MODULAR AND SCALABLE DRIVING SIMULATOR HARDWARE AND SOFTWARE FOR THE DEVELOPMENT OF FUTURE DRIVER ASSISTANCE AND AUTOMATION SYSTEMS

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Abstract – Currently, new-build vehicles are more and more equipped with various driver assistance and automation systems, ranging from adaptive-cruise-control, stop-and-go, active brake assist and emergency-brake systems for longitudinal control, blind-spot monitoring and lane-keeping systems for lateral control to parking assistance and advanced navigation systems. Through new emerging technologies, the integration of nomadic devices, Vehicle-2-X Communication in existing and new driver assistance and automation systems are the near future. The rising complexity due to more integrated, interactive and cooperative future assistance systems leads to increasing demands on driving simulators, used to develop and evaluate these devices in a time and cost efficient way. Thus, a number of driving simulators of the DLR Institute of Transportation Systems have been built or were upgraded with the major goal to provide a flexible, modular and scalable infrastructure, concerning both software and hardware, which enables a flexible set-up of the driving simulator according to the requirements of the test case – and not vice-versa!

This paper describes the implemented simulator landscape, the supporting software architecture and simulation applications, which enable a model-based design for assistance and automation systems. The underlying development concepts are described in more detail by Schröder [Schr10].

Key words: driving simulator design; software architecture; modularity; co-simulation

1. Introduction

Driving simulators are used as a tool in a broad range of use cases, e.g.

- early design evaluation and demonstration in order to find functional requirements for prototypes
- software or hardware in-the-loop tests
- parameter calibration or
- high-fidelity evaluation test runs with a large number of test drivers.

All these use cases lead to different requirements for simulator characteristics. In order to enable all kinds of tests in a cost-efficient manner and without the necessity to maintain a huge number of simulators, the DLR came up with a concept of modular simulator software and hardware components.

The first part of this paper introduces the hardware modules, distinguished in simulator platforms and mock-ups. The simulator platforms are providing the motion feedback capabilities, visualization systems and computer infrastructure. The mock-ups are consisting of chassis components, mirror and instrument-displays and integrated audio and haptic front-end devices. Further, additional special-purpose simulators which complement the flexible platform/mock-up combinations are described.

The second part of the paper will give a brief overview about the applied software architecture as well as utilised third party applications. The paper will end with an overview of projects that made use of the presented modular and scalable driving simulator environment.

2. Hardware infrastructure

As described in the introduction the hardware infrastructure is subdivided into simulator platforms and mock-ups. The mock-ups are exchangeable and can be (almost) freely combined with the simulator platforms.

An overview on the possible combinations is shown in Figure 1. A detailed description of each element follows in the next two sections.

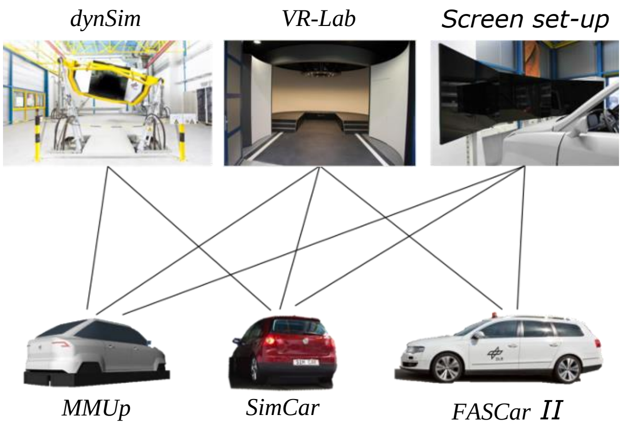

Figure 1: Possible combinations of simulator platforms (top) and mock-ups (bottom)

The simulator platforms and combinable mock-ups are complemented with special purpose simulators that have a closer coupling between the simulator base and the mock-up. These simulators will be described in the last section on hardware infrastructure.

