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SHPbench – a *Smart Hybrid Prototyping* based environment for early testing, verification and (user based) validation of Advanced Driver Assistant Systems of cars

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Abstract

Statistical analysis show that more than 90 percent of all car accidents result from human mistakes. Advanced Driver Assistant Systems (ADAS) are intended to support and assist the car driver, and therefore contribute significantly to the reduction of accidents. ADAS become more and more complex and demanding regarding hard- and software fulfilling the requirements applied onto assistant systems nowadays and in the future. They have to be considered as multi-functional multi-domain mechatronic systems. *Smart Hybrid Prototyping* (SHP) is a by now proven approach for handling ADAS' demands during and to the development process, specifically for early integrated component and system testing, its verification and validation with the focus on the interaction with the driver can only be reasonably and economically met by utilizing the SHP technology. For those mentioned purposes the *SHPbench*, an integrated development and validation environment, has been recently developed. The *SHPbench's* architecture and specification is presented and evaluated by applying a representative use case of an ADAS development process. This paper documents the use case setup, process steps and test results.

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Keywords: Model-based systems engineering, Simulation driven design, Hybrid Prototyping, verification and validation of complex systems

1. Introduction

Based on statistical analysis of vehicle data, more than 90 percent of all car accidents are caused by human mistakes [1]. Aiming to reduce the risk of accidents, a continuous increase of driver support functionalities in the automotive cockpit can be observed. A significant number of those support systems are considered as Driver Assistant Systems (DAS). Their core functionalities range from sole information visualizations upto accomplishing complex car control tasks.

As a subset of DAS, Advanced Driver Assistant Systems (ADAS) show the following properties and capabilities:

- active control of the vehicle system with the car's lateral and/or longitudinal dynamics [2] and
- driver's intention override functionality.

Consequentially, a successful application of ADAS in modern car cockpits requires a sufficient driver acceptance. This depends highly on the usability and the transparency of the ADAS's human machine interface (HMI) [1].

This functional extension leads on the one hand to a significant increase in system design tasks' complexity because the vehicle environment needs to be incorporated into the assistance function from the first design steps on. On the other hand, an early integration of the human-machine interaction into the whole vehicle's product development process is required for the successful deployment onto the market. Current ADAS development processes, their applied methods and tools do not sufficiently facilitate full system integration early enough during the process. This deficit is mainly caused by the missing availability of functional prototypes of the designated ADAS during the early design stages [3]. Because such late

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testing of systems usually leads to extremely costly and time consuming problem solving iterations [4], the designer should execute frontloading as an approach to "shift the identification and solving of design problems in earlier phase of a product development process" [4]. In 2009, Stark et al. [6] introduced the validation technology *Smart Hybrid Prototyping* (SHP). SHP comprises the usage of hybrid product and / or component prototypes providing fully functional validation setups for multimodal human-machine interaction early enough during the development process. Already evaluated in several use cases of vehicle development, SHP proved its suitability for usability and functional behavior validation.

This research article's objective is the documentation of the development of a concept for the application of the SHP technology for ADAS development processes. A proof of concept shows the applicability of this concept.

2. Development of Advanced Driver Assistant Systems

The broad range of existing ADAS on the market may be structured by different aspects such as **functionality** (e.g. brake assist), **sensor technology** (e.g. radar) and **vehicle type** (e.g. passenger car).

Despite of the differences in purpose, function and technology, ADAS are designed as a three-part structure that is generally applicable (derived from Lorenz [7]):

- **Data acquisition** by the technical element sensor,
- **Data processing** by the technical element controller and
- **Communication and intervention** by the technical element human machine interface (HMI).

The HMI elements can be distinguished between display interfaces for communication from machine to human and control elements as communication interface from human to machine [5].

2.1. State of the art ADAS development processes

The introduction of the V-Model as paradigm in development processes of electronic vehicle systems led to a structured development process established at car manufacturers and their system partners [5]. Systems engineering (SE), as it can be partially visualized by the V-model, offers an interdisciplinary approach to establish a foundation for the design and test of mechatronic systems [8]. SE thereby integrates all the system-related disciplines and their associated specialists into an interdisciplinary and structured systematic development process.

