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Extensions for Distributed Moving Base Driving Simulators

by

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Abstract

Modern vehicles are complex systems. Different design stages for such a complex system include evaluation using models and submodels, hardware-in-the-loop systems and complete vehicles. Once a vehicle is delivered to the market evaluation continues by the public. One kind of tool that can be used during many stages of a vehicle lifecycle is driving simulators.

The use of driving simulators with a human driver is commonly focused on driver behavior. In a high fidelity moving base driving simulator it is possible to provide realistic and repetitive driving situations using distinctive features such as: physical modelling of driven vehicle, a moving base, a physical cabin interface and an audio and visual representation of the driving environment. A desired but difficult goal to achieve using a moving base driving simulator is to have behavioral validity. In other words, *"A driver in a moving base driving simulator should have the same driving behavior as he or she would have during the same driving task in a real vehicle."*.

In this thesis the focus is on high fidelity moving base driving simulators. The main target is to improve the behavior validity or to maintain behavior validity while adding complexity to the simulator. One main assumption in this thesis is that systems closer to the final product provide better accuracy and are perceived better if properly integrated. Thus, the approach in this thesis is to try to ease incorporation of such systems using combinations of the methods hardware-in-the-loop and distributed simulation. Hardware-in-the-loop is a method where hardware is interfaced into a software controlled environment/simulation. Distributed simulation is a method where parts of a simulation at physically different locations are connected together. For some simulator laboratories distributed simulation is the only feasible option since some hardware cannot be moved in an easy way.

Results presented in this thesis show that a complete vehicle or hardware-in-the-loop test laboratory can successfully be connected to a moving base driving simulator. Further, it is demonstrated that using a framework for distributed simulation eases communication and integration due to standardized interfaces. One identified potential problem is complexity in interface wrappers when integrating hardware-in-the-loop in a distributed simulation framework. From this aspect, it is important to consider the model design and the intersections between software and hardware models. Another important issue discussed is the increased delay in overhead time when using a framework for distributed simulation.

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Anders Andersson
Linköping, Sweden
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Introduction

Chapter 1

Introduction

Modern vehicles are complex systems with high demands on quality across different areas, consider e.g. reliability, price, comfort, maneuverability, fun to drive, environmental friendliness, and of course safety. Evaluation of such a complex systems typically starts by testing individual components of the system from a functional aspect. Thus, these individual components are guaranteed to have the "by the first design" intended behavior. Further, evaluation continues with testing combined sets of components, commonly referred to as a system or subsystems. Components or subsystems that do not meet the requirements or do not work as intended are redesigned and the process starts over again by evaluation of the individual components and later the subsystems. If this process of design and refinement was linear it would take extensive time to complete a vehicle unless the first design is correct. To speed up this evaluation process it is run in parallel where simplified models of some components or subsystems can be used in early stages of the process. One issue with simplified models is that they might be too simplified and an incorrect behavior might not be detected. Thus, as the design process continues, simplified components or subsystems will be replaced by more detailed and accurate models or hardware-in-the-loop simulations. At late stages of evaluation, complete hardware subsystems are tested during actual driving conditions, and finally in the latest stage complete vehicle prototypes are tested.

During the described design process several tools are used. One example of such tools is driving simulators, and more specifically, which is the focus in this thesis, high fidelity moving base driving simulators. Studies performed on driving simulators with a human driver typically focus on driver behavior. Interacting with a digital driving environment requires a sense of immersion from the driver. In a high fidelity moving base driving simulator it is possible to present realistic and repetitive driving situations to drivers. This provides a cost effective way of collecting high quality data for analysis. The overall goal in this work is to provide further realism by constructing and exploring distributed hardware-in-the-loop platforms, and thus increase the sense of immersion in a high fidelity moving base driving simulator.

The problems that motivate this work are 1) parameterizing complex models are difficult and time-consuming, and 2) complex models are difficult to maintain and adjust. By combining hardware-in-the-loop and distributed simulation the required model complexity can be reduced. Two central research questions addressed in this work are thus the following. First, how to seamlessly integrate hardware-in-the-loop, requiring interfaces at intersections between software models and hardware, while preserving fidelity. Second, investigate if time delays introduced by system decoupling into a distributed set-up can have a negative impact on real-time systems, and if present, how to avoid the negative impact.

This thesis is structured in the following way: the first four subsections introduce the areas of moving base driving simulators, programming languages for model-based development, hardware-in-the-loop simulations, and distributed simulation respectively. In Subsection five of this thesis our contributions are presented. Subsection six presents future work followed by the contributing papers.

1.1 Driving Simulators

Simulations and simulators are today common and diverse tools for evaluation of existing systems or system designs. As such, driving simulators range from purely mathematical models running on a single computer to full size moving base driving simulators that take up the physical space of a smaller hangar including several computers, e.g. the National Advanced Driving Simulator (*NADS Overview PDF* 2015). A driving simulator commonly has a design in between these extremes. Vehicle hardware is also commonly included to various degrees, ranging from simple driver controls to a complete car where techniques such as augmented reality may be explored (Blissing 2016). The focus in this work are human drivers in a high fidelity moving base driving simulator. Such a moving base driving simulator consists of a few distinctive features:

1. A moving base presenting motion cues to the driver.

2. A real cabin for a driver to interact with the simulated vehicle.

3. A visual and auditive (sometimes also haptic) representation of the surrounding environment.

A moving base driving simulator with only one or two degrees of freedom will be referred to as a small moving base simulator. Thus, what is referred to as a moving base driving simulator will have three or more degrees of freedom. How these degrees of freedom are used varies depending on the simulator and its application. The strategy for providing motion feedback to the driver is called motion cueing. For an example of a motion cueing strategy see (Fischer et al. 2010).