2.1. Mock-up description

Each simulator platform can be combined with one of the two following mock-ups:

A modified commercial car with its original chassis components (*SimCar*) and a modular mock-up (*MMUp*), constructed with various separate chassis elements, interior parts, displays and active components, which can be mounted on top of a grid base plate using a resistant frame (see Figure 2).

To a great extend the mock-ups are composed of uniform hardware parts, e.g. motors, pedals, steering wheels, displays, etc. of a certain type with the intention of simplifying hardware integration, control software development and maintenance issues for the overall simulator infrastructure. Grid base plates are used for the majority of mock-ups to allow for flexible set-ups and fast integration of further hardware extensions.

The modular mock-up enables testing of new vehicle concepts or cockpit designs within the driving simulation by reconfiguring exterior and interior parts [Kös13].

Additionally, the integration of a real test vehicle (*FASCar II*) within the fixed-base simulator platforms allows a validation of the implemented assistance before proving it on the test ground or in real traffic. Its Drive-by-wire system allows the usage of the original control devices with the engine turned off.

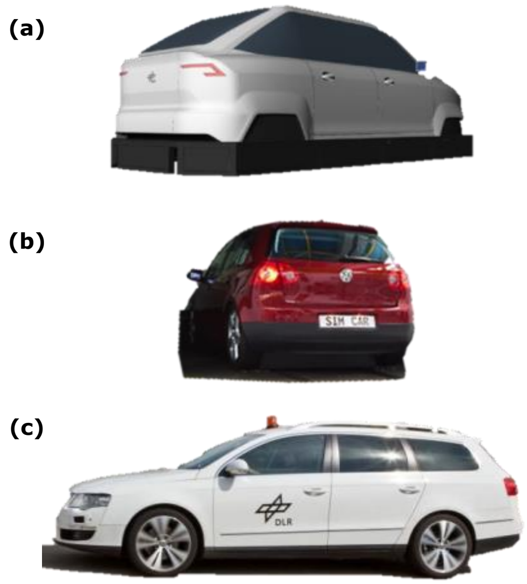

Figure 2: Mock-ups - *MMUp* (a), *SimCar* (b), *FASCar II* (c)

The main characteristics of the three different mock-ups are listed below in Table 1.

Table 1: Mock-up characteristics

Mock-up	*Main characteristics*
MMUp	Flexible and modular chassis and interior elements; Multiple displays for a free configurable HMI-Design; Changeable number and position of seats; Various input devices
SimCar	Modified production car; Original interior elements; Force feedback gas pedal and steering wheel; Touch screen for secondary tasks; Integrated head- and eytracking system; fully operable CAN-bus
FASCar	Real test vehicle; fully automated driving; force feedback gas pedal and steering wheel; touch screen for secondary tasks; full access to control signals via CAN-bus (driver overrule is possible)

The two mock-ups *MMUp* and *SimCar* are equipped with a full-HD LCD-Screen in the back of the car and small TFT-Screens as side-mirrors. For the test vehicle (*FASCar II*) it is also possible to integrate such screens. Signals between the mock-ups and the simulation control are sent using either CAN or UDP messages.

2.2. Simulator platform description

The simulator platforms provide either a simple but transportable visualisation solution using three LCD screens for quick evaluations or show-cases, a full 360°-front-projection visualization (*VR-Lab*) or a high-resolution 270°-back-projection visualisation (*dynSim*). The high-resolution visualization is combined with a moving-base hexapod platform whereas the other two solutions are set up as fixed-base simulators in order to reduce controlling complexity.

As already mentioned, these platforms can be combined with the different mock-ups described in the previous section. Figure 3 illustrates some of the possible combinations and provides both outside and inside views of the two simulator platforms *dynSim* and *VR-Lab*. In Figure 3 (c) the rear gates of the *VR-Lab's* screen dome are opened which enables the exchange of mock-ups. When closed, they are part of the surrounding screen which facilitates to display the virtual world with a 360° field-of-view.