Fig. 1 shows one view onto a potential ADAS development process. During the process from definition of the requirements until full system validation the perspective switches from system scope which requires parallel and integrated cross-domain activities to domain specific tasks and back. The process described by Winner [5] thereby focuses on the development of the subsystems *data processing* and *communication and intervention* respectively their technical elements *controller* and *HMI*. Not applying subsystem's data acquisition and their technical elements *sensors* is a circumstance described by Schwarz [2] stating that current ADAS development processes distinguish between "controllability" evaluation and the HMI evaluation. Controllability is here defined as "entire ADAS-driver-environment interaction comprising normal system use within system limits ... [] … and beyond" [2]. The controller subsystem thereby is evaluated based on its behavior depending on inputs from sensors providing information about the vehicle dynamics as well as the traffic environment the vehicle interacts with. The controllers' behavior of course provides outputs to actuators affecting the vehicle dynamics as well as the driver's behavior [9].

Requirements to the product ADAS are transferred to the product's functions which are reasonably structured and linked to their requirements for later traceability. The function structure is formalized as so-called logics representation [10]. This represents the core of the later components materializing those functions. These system level tasks are followed by the subsystem tasks of developing the subsystems controller and HMI. Those tasks are driven by the initially specified architecture, followed by the component specification, the design and implementation [10]. Based on test cases derived from the specification of the architecture and their fulfilling components, the sub-system's internal verification takes places and delivers test results to verify the subsystem functions according to the specifications.

After the subsystem verification, the subsystems are integrated into a complete ADAS system – still on a purely virtual base. The ADAS is then verified to behave according to logical and technical specification. The final step of the system validation task tests the ADAS as a system by processing human centered tests to validate that the system meets the requirements [10].

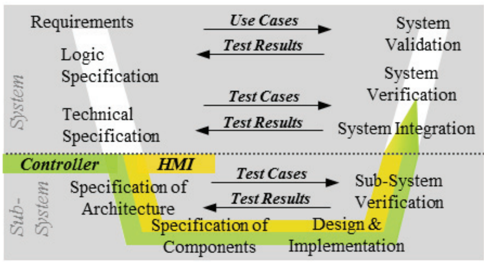


Fig. 1: V-model based ADAS development process (based on [2, 5])

2.2. Verification in ADAS development

The verification of the controller subsystem is done by dynamic behavior simulation within a control loop, simulating the input of vehicle dynamics, sensors, actuators, and the traffic environment [10]. Fig 2 (left) shows the test methods used to verify the controller subsystem. The first verification is done with a Model-in-the Loop (MiL) method using behavior models representing the controller. The MiL method is used to verify the controller algorithm [10]. After an implementing the behavior as software code in its final programming language multiple Software-in-the Loop (SiL) tests are run to evaluate the reaction of the software code to virtual input [10]. Finally, Hardware-in-the Loop (HiL) tests are run which incorporate the controller's software code implemented and executed on its controller hardware using the original compiler [10]. The HiL tests are used to evaluate the controller's behavior including potential biases and limitations due to the hardware it is run on. This also includes the validation against electrical and electronic effects of the controller hardware within the virtual environment [10].

To validate the proper fulfillment of the requirements to HMI under especially ergonomic or usability aspects the user (vehicle operator) is an essential participant of each test phase [5]. Niedermaier [3] describes a sequence of process steps shown in Fig 2 (right) starting with the specification, followed by the concept including the choice of selected human machine interaction modes and of selected interaction elements. First verification tests of the subsequent interface design are processed using criteria based methods such as checklists or heuristic methods [3]. The HMI's geometric shape and spatial / topological relation towards the user and its environment (car cockpit) are then designed in CAD [5]. The CAD models are validated against geometric specifications resulting from regulations, anthropometric databases and product requirements, preferably by using (virtual) human models (VHM).

This step is followed by physical implementation of the CAD model into a physical prototype. Using different levels of realizations of the future HMI (from simple geometric mock-ups up to fully functional HMIs), from there on further tests are run including real humans.

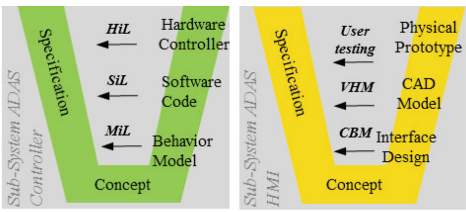


Fig. 2 (left): Verification methods in ADAS Controller development (based on [10]), Fig. 2 (right): Verification methods in ADAS HMI development (based on [3, 5])

3. Application of the *Smart Hybrid Prototyping* technology

The application of the SHP approach and its technology to support ADAS development processes required prior validations of its applicability utilizing already developed ADAS systems.

3.1. Smart Hybrid Prototyping (SHP)

The Smart Hybrid Prototype (SHP) technology provides multi-modal human-machine-interaction in very early phases of many product development processes by providing hybrid prototyping technology [6]. Following Bruno et al [11], hybrid (or mixed) prototypes can be described as a simultaneous presence of virtual and real objects that interact with each other. The SHP technology enriches mostly CAD model-based component or system representations with behavior models and allows even for haptic interaction between the product and human testers [12].

