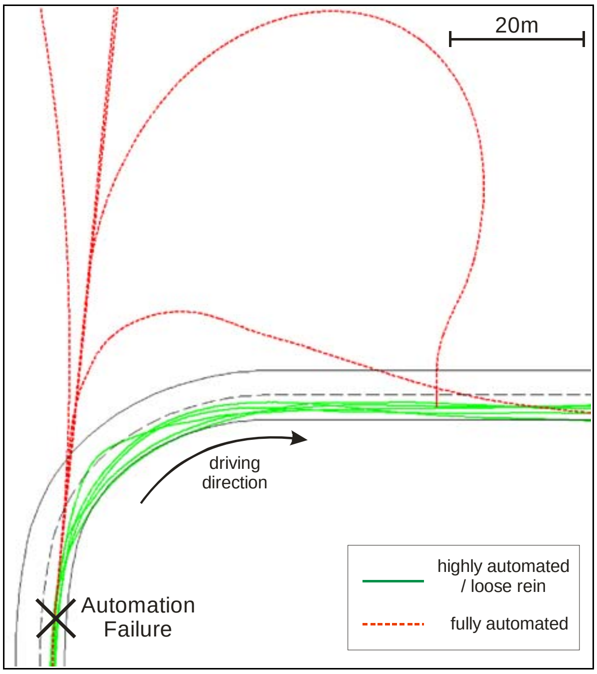

Figure 9: Individual recorded driving paths of the vehicle center in automation failure condition

This preliminary data is subject to more thorough investigation, especially statistical analysis, and should be used with caution. The tendency is not surprising: The automation that was developed and tested here brought clear benefits, but can bring unintended side effects that have to be controlled. Instead of full automation, highly automated solutions might achieve a better balance between workload and performance benefits on the one hand, and the driver’s ability to keep in the loop and take over if necessary, on the other hand. A dynamic transition between different levels of automations might bring even further benefits and will be subject to future research.

OUTLOOK: TOWARDS COOPERATIVE AUTOMATION AND CONTROL

When vehicles become highly automated, with varying degrees of automation, even H-Mode like, what are the most challenging aspects in the interaction between humans and such an automation? What should be addressed by future research and development?

We think that besides controlling the complexity of such human-machine systems, it is a promising direction to go beyond classical either/or automation and shared control, towards cooperative automation, e.g. (17), (18), (19):

Cooperation can be understood as working jointly towards the same goal. Applied to vehicle control this concept means that the functions which are needed to steer a vehicle are handled together. The driver as well as the automation can have control over the vehicle at the same time. Furthermore, the automation should actively support a harmonization of driving strategies of both actors (automation and driver) towards a common driving strategy. To enable this, the inner and outer design of the automation has to be compatible with the human and a continuous interaction has to be established. Intentions for actions have to be matched via a human-machine-interface and a joint action implementation enabled (see Figure 10).

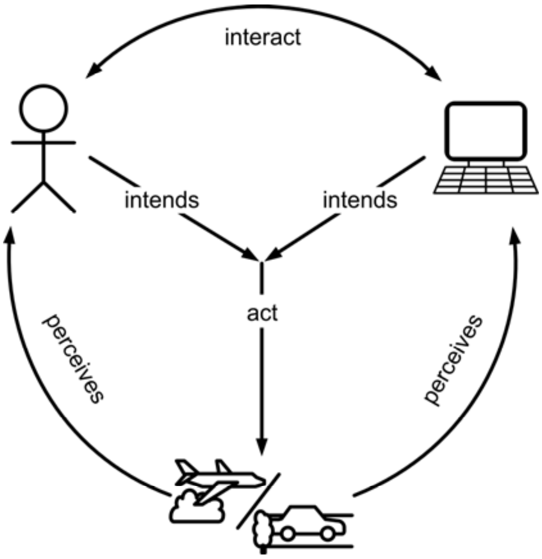

Figure 10: Shared and Cooperative vehicle control between human and computer

Cooperative control should make the automation responsive to the driver's intentions. For this, the automation needs the ability to change its strategy and to adapt this strategy to the human strategy. On the other hand, the automation gives the driver the opportunity to optimize his own strategy or to adapt his strategy to the strategy of the automation. This driver adaptivity has to be respected when automation adaptivity is introduced. For further information about the concept of cooperative automation and requirements to realize such automation see (19), (3).

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