Designing cooperative interaction of automated vehicles with other road users in mixed traffic environments

interACT D4.3 – Final design and HMI solutions for the interaction of AVs with user on-board and other traffic participants ready for final implementation

Work package	WP4: Suitable HMI for successful human-vehicle interaction.
Task(s)	Task 4.3: Technical development of HMI software and hardware components for human-vehicle interaction.
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Glossary of terms

Term	Description
Addressed messages	Messages that refer to one or more specific TPs
Automated vehicle (AV)	Vehicle that provides automation of longitudinal and lateral vehicle control and can free the driver from the driving task - at least in some driving situations
iHMI	Internal Human-Machine Interface of the AV that is meant to communicate with the user on board
eHMI/external HMI	External Human-Machine-Interface of the AV that is meant to communicate with surrounding traffic participants
Non-addressed messages	Messages for everyone in the environment
On-board user	Human on-board of the AV who acts as a driver in all cases the AV cannot handle (SAE level 3) or is a passenger for all SAE 4 and 5 applications
Other road user	All possible road users from the perspective of the ego vehicle (the AV) i.e. pedestrians, bicyclists, motorcyclists, vehicles, automated vehicles
Perceivable for one or more specific TPs	Sent messages (no matter what modality) that are only perceivable by specific TPs (one or more)
Perceivable for everyone in the environment	Sent messages (no matter what modality) that are perceivable by anyone in the environment
Scenario	Description regarding the sequences of actions and events performed by different actors over a certain amount of time
Scene	Snapshot of the environment. All dynamic elements, as well as all actors and the scenery are included in this snapshot
Use Case	Functional description of the behaviour of the AV in a traffic situation

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List of abbreviations and acronyms

Abbreviation	Meaning
ADS	Automated Driving System
AV	Automated vehicle
CCPU	Coordination and Communication Planning Unit
D	Deliverable
EC	European Commission
ECU	Electronic Control Unit
eHMI	External Human-Machine-Interface
HMI	Human-Machine-Interface
HRU	Human road user
HW	Hardware
iHMI	Internal Human-Machine-Interface (On-Board of the AV)
LCD	Liquid Crystal Display
LED	Light Emitting Diode
PCB	Printed Circuit Board
ROS	Robot Operating System
SW	Software
T	Task
TP	Traffic participant
WP	Work package

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Executive Summary

The interACT project aims to enable the safe deployment of automated vehicles (AVs) by developing novel software and hardware components for reliable communication between an AV, its on-board user and other human road users (HRUs). The project places a particular focus on the design of innovative Human Machine Interfaces (HMIs) to replace current human-human communications in mixed traffic environments. It is expected that the project's goals will facilitate the gradual integration of AVs in future traffic environments.

In this context, Task 4.3 of Work Package (WP) 4 focuses on the technical development of specific HMI solutions. This includes technical components for visual messages, i.e. the technical implementation of new light-based exterior components for the AV (eHMI) and on-board interfaces (iHMI). Final outputs of this task are prototypes, which provide a light-based communication system around the whole vehicle for communication with other traffic participants. In detail: Two eHMI technologies were selected and developed, a Light Band and a so-called Directed Signal Lamp. These devices put the project into a position to implement an intention-based or perception-based interaction strategy or a combination of both. In accordance with overall interaction strategies, two iHMI technologies were selected for the interACT project as well. The communication with the on-board user will be established via a 360° Light Band and an Automation Display.

This deliverable is the final document of WP 4 and describes the HMI solutions. The technical hardware and software components, described in this deliverable, serve as crucial inputs for WP5 "*Integration, Testing and Demonstration*".

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1. Introduction

1.1 Purpose and scope

As Automated Vehicles (AVs) are likely to be deployed in mixed traffic, they need to interact safely and efficiently with other Human Road Users (HRU), including manually driven vehicles, cyclists and pedestrians. To ensure clear, learnable and cooperative interaction between the AV and others, as well as a smooth flow of all traffic, it is essential that there is good means of communication between all actors. The main objective of interACT is to substantially improve this communication and cooperation strategy. In this context, WP 4 develops the overall interaction strategies to govern the interaction between the AV and the on-board user, as well as that between the AV and other HRU. The final Task of WP 4 (T4.3) is to enabe the interACT AV to interact with other human road users in a mixed traffic environment using external Human Machine Interfaces (eHMIs), as well as to transfer information to AV passengers via internal interfaces (iHMIs).

1.2 Intended readership

This deliverable gives final insight into the work of WP 4 and reports the results for the concrete technical HMI design of T4.2 and T4.3 realizing human vehicle interaction strategies reported in D4.1 (Wilbrink, et al., 2018) and D4.2 (Weber, et al., 2019). This deliverable describes the HMI hardware and software components, which were developed and launched within WP4, will be integrated within WP 5 and then evaluated within WP 6. Therefore, this document serves as an input for interACT partners from WP 5 and 6 presenting relevant information on the concrete technical HMI design for the use cases defined in D1.1 (Wilbrink, et al., 2017). It also serves as a documentation of the final work in WP 4 for our Project Officer, the reviewers and the EC. As this deliverable is public, the document is also written for our stakeholders, for other researchers and industrial partners who are interested to know more about the project's technical design approach.