The *smart* component of SHP characterizes the versatility of the hybrid prototypes, as they can be assembled on an easy-to-reconfigure basis out of existing physical and virtual components [12]. Furthermore it references to the modularity of the smart hybrid prototype components out of which the desired prototype can be easily assembled to represent the required set of product functionalities [9]. It is obvious that this results in cost efficiency and quick test setup creation for a broad field of applications at low costs [13].

The SHP technology was validated by developing, assembling and testing a passenger car's tailgate device [12]. The tailgate test setup is shown at Fig 3. Yet, the application of SHPs requires to distinguish between the object (product to be developed) that needs to be tested and the environment in which the specimen is to be tested. Schäuffele/Zurawka [10] defined a "prototyping setup" consisting of the **prototype** and the **prototyping environment** where the latter creates the conditions that are directly connected to the prototype to verify the prototype.

Such a setup has also been established for the above mentioned tailgate test using virtual behavior models of the tailgate, a haptic interaction device and a virtual environment representing the future application environment of the tailgate. As the tailgate was designed to validate the functional opening and closing behavior [12], the controller behavior model is the prototype in this setup (light green block). The specific hybrid prototyping environment (dark grey blocks) consists of the physical tailgate device (haptic device) coupled with the functional virtual tailgate.

Figure 3: SHP tailgate device prototype setup

To display the virtual parts of the setup an active-stereoscopic CAVE environment allows for the required immersion. All these elements have specific interfaces for visual and haptic interaction with the user which are here displayed by the arrows.

3.2. Applicability of SHP for ADAS development tasks

The tailgate device can be described as a composed application of model-in-the-loop and user testing methods according to the considerations in chapter 2. For proof of its applicability for product validation purpose [12] the usability of its behavior models, as they are also used in ADAS controller development, needed to be shown.

The tailgate haptic device's design bases on geometric specification of the car tailgate (product). It provides the functional haptic interaction experience between user and behavior models [12]. It is built out of standard fixture elements such as light weight bars and connectors to provide a high durability and reliability at low costs and with a small number of individually manufactured parts [12]. These design principles can be used for ADAS HMI hybrid prototyping, with the ADAS interface design providing specifications of the necessary functional behavior of the future product's display and control elements as well as the output design for displays and the HMI CAD model providing geometric properties of the HMI elements.

4. Development of *SHPbench*

It was shown in chapter 3 that the SHP approach provides the ability to integrate behavior models and enables the design of HMI prototypes based on HMI interface design and HMI CAD model.

A functional prototyping environment for ADAS has to provide a control loop that simulates the input of vehicle dynamics, sensors, actuators, and the traffic environment according to the MiL specifications described in chapter 2. Furthermore, the driver has to be integrated into the test setups for the desired high level of detail of the early test including human interaction with the future product. Drive simulators provide these capabilities to some extent [14]. They thereby deliver a virtual prototyping environment consisting of the virtual car and its surrounding virtual environment as well as a physical prototyping environment consisting of drive task related control elements (HMIs) such as a physical (haptic) steering wheel, brake and drive pedal and visual and auditive displays to let the user truly experience the virtual content [14].

The concept of *SHPbench* – an acronym for "*Smart Hybrid Prototyping* test bench" – was developed and described as the basis for interconnected SHP devices and (conventional) drive simulator environments.

4.1. SHPbench requirements

Based on the analysis of ADAS development processes and the SHP approach two categories of design requirements to the *SHPbench* itself were identified and stated in table 1.

Table 1. Top level requirement list to *SHPbench*

	No	Requirement
ADAS development	1	Behavior models from controller development need to be integrated.
ADAS development	2	Interface design information from HMI development need to be functional integrated.
ADAS development	3	CAD model based information from HMI development need to be integrated.
ADAS development	4	Functional physical HMI prototypes need to be integrated to enable user testing.
ADAS development	5	A drive simulator needs to provide the "control loop" including a virtual vehicle and virtual environment.
ADAS development	6	A drive simulator needs to provide the HMI for primary drive task and display of virtual content.
SHP	7	High usability and flexibility of the test environment for the ADAS developer needs to be ensured.
SHP	8	A flexible setup, including simple exchange of elements and user test setups has to be provided.
SHP	9	Modular and cost efficient hardware components need to be provided.

