Towards an H-Mode for highly automated vehicles: Driving with side sticks

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ABSTRACT

The increasing traffic volume confronts the road user with a challenging task. The high number of traffic deaths might not be reducible with passive safety alone. However systems that actively influence the guidance of vehicles, like assistance and automation systems, can make a difference towards higher safety, comfort and efficiency. Some of these systems completely take over single subtasks like speed or distance control. This, in turn can lead to effects like "out of the loop", where the driver withdraws from the actual task and even stops monitoring. In order to realize a safe automation system, the project H-Mode follows an approach where both, driver and assistance system are simultaneously affecting the vehicle, whereby the operator is kept in the loop and active. Moreover a haptic-multimodal communication between driver and automation is established by using active interfaces. Regarding this communication alternative control elements, especially two dimensional ones have to be considered.

The study presented in this paper compares conventional interfaces (steering wheel and pedals) with different configurations of an active side stick. It is shown, that two dimensional elements have the potential to combine the driver-automation communication with acceptable drivability.

Categories and Subject Descriptors

H.5.2 [User Interfaces]: Haptic I/O

General Terms

Performance, Design, Ergonomics, Experimentation

Keywords

Haptic interaction, active control element, cooperative automation, highly automated vehicles, haptic interaction, automation, assistance, interaction

1. H-MODE: AN INTUITIVE CONTROL CONCEPT FOR HIGHLY AUTOMATED VEHICLES

Technological progress enables more and more automation in vehicles. In the sky, highly automated planes are flying for decades with a relatively high safety record. On the ground, assistance systems like Adaptive Cruise Control (ACC) or Lane Keeping Assistant Systems (LKAS), which enable partially automated driving, can be bought in many cars. Fully automated vehicles have been demonstrated in public traffic [3], in desert and urban challenges [12] and as demonstrator vehicles "cybercars" in city environment [9]. While fully automated cars might be technologically feasible and legally acceptable much further in the future, highly automated cars, where the automation is capable of driving almost autonomous, but where the driver is still kept active and in the loop, might be possible in a near term future [7].

One of the challenges for highly automated vehicles is to reduce a relatively high complexity of the automation into a manageable complexity for the human. Here aviation can only be a limited role model: In most aircraft, two well-trained pilots keep the system safe, a luxury that is usually not available in ground vehicles. New concepts for an intuitive approach to automation that everybody can operate without extensive training have to be developed and tested.

One potential technique for increasing intuitiveness is the use of design metaphors. In the computer domain, the desktop metaphor took a natural desktop as an inspiration for the organisation of a PC user interface with folders, trash cans etc. For intelligent vehicles, the H-Metaphor (Figure 1) takes the natural example of the rider-horse relationship to describe a cooperative interaction between a highly automated vehicle and a driver (H-Mode).

Initially developed for air vehicles [5][6], it is now systematically applied to cars and trucks [2][8].

Figure 1. Design Metaphors as technique to create mental models (Example Desktop-metaphor and H-metaphor)

One of the essential features of the H-Mode is a bi-directional haptic-multimodal coupling with continuous and/or discrete communication between driver and automation.

In order to provide the driver with a haptic feedback of automation recommendations, active control elements are used as a basis. This means that the H-Mode can be driven with conventional, but active interfaces like an active steering wheel and active acceleration pedal. However new and unconventional interfaces like active side sticks might offer benefits that cannot be reached with conventional interfaces, especially regarding the haptic communication between driver and automation.

Although such new control elements might have advantages when driving with assistance/automation, a minimum of drivability has to be ensured in case of a breakdown or shutdown of the assistance system, leading to manual driving. Therefore the following article focuses especially on different ways to configure active control elements for manual driving, in this case an active side stick. The goal is to achieve a potentially similar driving performance as with conventional interfaces.

2. ACTIVE CONTROL ELEMENTS FOR HAPTIC FEEDBACK

Active control elements provide a way to benefit from haptic feedback. Forces, which can be generated by the integrated actuators can be used to transmit vital information to the operator. Therefore the mechanical connection between machine and operator can be separated and replaced by an electronic one. On the one hand, the accompanied decoupling of these by-wire systems makes it possible to completely redesign the interface. On the other hand the induced reduction of information flow aggravates the user's ability to operate the system. The loss of information flow is thereby due to the fact that the operator can only feel the dynamic of the control element, but not the dynamic of the controlled system itself. Therefore the user has to estimate the system's behavior [11] in order to keep the system within safety limits. For technical purposes active operating elements must be distinguished between two concepts: force and position reflective elements [1][4][10]. In the following these drafts are exemplified with driving a side stick based vehicle.