1.3 Relationship with other interACT deliverables

As shown in Figure 1, WP 4 is closely related to the scenario definition in WP 1 *"Scenarios, Requirements and interACT System Architecture",* as the selected use cases for the first WP 4 designs are the must-have use cases defined in D1.1 (Wilbrink, et al., 2017). Furthermore, the HMI requirements reported in D1.2 (Drakoulis, et al., 2017) influence the work of WP 4.

This deliverable continues the work described in D4.1 (Wilbrink, et al., 2018) and D4.2 (Weber, et al., 2019) including interaction strategies for the interACT AVs. As culmination of WP 4, final HMI hardware and software solutions are defined and documented that are avaliable to be integrated into interACT demonstrator vehicles and simulators.

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All results presented in this deliverable are closely related to results of WP 3 *"Cooperation and Communication Planning Unit"* and WP 5 *"Integration, Testing and Demonstration"* that deals with the integration of different components including HMI for the interACT demonstrator vehicles.

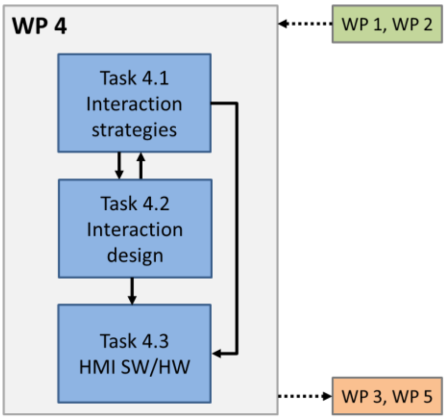

Figure 1: Connection of WP 4 to other work packages.

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2. Objectives in WP 4

WP 4 "*Suitable HMI for successful human-vehicle interaction*" develops the overall interaction strategies and HMI solutions to govern the interaction between the AV and the on-board user, as well as that between the AV and other traffic participants (TPs), such as pedestrians and drivers of other vehicles.

In more detail, the objectives of this WP are to:

- develop generic interaction strategies and general HMI messages to enhance the cooperation and safe interaction between traffic participants, the on-board user and the AV. This work was be based on the interACT scenarios and the requirements of WP 1, as well as the findings and human-human interaction models of WP 2 and is reported in D4.1 (Wilbrink, et al., 2018).
- design the concrete HMI messages to be used by the AV. These include explicit communication via HMI and the transfer of implicit cues, by adjusting the driving behaviour of the AV. This work is presented in D4.2 (Weber, et al., 2019).
- develop and adapt technical HMI hardware solutions, to be employed as explicit communication means, and provide software modules for controlling the HMI hardware elements for simulators and demonstrator vehicles via the CCPU of WP 3. This work is documented in this deliverable D4.3.

All this is done in an iterative, user-centred design process to allow for improvements of the chosen design based on user feedback during the whole design process. Figure 2 shows this process followed within WP 4 of interACT.

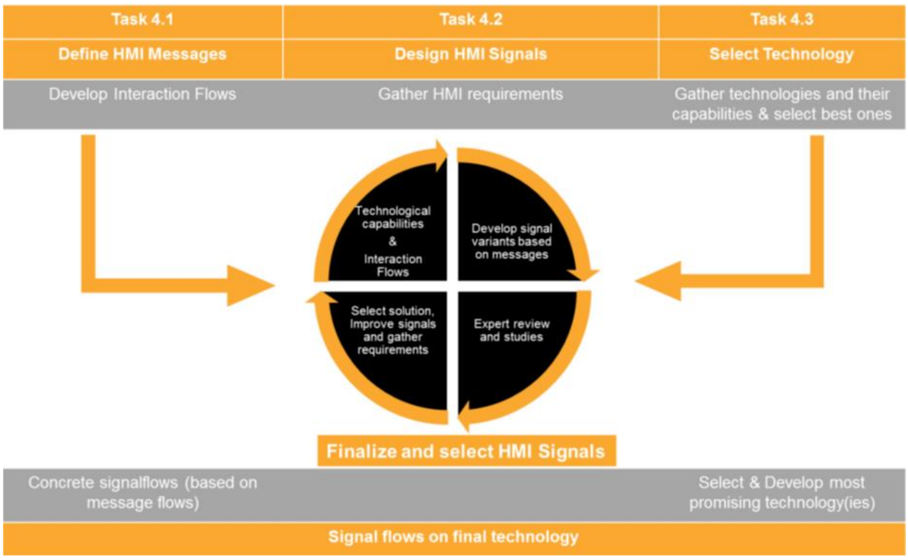

Figure 2: WP 4 working process in interACT.