4.2. SHPbench concept

The *SHPbench* provides a standardized framework containing standardized interfaces and standardized to enable sufficient usability and re-configurability (Fig. 4.). It may be separated into the *SHPbench* (prototyping) framework and its three sub-frameworks (light grey blocks) and the *SHPbench* (prototyping) environment (dark grey blocks). The models used in the ADAS development process (white, light green and yellow blocks) are utilized as input into the *SHPbench* framework to design smart hybrid prototypes. All these elements have specific interfaces as displayed by the arrows.

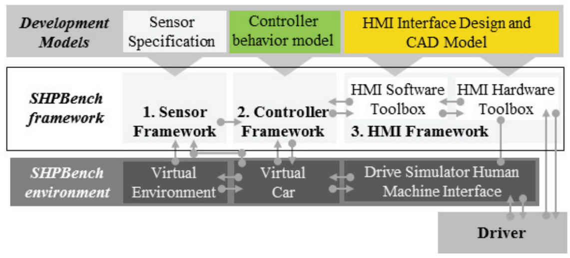


Figure 4: *SHPbench*

4.3. SHPbench sub-frameworks & toolboxes

The first *SHPbench* sub-framework element is the **sensor framework**. A holistic view of the ADAS necessitates the consideration of the (real-time) data acquisition from the virtual environment and the virtual car because the position and type of the applied sensors have a significant impact on the ADAS functionality [15]. Thus, the sensor framework provides basic sensor models that can be configured according to the ADAS sensor specification. The three standard interfaces act as gateways for the information flow from the virtual drive environment (e.g. position of virtual traffic), the virtual car and the information transfer to the controller framework (translated sensor data).

The second element, the **controller framework,** provides five standard interfaces the controller behavior model can be connected to. This enables unidirectional information transfer from the sensor framework (sensor data) and bi-directional information exchange between the controller and the virtual car (vehicle condition and vehicle control). Furthermore, bi-directional information transfer between controller and HMI is enabled (HMI control and driver input using HMI). To allow an easy and flexible integration of the behavior models, the interfaces are pooled to interface blocks inspired by the design principle of electronic terminal blocks. By default, these interface blocks provide all possible interfaces that can be "clamped" to the behavior model by using logic connectors.

The third element is the **HMI Framework** that provides standard software interfaces to the controller framework and hardware interfaces to the Drive Simulator HMI and Motion System. The HMI Framework furthermore integrates two toolboxes enabling the fast configuration and assembly of HMI prototypes:

The **HMI Software Toolbox** provides predefined software elements of visual, auditive and haptic human-machine interaction. The **HMI Hardware Toolbox** provides predefined HMI Hardware elements to enable a fast assembly process of the required HMI components. For fast and user-friendly exchangeability and assembly of hardware, the hardware interfaces are based standardized aluminum building kits which contain profiles and fasteners.

These elements are designed according to the SHP technology principle. Thereby six sub-toolboxes are available: visual, auditive and haptic toolboxes for both displays and control elements.

For standardized data exchange all software interfaces are based on the state of the art interface protocol OPC UA [16].

The *SHPbench* approach is providing the possibility of a fully integrated ADAS test and verification process in combining all the different sub-frameworks and toolboxes. By stand-alone sub-toolbox usage, subsystem tests for controllability or HMI specific testing and verification as MiL or user test can be processed.

4.4. SHPbench prototyping environment

Based on literature review of drive simulator configurations used in industrial development processes, Negele [14] derives recommendations of drive simulator configurations for ADAS development. Based on this research as well as the previously described considerations, the *SHPbench* prototyping environment contains the following elements. The *SHPbench* prototyping environment visual HMI to display the virtual content have a minimum configuration of a 180° 2D visualization with a display resolution of 2-3 arc minutes per pixel [14]. According to the recommendations of Negele [14], the provision of stereoscopic 360° view field with (drivers) head tracking shall be used in order to enable a testing opportunity for all types of ADAS. The control HMI for primary drive task builds the minimum configuration by providing steering system, brake and throttle pedal in an appropriate realism reproduction quality. A motion system with travel of 0,5m to 1,0m in lateral and longitudinal direction can be added in order to increase test prediction quality and validity [14].

The *SHPbench* prototyping environment has to provide hardware interfaces for the standardized aluminum building kits.

5. Proof of Concept: A specific *SHPbench* configuration

An industrial use case was defined and a use case "specific *SHPbench*" was configured.

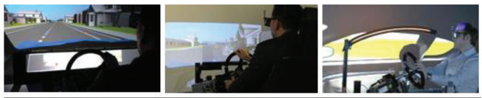
5.1. Use Case for ADAS development

As a specific use case for evaluation, an ADAS with both active, intervening as well and passive, warning assistance functionality for avoiding accidents with bicycles in urban situations was chosen.