Table 2 lists the main characteristics of the different visualisation systems.

Table 2: simulator platform visualisation systems

Simulator platform	*Type*	*Field-of-View (horizontal)*	*Resolution H x V*
dynSim	Eyvis ESP-SXT+	270°	1400 x 2100 for each 30°
VR-Lab	Eyvis ESP-WXT	360°	1200 x 1920 for each 30°
Screens	Samsung LCD	100°	1920 x 1080 for each Screen

The motion base of the *dynSim* simulator platform enables the driver to feel a direct feedback of driving control actions. This is of high importance for dynamic manoeuvers or for the evaluation of assistance systems which influence the vehicle control. Furthermore, it generally improves the driver's immersion into the virtual world.

Some performance indicators of the motion-base are given in Table 3. The motion-base is able to bear up to 1200 kg payload while maintaining the performance.

(a) (b) (c) (d)

Figure 3: Simulator platform *dynSim* with the *SimCar*(a & b), *VR-Lab* in combination with the *FASCar* (c) and the *MMUp* (d)

Table 3: Motion characteristics (*dynSim*)

	Position	*Velocity*	*Acceleration*
Longitudinal	±1,50 m	±2 m/s	±10 m/s²
Lateral	±1,40 m	±2 m/s	±10 m/s²
Vertical	±1,40 m	±1 m/s	±10 m/s²
Pitch	±20 °	±50 °/s	±250 °/s²
Roll	±21 °	±50 °/s	±250 °/s²
Yaw	±21 °	±50 °/s	±250 °/s²

2.3. Special purpose simulators

In addition to the flexible platform/mock-up combinations, special purpose simulators complement the simulation infrastructure of the institute: The *HMI-Lab*, the *IDeE-Lab* and the *MoSAIC-Lab* (see Figure 4).

(a) **(b)** **(c)**

Figure 4: Special purpose simulators - *MoSAIC-Lab* (a), *HMI-Lab* and *MMUp* + *Screen set-up* (b), *IDeE-Lab* (c)

Each facility is briefly described in Table 4 and in more detail in the following subsections.

Table 4: Special purpose simulator characteristics

Simulator	*Main purpose*	*Main characteristics*
HMI-Lab	Demonstrations; HMI-Design evaluation	Quarter-car chassis; transportable
IDeE-Lab	HMI-Design evaluation by using the theater system technique	2 basic mock-ups with mechanically and electronically coupled steering systems; various HMI devices and active inceptors
MoSAIC-Lab	Cooperative system evaluation	3 identical mock-ups, which can be involved in one common simulation

2.3.1. HMI-Lab

The *HMI-Lab* is a small mobile simulator with a couple of displays and force feedback inceptors, i.e. an active steering wheel as well as active brake and throttle pedals. It is intended to be used for show-cases where a wide spectrum of functionalities has to be shown. Thus, the basic requirement for this simulator is to provide a high fidelity simulator in a compact, representable design which enables an easy and fast set-up and transportation. Therefore it basically consists of a quarter-car chassis in connection to a glass-topped counter containing the necessary computers and control units for the force-feedback devices. The instrument cluster, the left outer mirror and the front view are presented on LCD screens. Instead of a standard middle console, a touch-screen is installed.

2.3.2. IDeE-Lab

The "Interaction Design and Ergonomics Laboratory" (*IDeE-Lab*) is a laboratory for the design of advanced interactive and cooperative driver assistance systems [Kel13]. Therefore, the room is equipped with everything needed for discussion, e.g. several beamers and whiteboards. Furthermore, it holds two basic mock-ups with the focus on maximum flexibility, which are simply created by Bosch-Rexroth-Profiles. The absence of covering chassis elements enable rapid mounting and remounting of any additional device. Each mock-up is equipped with high-performance force feedback pedals, steering wheels, and side-sticks. Additionally, the basic mock-ups can optionally be coupled in a mechanical and electronic way, enabling a design method called the theatre system technique [Sch09]. By this technique interaction behaviour and user needs can be played through, discussed and documented in very high detail even before the prototypic implementation has started. After clarifying the HMI requirements, the interaction prototype can be developed by a model-based approach and tested step by step in usability studies.