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While Task 4.1 and Task 4.2 delivered the theoretical background of the HMI design, Task 4.3 focuses on the technical development of specific HMI solutions, which is described in present D4.3. This includes technical components for visual messages, i.e. the technical development of new light-based exterior components for the AV (eHMI) and on-board interfaces (iHMI). Final outputs of this task are prototypes, which provide a light-based communication system around the whole vehicle for communication with other traffic participants. While essential framework parameters like type, mounting position, angle ranges and light colour are already set in D4.2 (Weber, et al., 2019), the present D4.3 provides all technical details of the HMI prototypes.

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3. Technical Implementation of HMI Technologies

This chapter is mainly based on the preliminary interACT interaction strategies, the message catalogue (Wilbrink, et al., 2018) and selection of most promising eHMI and iHMI technologies (Weber, et al., 2019). Furthermore, the technically implemented solutions fulfil the relevant overall project requirements (Drakoulis, et al., 2017) and address the interACT use cases and scenarios (Wilbrink, et al., 2017).

3.1 External HMI

Depending on interaction strategy and messages that should be transferred, the AV can communicate information that refer to the vehicle itself, as well as information that refers to certain TPs. Information that refers to the vehicle itself can be communicated to every TP. If information is addressed to one certain HRU, it can be an option to reduce the visibility to only that addressed person. The interACT project decided to have a closer look on both possibilities. This is the main reason why two different kinds of eHMI are developed and investigated during project duration.

The design work was based on the following results from WP 4 research work:

- Visual channel was turned out to be most suitable for an AV's eHMI;
- Cyan/turquoise/blue-green (different terms for same colour range) emerges as colour of choice for novel AV Lighting functions;
- Light Band (eHMI_1) and Directed Signal Lamp (eHMI_2) were already chosen to transfer different kind of messages in variable signal designs. (Weber, et al., 2019)

It is iimportant to mention, that the novel eHMI units and functions of the interACT project are not meant to replace existing and established light units and functions (such as braking lights or indicators). They are an add-on, no substitution.

In addition to the overall and specific requirements from D1.2 (Drakoulis, et al., 2017) and D4.2 (Weber, et al., 2019), the eHMI development pursues the target to keep the impact on the demonstrator car bodies as small as possible. Thus, smooth integration played a main role right from the start of design work. Figure 3 shows the targeted appearance of the selected eHMI elements exemplarily on the BMW i3s demonstrator vehicle.

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Figure 3: Type, mounting position and light colour of selected eHMI technologies for the BMW i3s – Light Band (left) and Directed Signal Lamp (right).

3.1.1 Light Band

Idea

The Light Band is a direct light-emitting and more or less horizontal ring around the vehicle, which can be illuminated completely or segmentally (see left side of Figure 3). It ideally covers 360° and follows the contours of the car. The Light Band can be realized by integrating several light-emitting surfaces in a row. An individual driving circuit for each light source allows the individual control of small segments (Weber, et al., 2019).

The fundamental idea of a Light Band is already described in interACT related papers (Sorokin, et al., 2019), (Weber, et al., 2019) as well as preceded foreign studies like Nissan IDS concept (Nissan IDS, 2015) or the funded project AVIP (AVIP, 2015).

Concept

Core components of the Light Band concept are blue-green light emitting diodes (LEDs) with a dominant wavelength of ≥ 495 nm. Within WP 4 a decision was made to use monochromatic, narrow band semiconductor light sources and <u>not</u> to mix up a light colour by using converters or even RGB-LEDs. Because – independent of any colour – the more saturated a colour is, the better is its signalization effect (Tiesler-Wittig, 2018).

The overall concept and implementation are orientated on later integration of the Light Band into the BMW demonstrator vehicle. The bottleneck of the concept, because of minimum design space, is the

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BMW i3s' A-pillar, as well as the area above the doors. Thus, the technical development and mechanical design started at these most critical car body parts. The result is a concept shown in Figure 4, detailing a sectional view on the area above the driver's door.

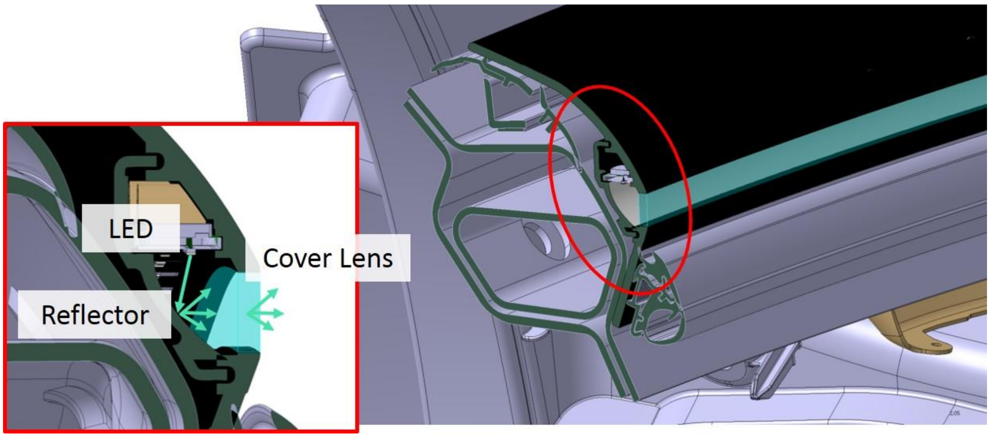

Figure 4: Concept of Light Band at minimal construction spaces.