Within a representative development project three different collision avoidance ADAS were developed. Development artefacts of sensor specification, behavior model of the controller and HMI Interface design as well as CAD Model were designed. The ADAS HMI was designed to include all three display modes of visual, auditive and haptic feedback: Visual displays were combined with vibration or stepper motors and loudspeakers at different positions for haptic and auditive feedback. A touch surface and several push buttons and switch configurations were foreseen as control elements.

5.2. Use Case specific SHPbench configuration

Fig. 5 shows the ADAS prototype configurations installed in the specific *SHPbench* prototyping environment.



visual display	Cockpit Panel	Head Up Display	LED light Bar
haptic display	2x steering wheel vibration	3x steering wheel vibration	stepper motor
auditive display	2 speakers in back (car back)	2 speakers in back (C pillar)	3 speakers on top (car roof)
haptic control element	touch surface	4 push buttons	1 switch, 2 push buttons

Figure 5: Specific *SHPbench* for collision avoidance ADAS testing

As drive simulator base of *SHPbench*, the Functional Drive Simulator (FDS) of Technische Universität Berlin is used. The FDS provides a 360° stereoscopic visualization that surrounds a multi axis drive simulator [18]. The drive simulator consist out of the primary HMI including an high end simulator steering system, an advanced consumer pedalset and a motion system consisting of a hexapod on a two-axis motion platform. The *dSpace* drive simulation environment, as it is used by multiple industrial developers such as the Volkswagen AG [19], provides the virtual car and the virtual environment in an appropriate quality.

The *dSpace* environment provides the configurations of virtual sensors in the car according to the sensor specification.

With the behavior model being developed in *Dymola*, which is used by industrial developers such Volkswagen, BMW or Daimler [20] for the same purpose, the specific *SHPbench* Controller Framework was implement with *Dymola*.

With *Processing*, a software for visual prototyping and data visualization e.g. used by Google and Intel [21], the specific

HMI framework was designed to provide standardized interfaces. By enabling the integration of standardized software blocks, *Processing* was used to build the software toolbox consisting of predefined functional visual, haptic and auditive displays.

The hardware toolbox that was used for the specific use case includes a 28 inch wide screen monitor for prototyping of the different screen configurations located around the cars primary instrument cluster, a prototypic head up display and LED lights bars for visual feedback. Furthermore loudspeaker and subwoofers for acoustic and vibration and stepper motors for haptic feedback from the ADAS to the driver are provided. A touch screen and several push buttons and switches enable the functional prototyping of the control elements.

5.3. Findings

Within the proof of concept, three different smart hybrid ADAS prototypes were built and evaluated in driving tests with human drivers. For this purpose, the three different ADAS controller behavior models were integrated into the *SHPbench* framework. The respective HMI hybrid prototypes were build based on the respective HMI interface designs and HMI CAD models by using the *SHPbench* HMI toolboxes. Virtual sensors were configured according to the ADAS sensor specification.

The integration of the behavior models was observed to be easy for the developers. The provision of the standardized HMI software toolbox supported the process as bespoke solutions thereby result mainly in the selection, configuration and adaption of the components and their source code. The buildup of the HMI hardware was easy due to the provided building kits as well as the connection of hard- and software caused by the provision of tested and verified hybrid prototypes. The configuration of the sensors in *dSpace* was observed to be easy for the developers, as comprehensible input templates are provided.

6. Conclusion and Outlook

Within this publication, the objective is to develop a concept for the application of the SHP approach in the ADAS development process in order to provide an environment for early integrated ADAS verification and validation. This objective has been achieved, as the *SHPbench* concept enables the use of ADAS development artefacts for integrated verification and validation earlier than in state of the art ADAS development processes. The SHP approach furthermore proves to be useful in this context as it enables the provision of cost efficient hybrid HMI prototypes.

Although the ability of the *SHPbench* to provide an integrated verification and validation environment was shown, the verification and validation extent is not clarified. Furthermore it needs to be proven, that the use of frontloading these activities is higher than the effort to provide the environment in order to accelerate the ADAS development process and reduce its overall costs. Thus, the *SHPbench* concept should be evaluated in real industrial applications and by the usage of appropriate evaluation methods.

Nevertheless, the “in-the-loop” integration of smart hybrid prototypes into a drive simulator enables the functional, human centered integrated ADAS verification and validation in early development stages. The acceleration of ADAS development projects is therefore possible with this approach.

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