2.3.3. MoSAIC-Lab

Modular and Scalable Application platform for ITS Components (*MoSAIC*) is the DLR ITS concept for linking several mock-ups or even whole laboratories in order to provide scenarios with more than one ego driver [Lor11]. The basic *MoSAIC* concept can be applied to any of the simulator platforms, mock-ups and laboratories at DLR ITS. Exemplarily, the coupling of the *HMI-Lab* and the *MMUp*/LCD-Screen set-up is shown in Figure 4 (b).

Thereby a broad spectrum of research ranging from exploration of cooperative behaviour of two or more drivers in common vehicles up to exploration of cooperative effects of several human-machine systems supported by ADAS in complex traffic situations becomes possible.

The *MoSAIC-Lab* permanently provides this opportunity as it is equipped with three connected standard DLR fixed based simulators, each set-up providing a 140° field-of-view, an active steering system and active pedals, allowing a wide spectrum of haptic HMI, as well as a number of additional buttons and displays used for the interaction with other drivers. Hence, the *MoSAIC-Lab* offers the possibility to easily investigate cooperative ADAS systems

As the creation of scenarios with multiple ego drivers is challenging, a new approach for the design of scenarios has been developed. This approach is described in detail by Schindler [Sch14].

3. Simulation software and system architecture

The basic in-house developed system architecture *Dominion* [Gac08] provides a service oriented concept that supports tightly embedded in-vehicle assistance and automation systems as well as loosely coupled comfort oriented applications. A semiformal description of the data and the services is the core of *Dominion*. It comes along with automatic code generation for generating the application frames [Mon10], standardized user-interfaces for integrating third party applications and components and supporting tools for the operation of laboratories and for conducting test runs which facilitate fast development of new applications and services and simplifies the control of the simulation session as well as data logging and data analysis. The general *Dominion* structure is shown in Figure 5.

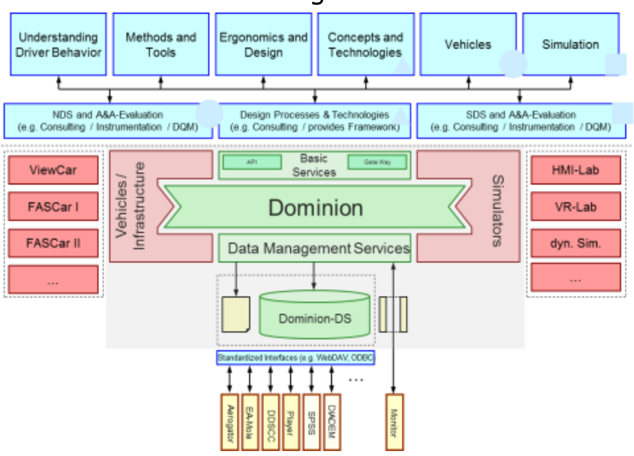

Figure 5: General Dominion system architecture with vehicles on the lower left corner and simulators on the lower right corner

The supporting tool *DominionRemote* is able to manage a full-scale simulator setup including third party applications by starting, parameterising, monitoring and if necessary relocating the applications. It integrates *Dominion's* server communication for life-cycle management of all modules. Also the data recording is coupled so that the study operator only has to deal with one software frontend. The *DominionDataStore* handles the data recording. It includes the runtime data as well as meta–data, which is modelled within the *Dominion* data core.

Recorded time series can be assessed and visualised with the in-house-developed *DominionDataStoreControlCenter* as well as with commercial software like *SPSS.* For play-backs *DominionPlayer* can be used in order to rerun a recorded simulation. With the help of the stored meta-data it is possible to rerun a simulation in another simulator as the one where it was recorded as well as at office computers.