An additional view (red square) illustrates the optical concept in detail for one LED. In general, LEDs are almost predestined for applications like this, because they are established as robust, efficient, monochromatic light sources in automotive signal lamps. In the present concept, all LEDs as part of the Light Band have their main radiation direction to the ground. The light is reflected, redirected (ca. 90°) and scattered by a white reflector, before it passes the outer lens. This cover lens, which gives the Light Band its appearance is 10 mm high and has got a micro-structured scattering inner surface. A homogeneous overall appearance across the length of the Light Band can be realized using multiple LEDs placed 10 mm apart from each other. That means 100 LED per meter of Light Band. Figure 5 shows a light simulation of the concept (ten neighbouring LED switched on) by using false-colours to get a visual impression about inhomogeneity.

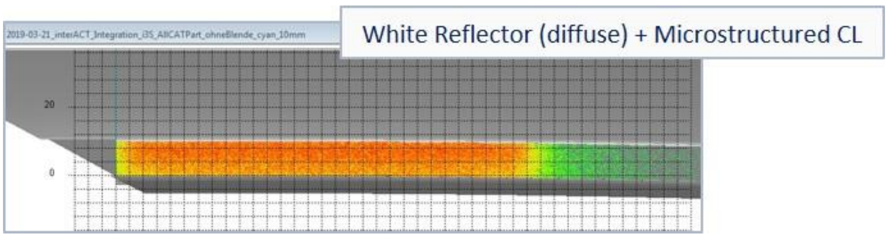

Figure 5: Simulated qualitative luminance distribution of Light Band Concept.

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Finally, the overall concept for the project is a compromise of design space, integrability, efficiency, visual homogeneity (while all LED are switched on), thermal management and electronics. Electronics further include the addressability and signal refreshing of each single LED in real time. This enables an implementation of any Light Band animation (signal design) and an adaptation to environmental conditions, use cases, etc.

Implementation

A first implementation of the Light Band concept led to a desktop sample shown in Figure 6. This sample helped the developers during the development phase to check and validate the concept simulation. Furthermore, this mock up delivered a first impression about the expected light colour, visibility and overall appearance for the modules which will be integrated into the interACT demo vehicles.

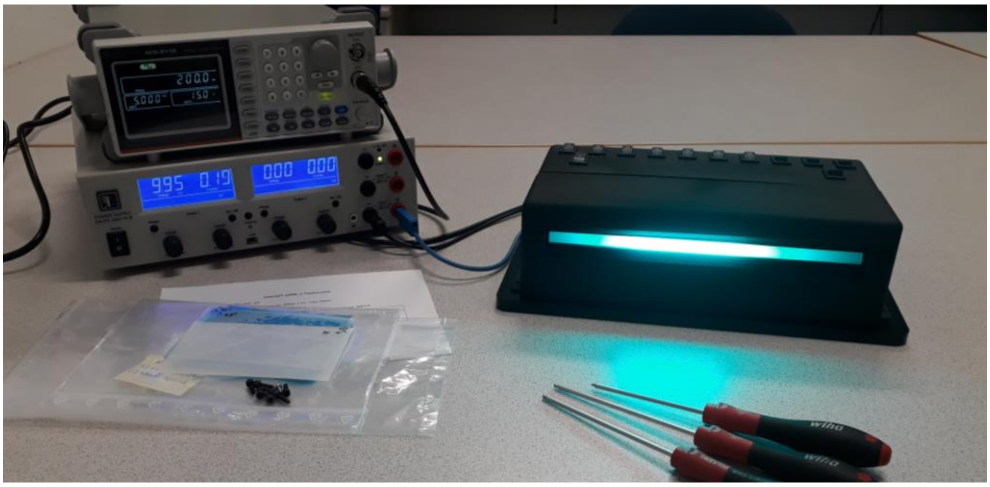

Figure 6: Desktop sample of Light Band.

Integration

As an outlook to WP 5, the Light Band concept (eHMI_1) will be integrated into both interACT demonstrator vehicles. In detail, these are the BMW's i3s and CRF's JEEP Renegade. Figure 7 shows the Light Band with its thin 10 mm high outer lens, embedded in the black car body parts of the BMW vehicle's front, side and back.