For driving the vessel the operator creates forces on the stick. The underlying spring characteristic of the force reflective operating element (see Figure 2) determines its movement with addition of the load injected by the operator. Through the stick position the user adjusts the setpoint settings of the vehicle. Consequently the dynamic of the stick is autonomous and does not predicate conclusions about the vehicle's state. This means that, for example in lateral direction, the driver manipulates the steering angle but has no knowledge about its actual state. He can only estimate the wheel position through the sensed accelerations.

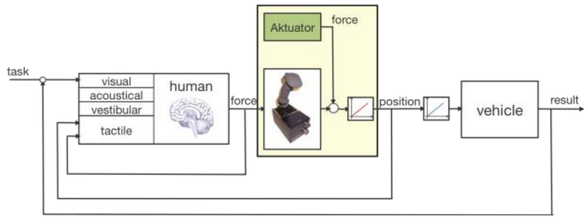

Figure 2. Force reflective element

In contrast position reflective elements (see Figure 3) use the applied forces to generate the setpoint settings. More precisely the forces are measured and translated into control inputs. The feedback information is returned by the position of the element. As opposed to the spring centered stick, where the position results from the balance of forces, the position reflective control element stays fixed for the operator and is only moved by the controlled system.

In doing so, the position of the element represents the actual state and its movement the dynamic of the system itself. Consequently the operator senses the behavior of the system.

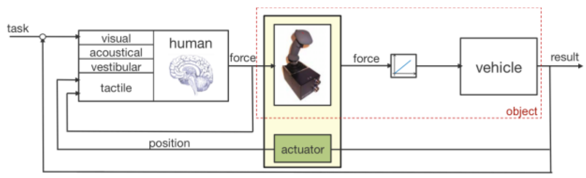

Figure 3. Position reflective element

This configuration works similar to the direct interaction with objects. Raising forces by the user manipulates the item, which responds with movement (see Figure 3).

As a result, position reflective elements seem not only suitable for compensating the decrease of information flow but also enable a specific feedback of essential information that supports the operator fulfilling the task.

In order to keep the vehicle controllable at all times and thus to increase stability, a bottom-up approach is preferred. That is why an experiment is performed without any kind of assistance. The most promising prototype represents the basis for the automation attachment.

3. EXPERIMENT DESIGN

3.1 Experiment Assembly

The experiment takes place at the department of ergonomics, TU München. The static driving simulator includes a mockup with a BWM car and three projection screens, which support 180 degree of sight (see Figure 4).

Figure 4. Static driving simulator

Similar to the steering wheel, substituted by an active wheel, the original accelerator pedal has been replaced by a pedal from Continental. Moreover a side stick from Stirling Dynamics ltd. is integrated into the central console to provide driving capability (see Figure 5).

Figure 5. Central console with side stick from Stirling Dynamics ltd.

The driving simulator software "SILAB", that is developed by the Institute for Traffic Sciences in Wuerzburg receives all necessary commands from these control elements, simulates the vehicle as well as the whole environment and presents the scenery on the three projection surfaces. Furthermore all essential driving values are logged to provide objective data to evaluate the prototypes.

3.2 Prototypes

In this experiment the following four prototypes are being compared:

- Spring centered force reflective side stick
- Position reflective side stick with yaw rate feedback
- Position reflective side stick with steering angle feedback
- Steering wheel, accelerator and brake pedal

All models are tested in manual driving mode, which implies that no assistance is provided.

The force reflective side stick prototype only uses a spring characteristic, which centers the stick in the middle. Longitudinal movement is interpreted as throttle valve attitude or braking depending on the angle. Because there are no additional forces added this version is comparable with a conventional computer joystick.

Both position reflective side stick models measure the force in longitudinal direction and generate the throttle valve attitude or braking accordingly. The position of the stick is correlatively set to the vehicle's velocity. In lateral direction, forces are converted into a change of the steering angle. However the lateral feedback of both prototypes differs. The first sets the angle of the element according to the yaw rate, while the second position reflective alternative reflects the steering angle.

The last prototype, which uses a steering wheel, accelerator and brake pedal as control device composes the conventional manner of driving. Objective driving data of the other versions compared to this one shed light on the potential of increasing driving performance by using other control elements.