Dominion is used in both types of test facilities: in simulators and test vehicles (e.g. *FASCar II*). Therefore a transfer of software prototypes and special hardware interfaces (e.g. for LED-lights or side sticks) causes minimal migration effort.

In-house software-modules for all parts of the simulation (e.g. scenario control, traffic simulation, vehicle dynamics, image generation, motion cueing, visual/haptic/audio feedback, hardware control, etc.) have been developed throughout the last years [Sch11]. Full access to the source code guarantees flexible adaption to new requirements and continuous improvements to support new methodological and technical demands.

Additional to that, it is possible to share this simulation environment with project partners as no third party applications are required.

External modules can be integrated through standard communication protocols (UDP, CAN, TCP) or additional interface applications as well as web services.

For example, VIRES' commercial simulation software *VirtualTestDrive* was integrated in order to extend the feasible features of the overall simulation. Because of the modular concept of *VirtualTestDrive* it is possible to use only parts of it (e.g. visualization, traffic) and complement the simulation with *Dominion* applications (e.g. vehicle dynamics, automation). For compatibility reasons standardized formats and open source software are widely used, for example,

- the visualization is based on *OpenSceneGraph* [Wan12], that is also used for additional simulation issues (e.g. communication simulation [Ric2012]),

- the road description format *OpenDRIVE* is used. *OpenDRIVE* is an open XML description format for road logic and layout. It was established 2005 and is constantly improved by an industry and research institute driven consortium. The *OpenDRIVE* description is also the basis for generating the 3d virtual world using *OpenSceneGraph*.

Summing up, the facilitated system architecture and the integrated software components enable a great flexibility for the set-up of simulator experiments.

4. Related Projects

Current or recently finished projects that made use of the broad simulator infrastructure and demonstrated its capacities are e.g. the following projects:

- ***eCoMove*** (http://www.ecomove-project.eu/) conducted a study about a green efficiency assistant system providing gearshift suggestions in the dynamic simulator *dynSim* and the final event demonstration was performed within the mobile *HMI-Lab* Simulator.
- ***InteractIVe*** (http://www.interactive-ip.eu) performed studies about emergency evading assistant using the same automation strategies and applications realized within *Dominion* in both the *FASCar II* on a real test track and in the dynamic driving simulator *dynSim* [Hes13].
- ***D3CoS*** (http://www.d3cos.eu/) studies with cooperative merging assistance were performed in the *MoSAIC-Lab* with different quantity of ego vehicles [D3C14a][D3C14b] and were later on demonstrated combining the *MMUp* and the *HMI-Lab*.
- ***UR:BAN*** (http://www.urban-online.de/) also performed in the *MoSAIC-Lab* a study about cooperative driver behaviour regarding vehicles partly equipped with traffic light assistance. The study relied on adapting the behaviour of other probands.
- ***MobiFAS*** demonstrated the integration of nomadic devices with automation systems using the *FASCar II* within the simulation in either the simple LCD-screen set-up or the *VR-Lab.*
- ***AdaptIVe*** is an EU-founded integrated project with 29 partners across the EU. The aim of the project is on the ideal cooperative interaction between the driver and the automated system by using advanced sensors, cooperative vehicle technologies and adaptive strategies in which the level of automation is dynamically adapted to the situation and driver status.

5. Summary

A landscape of diverse simulators were built, which can be handled by a small team of operators and developers due to standardization of components and interfaces, customization of operator controls and an flexible system architecture as a solid foundation for the simulation software. Their flexibility and adaptability where shown in diverse projects over the last years. These driving simulators are well prepared for being involved in research and development projects in order to answer current and future research questions – especially within the upcoming tasks connected to the development of exceedingly complex, highly automated and/or cooperative assistance systems.

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