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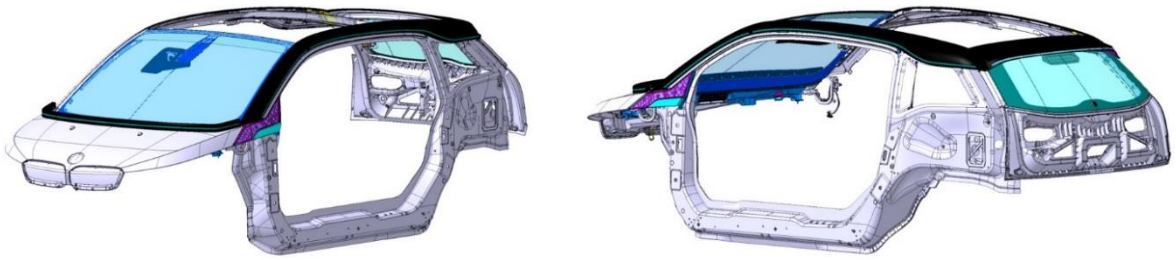

Figure 7: Integration of Light Band into BMW i3s.

In the end, 774 individually controllable LED will form the 360° Light Band of the BMW i3s. To realize a Light Band mounting under the windshield and a main vertical light beam in driving direction, the car body has to be modified. Thus, a housing including light sources and optics is put on the BMW's bonnet. This approach is the same for the CRF vehicle, depicted in Figure 8.

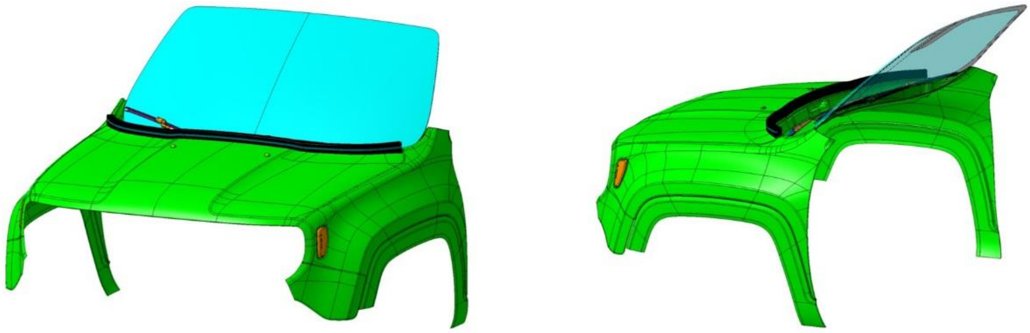

Figure 8: Integration of Light Band into the JEEP Renegade demonstrator.

For the JEEP demonstrator, the Light Band application of the BMW was adapted so that 150 discrete LED represent the Light Band in this case. Due to resources and time constraints the Light Band application for the CRF demo vehicle is limited to scenarios where relevant TPs have got a view on the vehicle's front.

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3.1.2 Directed Signal Lamp

Idea

While a display is able to show symbols, text or animation, a signal lamp only uses light signals to transport a certain message. By using codes, different frequencies or light colours, different messages can be coded. A conventional signal lamp can be used to signalize e.g. a certain vehicle state or a next manoeuvre. Those messages refer to the vehicle itself, while it is useful that the light signals are visible for any other TP. As soon as a light signal can only be seen by one traffic participant, to whom a message refers, a light signal could contain messages that refer only to the related traffic participant. Thus, the concept of a Directed Signal Lamp was used in the project to allow the transfer of perception-based design messages that are meant for specific traffic participants (Figure 9).

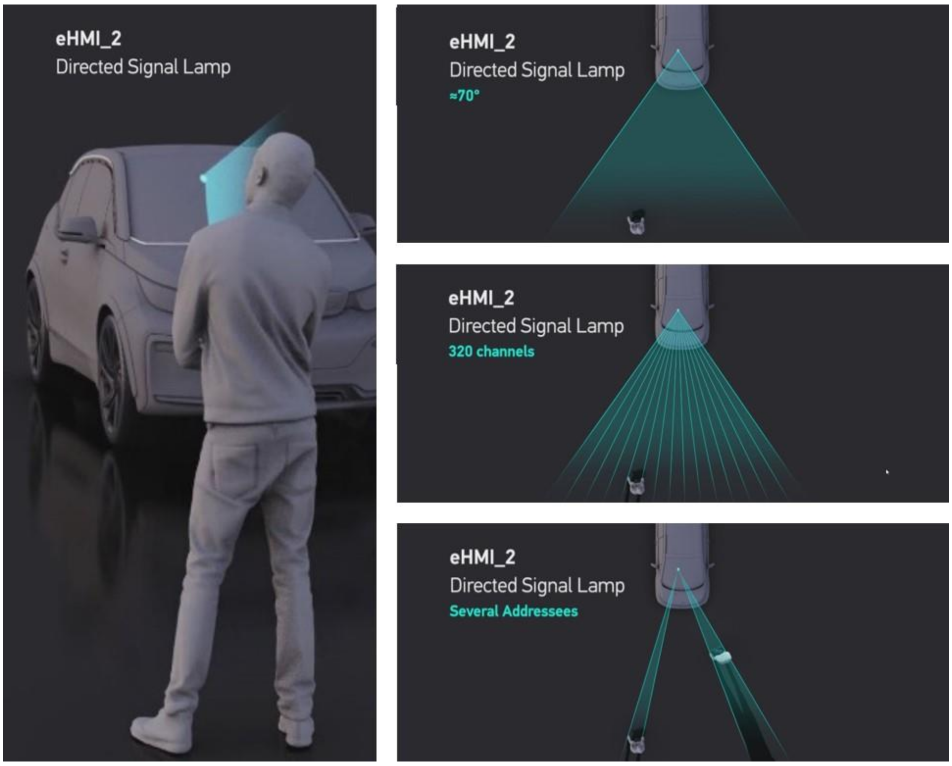

Figure 9: Abstract idea and properties of Directed Signal Lamp.