3.3 Proband Collective

The sample consists of 24 subjects (13 male, 11 female) divided into two groups. Test persons under the age of 18 with minimal driving experience and test persons above, who own a driving license. These two groups with the average age of 15.4 or respectively 29.1 years have to complete a test track with the total length of 18.8 kilometer (5.5 kilometer highway, 13.3 kilometer road) with all four types of control.

4. EXPERIMENT RESULTS

4.1 Subjective Acceptance

After each run the subjects are asked to assess the driven prototype regarding controllability and strain. The study is completed by a final questionnaire in which all kinds of control interfaces have to be judged in direct comparison.

Figure 6 shows the results for the subjective impression of controllability depending on the kind of control. The subjective rating covers a scale from -3 (no control) to +3 (excellent control).

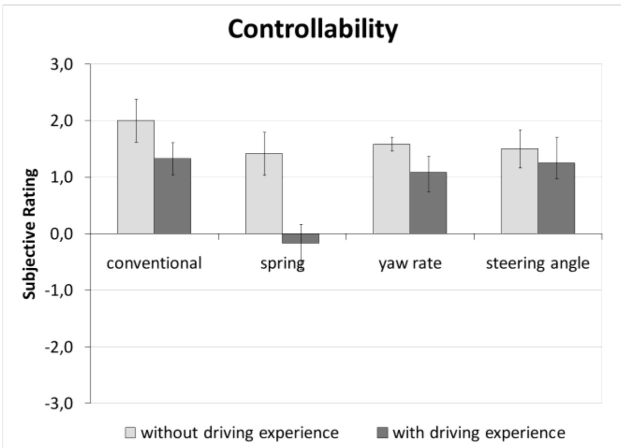

Figure 6. Subjective Rating of Controllability

The results for the group without driving experience show no significant difference between the four types of control interface. That means, that group 1 (without driving experience) has the subjective impression that their performance in car driving is independent from the control element. Much more interesting than that is the fact, that even the group with driving experience states, that the side stick versions with yaw rate or steering angle feedback grant the same controllability as the conventional controls. Only the spring centered side stick version is rated significantly worse. This is due to the fact that this version only gives a feedback about the dynamic properties of the control element itself (spring damper system), but no feedback about the system that has to be controlled.

Regarding the NASA-TLX Overall Workload Index (Figure 7) similar results can be found. Group 1 shows the same strain regardless of the kind of control; whether it is a side stick or steering wheel and pedals. Similar to the controllability results, Group 2 (with driving experience) shows no significant difference between the feedback versions of the side stick and the conventional control elements. The spring centered version of the stick however is rated significantly worse here, too.

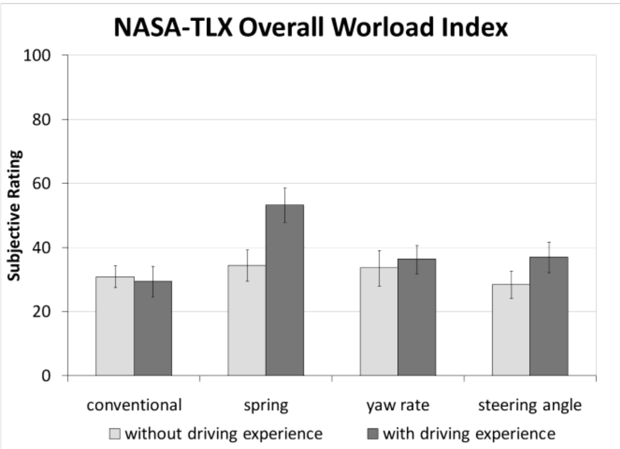

Figure 7. Subjective Rating of the Workload regarding the respective prototypes

4.2 Objective Performance

In addition to the subjective rating the objective driving performance is measured. The assessment of the objective data is divided into longitudinal and lateral driving efficiency.

Figure 8 shows the mean standard deviation of longitudinal speed in a part of the test track where the test persons had to maintain a constant speed of 80 km/h. The mean standard deviation in this case is a characteristic value to assess how good the subjects were able to perform this task.