The idea behind the Directed Signal Lamp works as follows: Every detected traffic participant (regarded as "relevant") sees a light signal that lets her/him know that s/he has been detected and that the vehicle is aware of that, while other, possibly not detected or not relevant traffic participants, would not see a light signal at all. This leads to avoidance of distraction, miscommunication and overstimulation for none-relevant TPs (Dietrich, et al., 2018). All in all, the Directed Signal Lamp idea

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was developed while dealing with the question if and how addressed messages could be conveyed only to specific relevant HRU.

Concept

The technical conception of the Directed Signal Lamp module can be obtained by combining a light source, an addressable imaging element and optics. Overarching goal is a directed interaction over a distance of up to 25 m. To address one HRU separately, discrete light channels, each with a theoretical horizontal angle of ≤ 0,25°, are utilized (Willrodt, et al., 2017b).

By using small light emitting areas that are punctiform light sources in the eyes of an observer, the minimal addressing intensity is described in luminous intensity (RICCO's law) (Ricco, 1877). In a study, the visibility of green punctiform light sources at daytime for different luminous intensities have been investigated. The luminous intensity for addressing is 8 cd, areas that are not addressed should be darker than 0,2 cd (Willrodt, et al., 2017a).

The most promising optical concept for near term realization of a Directed Signal Lamp is an imaging lens system (Figure 10). Four lenses ④ image a display ③ over an angle of 70°. By imaging 320 columns of an display, 320 separate light channels, each one ≤ 0,25°, can be realized.

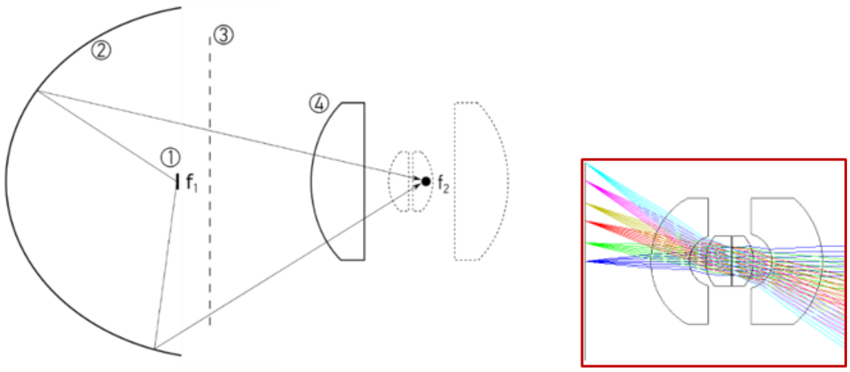

Figure 10: Optical Concept of Directed Signal Lamp (Willrodt, et al., 2018)**.**

As shown in Figure 10, a parallel backlight illumination of the display ③ with active width of 45 mm would cause that the light of the edge regions would not couple into the optical lens system ④ with its maximum diameter of 28,5 mm. Thus, an elliptical reflector ② with its two focal points reflects the emitted light of a light source ① to the display ③. The edge regions are illuminated under higher angles than the regions in the middle of the display. This causes an optimal coupling into the first lens of the lens system ④.

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Implementation

Core of the optical concept is an exclusive Liquid Crystal Display (LCD), which fits with regard to display size and number of columns to the overall concept. Furthermore, the LCD is a monochromatic device, optimized to a dominant wavelength between "blue" and "green". Another crucial reason why not any desired display can be chosen is that high contrasts are needed for any illumination angle of incidence between 0° and 35°. Automotive qualification of this device is not part of interACT, but the state of the art already demonstrates that LCDs are able to fulfil automotive requirements for exterior lighting functions (Duhme, et al., 2017).

Figure 11 visualizes the Directed Signal Lamp from different perspectives. A sectional view shows the main components known from the concept and already its mounting position behind the windshield. The LCD is illustrated as a "purple plane" in these graphics.

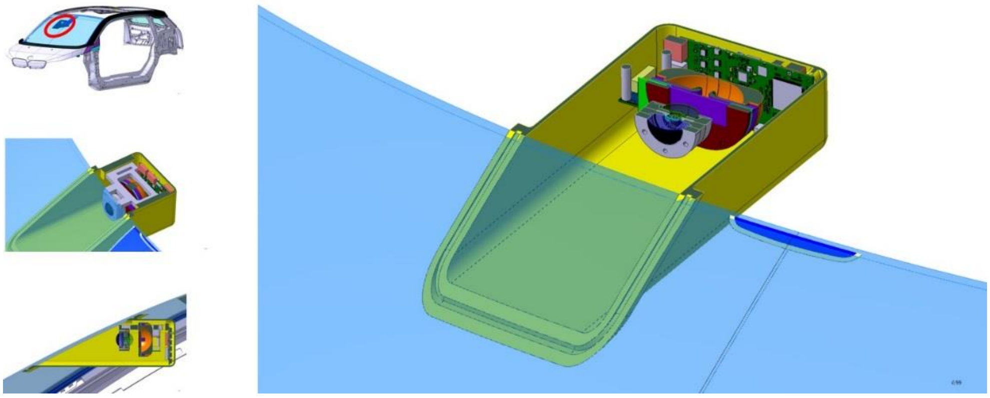

Figure 11: Implementation of Directed Signal Lamp.

With regard to light colour, a compromise has to be accepted for this Signal Lamp prototype, because current cyan/turquoise/blue-green LEDs do not reach the needed luminance for an application like this to fulfil the luminous intensity from concept. This is why "brighter" green LEDs serve as light sources inside the very first Directed Signal Lamp mock up, implemented during the interACT project duration. In parallel, light source suppliers are working with much effort on this overall topic, developing blue-green semiconductor light sources for potential future AV applications (Tiesler-Wittig, 2018).

While the appearance of this signal lamp is monochromatic and one-dimensional, a coding of different messages (if needed) has to be done by frequency modulation (flashing or pulsing). This can be done via eHMI-ECU (Electronic Control Unit) by the LED or the LCD or a combination of both.

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Integration

Within interACT, the Directed Signal Lamp will not only be build up as an independent desktop sample. One module will also be integrated in one of the demo vehicles. In Figure 12 the technical integration of both eHMI solutions into the BMW i3s is presented as a next step in comparison to the surface framework design described in D4.2 (Weber, et al., 2019).

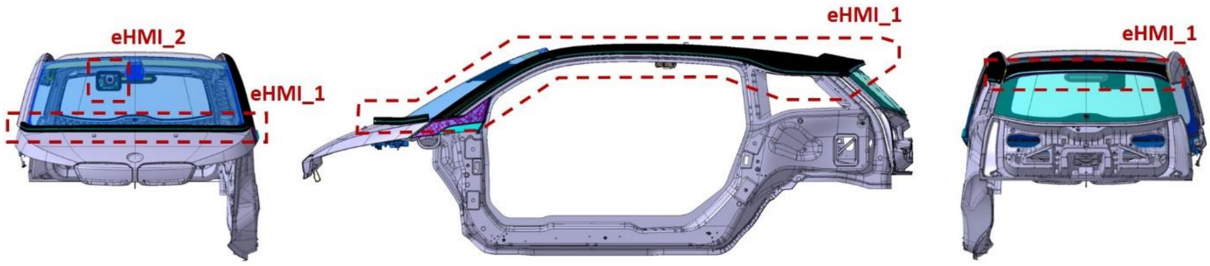

Figure 12: Integration of eHMI_1 (Light Band) and eHMI_2 (Directed Signal Lamp) in the BMW i3s.

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3.2 Internal HMI (iHMI)

In parallel to the eHMI solutions for communication to other road users, an iHMI strategy for the interaction with the on-board user was developed. The iHMI should enhance transparency regarding the behaviour of the AV resulting in higher trust, acceptance and perceived safety by the on-board user. The interaction with the on-board user will be realized via a 360° Light Band and an automation display.

3.2.1 360° Light Band

Idea

The 360° Light Band uses the peripheral vision of the on-board user to transfer messages and information in an unobtrusive way. Therefore, the Light Band display animations change its colour or pulses in a certain frequency. Users are able to perceive information, communicated via the Light Band independent from their seating position and without focusing on the Light Band.

Concept

The 360° LED band for the interior of the vehicle is used as a visual concept for the user on-board interaction. Therefore, it focuses on the visual modality to transfer information from the AV to the on-board user.

As hardware, the LED band "MagiarLEDIII felx stripe 114" from "DMX4ALL" is used. The main advantage of the used LED band is that it consists of RGB LEDs which can produce over 16 million different colours. Furthermore, each LED can be triggered independently from the other LEDs on the band. The Light Band consists of 360 LED (48 LEDs per meter) and has a complete length of 7,5 m. The LED Band runs with 5V DC and is controlled by an Arduino Uno. The triggering of the LED band is done by a customized software solution programmed by DLR. The software makes it possible to display different colours and animations, which are triggered by the automation.

The concept for the interaction with the LED band is that the light should be perceived as a homogeneous surface. Therefore, we installed the LED band inside a c-profile and used a translucent glass as diffuser (see Figure 13). The LED directly faces the diffusor, which is installed in a distance of 30 mm to the LED band. The distance between the LEDs (ca. 210 mm) was chosen as a compromise between having a homogeneous appearance of the light and the visual effect of triggering single LEDs. Only one stripe was used so there was no effect of multiple vertical LEDs possible. Due to the RGB LEDs a huge variant of different designs were possible to implement on the LED band.