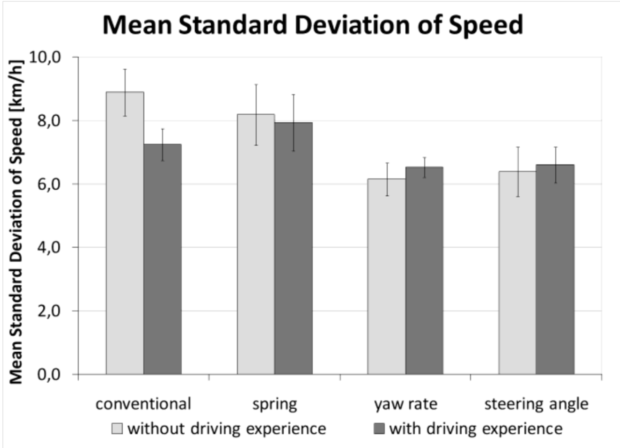

Figure 8. Performance at a longitudinal speed control task

Both, conventional control elements as well as the spring centered side stick give no feedback about the current vehicle speed which leads to a high mean standard deviation of velocity. The feedback versions of the side stick however indicate the driven speed by means of the position of the stick in longitudinal direction. As the figure shows, this feedback leads to a significantly reduced mean standard deviation and therefore to a significant better performance at longitudinal vehicle guidance. This performance enhancement is independent from the level of driving experience.

Representative for the results of the lateral driving performance Figure 9 shows the mean standard deviation of the lateral deviation in right hand bends.

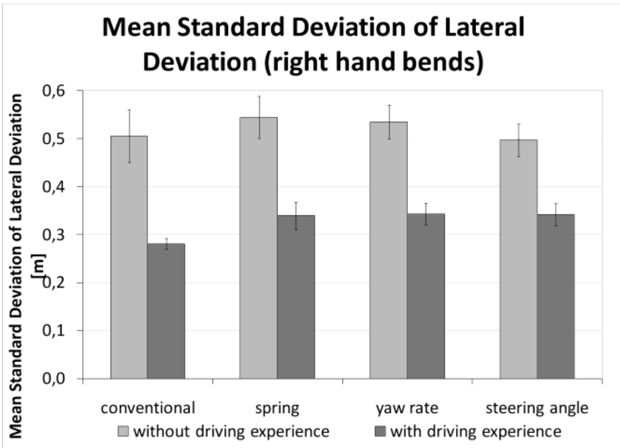

Figure 9. Performance while driving right hand bends

Here statistics show a significantly better performance in lateral control with the conventional control elements compared to the spring centered side stick (α-error = 0.007) and the yaw rate feedback version of the stick (α error = 0.050). The side stick with steering angle feedback however leads to a similar performance as driving with a steering wheel. The differences between the respective interface versions can be found regardless of the level of driving experience.

In left hand bends all of the interface versions show a statistically similar driving performance independently of the level of driving experience. This is most probably due to the bigger and therefore easier controllable radiuses driven in left hand bends.

4.3 Summary

In summary the subjective data of the study shows, that regarding controllability and strain, the position feedback versions of the side stick are rated equal to the conventional control elements.

Moreover the objective data show slight differences between the different interface versions. The side stick with steering angle feedback however shows equal performance in lateral driving tasks as the conventional control elements. In longitudinal driving tasks the position feedback principle even surpasses the performance of the combination steering wheel and pedals.

As a general result it can be said, that the principle of two dimensional control interfaces with position feedback, especially steering angle and speed feedback, is a promising idea to realize the idea of cooperative vehicles.

5. EXTENDING THE PROTOTYPES WITH ASSISTANT INTERACTION

Based on the experimental results, the position reflective side stick with steering angle feedback represents the fundament for additional assistance. As described above, one of the main features of H-Mode is the bi-directional haptic-multimodal coupling with continuous and/or discrete communication between driver and automation. This means that the co-system is able to apply forces to the stick in order to inform the driver about automation recommendations.

The diagram in Figure 10 shows how the system is extended with an arm parallel to the operator, thus allowing the co-system to add signals from the H-Mode automation to the stick.

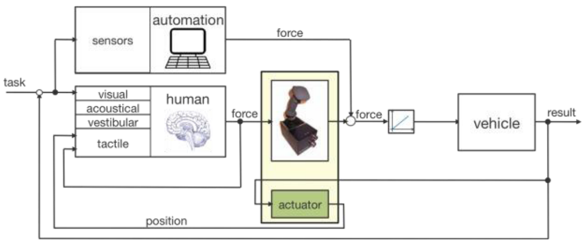

Figure 10. Signal diagram of stick with dynamic feedback and automation

By this means driver and automation system are affecting the vehicle parallel to each other, creating a combined control desire via the convergence point between the active stick and the vehicle. In this way, advantages of redundancy can be used, which leads to a safer overall system. By altering the balance between the human and the automation force the degree of automation can be changed.

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