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Figure 13: Sketch of the LED stripe (left), bended diffusor for side elements (right).

Implementation

The LED band is positioned inside the simulator vehicle (Figure 14). At the sides, it is located at the root of the side windows approximately on shoulder height. In the front the LED band is installed at the root of the windshield. In the back the LED band is implemented under the roof of the simulator vehicle.

Figure 14: Integration of the 360° Light Band in driving simulator vehicle.

Integration

The LED band is integrated DLR driving simulator vehicle. As part of the evaluation it is planned to use the DLR driving simulator with the LED band in WP 6.

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3.2.2 Automation display

General approach

The automation display is an additional display used to transfer information for the user on board to inform her/him about interaction partners of the AV and/or the intention of the AV e.g. slowing down or starting to move. On the display, symbolic and textual communication is used to enhance the transparency of the AV behaviour. The design for this is described in detail in D4.2 (Weber, et al., 2019). Figure 15 shows an example of a display message.

Figure 15: Example for the on-board HMI display.

Integration

The automation display will be integrated in the CRF JEEP Renegade demo vehicle. The display will be positioned on the right-hand side of the on-board user in the height of the navigation display. Figure 16 shows a sketch of the display position in the JEEP Renegade.

Figure 16: Sketch of the display position in the JEEP Renegade.

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Software control of the display

The Robot Operating System (ROS) is used on the CCPU for the inter-process communication, exchanging data about the current traffic situation and detected traffic participants between computers and applications. The CCPU generates the interaction orders for the external and internal HMI, based on the current situation and the planned driving behaviour.

A CCPU Display ROS node will be developed, which is capable of displaying the generated interaction strategy to the on-board user. The LCD display is connected to the CCPU Display ROS-node via HDMI (Figure 17). For the visualisation of the data the rqt-API will be used, which is based on QT-GUI. The main input for the CCPU Display node will be the CCPU node and other ROS nodes that are related to the sensors data fusion. Further information regarding the current scenario will be taken into account for displaying relevant information to the on-board user.

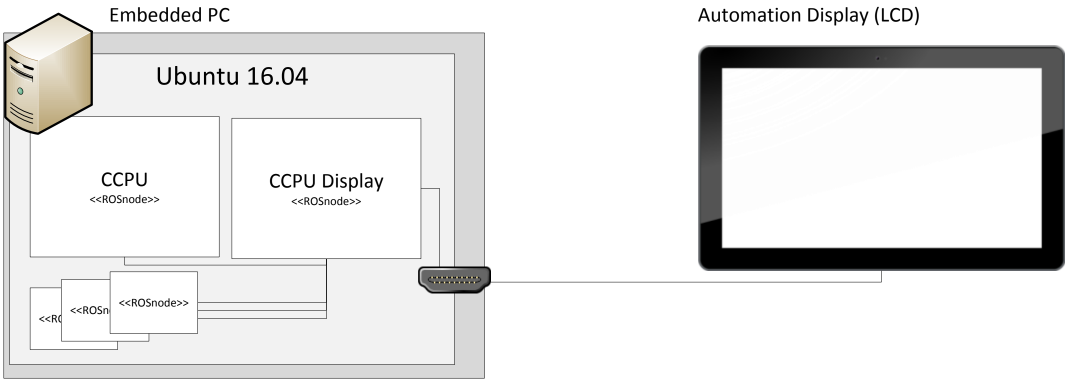

Figure 17: Diagram showing HW/SW components and the data transmission between CCPU and automation display.

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4. Conclusion & Outlook

D4.3 presents the technical HMI prototypes for the interaction of AVs with other traffic participants and on-board users. The present deliverable focuses on the technical realisation of the interaction strategies described in D4.2. Therefore, the final hardware and software components required for the implementation of the interaction strategies are documented and described in this deliverable.

Two eHMI technologies were selected and developed, which are now available for the integration in the interACT project (WP5): the Light Band (eHMI_1) and the Directed Signal Lamp (eHMI_2). These devices put the project into a position to implement an intention-based or perception-based interaction strategy or a combination of both. Furthermore, both eHMI variants are able to transfer messages in accordance with the message catalogue and signal design catalogue compiled in WP 4.

As next step, these two eHMI-technologies will be integrated within WP 5. Furthermore, all components will be launched inside the demonstrator vehicles for evaluation (WP 6).

In coordination with the eHMI strategies, two iHMI technologies were selected and further developed for the interACT project as well. The communication with the on-board user will be established via a 360° Light Band and an Automation Display. The display was chosen to be installed in the interior of the CRF demo vehicle within WP 5. The evaluation of the iHMI will take place in WP 6.

With the successful completion of the technical development of the HMI prototypes as documented in this deliverable, WP 4 is finished and the WP 4 related results of the interACT Milestone 4 are reached.

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Designing cooperative interaction of automated vehicles with other road users in mixed traffic environments