These distinctive features only describe the top layer of a moving base driving simulator. Other important technical aspects include capabilities of logging of data, a vehicle dynamics model, models for surrounding traffic behavior and digital environments representing actual roads/cities or totally fictional environments. There can also be additional study dependent equipment, such as systems for logging biological signals or tasks for driver distraction. Sometimes the system or component under test is actual hardware that is run as hardware-in-the-loop.

Two of the main benefits of using a moving base driving simulator are the repeatability, so that every driver experiences the same situations, and the possibility to create virtual dangerous situations in a controlled environment. Usually the goal is to study driver behavior during these situations and thus, it is crucial that the driver is immersed into a normal driving behavior. This goal is phrased as the simulator driver behavioral validity in this work:

Simulator driver behavioral validity: *A driver in a moving base driving simulator should have the same driving behavior as he or she would have during the same driving task in a real vehicle.*

Absolute validity, where there is no statistical difference between driving in a simulator or on the road, is a hard goal to achieve (Törnros et al. 1997). Thus, usually the aim is to achieve behavior validity for specific parts of a simulator study. One example of a study performed at the Swedish National Road and Transport Research Institute (VTI), where the goal of absolute validity was achieved for parts of the study, is (Ahlström et al. 2012). In this study a lot of effort was put into preparations of the simulator since drivers would drive on roads close to Linköping consecutively both in the simulator and outdoors. Thus, the simulator environment had to match the outdoor environment with e.g. landmarks. Also, the vehicle model within the moving base driving simulator was parameterized to match the specific vehicle driven on the road. For certain applications where a specific driving maneuver is known or predicted to occur, the simulator can be optimized for it beforehand, to get closer to absolute validity. As an example the simulator can be prepositioned for curves, see (Hansson et al. 2015), although most cases of normal driving do not allow such optimizations. Since it is often not possible to put this amount of effort into constructing the environment and simulator calibration the goal of the driver perception would be to have relative validity. This means that driver behavior in a driving simulator is relatively correct compared with drivers on the road. As an example consider a driving simulator study comparing two different designs of an active safety system alerting the driver. Assume that one of the systems results in a decreased reaction time when compared to the other system for a specific situation. Then, if relatively valid, the same system will have a decreased reaction time compared to the other system in real driving as well.

Improving the simulation immersion and perception increases the precision in driving perception and thus aids the validity of the results, but it has to be done in a cost effective way.

1.1.1 Driving Simulators at VTI

At VTI moving base driving simulators have been used and developed for more than thirty years starting in 1978 with the presentation of the first construction plans for Sim I which was later completed in 1984. Sim I had a moving base, a visual system, a cabin and a model of a vehicle (Nilsson 1993) but was dismantled several years ago. When continuing the simulator development it became quite clear that simulators and the studies they perform are quite connected and that there will always be limits to what is possible to perform (Nordmark 1994). A common study performed using the VTI moving base driving simulators focuses on driver behavior. For a few examples see an early collection of behavior research (Nilsson 1993), a study of mobile phone usage (Kircher et al. 2004), a study about detection of sleepiness (Fors et al. 2011) and a study evaluating steering feeling in heavy vehicles (Rothhämel 2013). But studies at VTI are not limited to only behavioral studies and several other aspects have been investigated e.g. collision avoidance dynamic performance of trucks on low friction surfaces (Markkula et al. 2013) and visualizations of construction plans for a tunnel (Patten and Mårdh 2012).

Currently there are three operational moving base driving simulators at VTI which are:

Sim II: *Sim II was constructed in 1991 to be used as a truck simulator (Nordmark 1992). The simulator provides 3 degrees of freedom for larger motion and a vibration table for road roughness and has been upgraded in several steps improving e.g. the visual and audio system.*

Sim III: *Further developing the design used in Sim II one more degree of freedom was added when constructing Sim III which was finished in 2003 (Nordmark et al. 2004). The simulator is mostly used as a passenger car simulator with a smooth linear motion with world top performance.*

Sim IV: *Sim IV was built with a new design combining a hexapod with an xy-table providing large linear motion in the plane (Jansson et al. 2014). The simulator was inaugurated in 2011 and is used with a car or a truck cabin.*

In addition to the moving base driving simulators at VTI, smaller driving simulators are also used, e.g. a fixed based driving simulator named SimFoerst.

Although work done in this thesis focuses on road-bound driving simulators, it might be of interest to mention that VTI also develops railway train simulators. To reduce the amount of different software and hardware systems, an architecture structure where the train simulators share as much as possible with the driving simulators is desired. An example of hardware interoperability is that the dimensions of one train simulator cabin are such that it is possible to mount the train cabin onto the moving base in Sim III.

1.2 Physical Modelling

A model of a physical system should capture essential characteristics for an intended usage. Furthermore, in a broad sense a simulation presents how such a model behaves over time. As such, the name driving simulator specifies the usage of a physically modelled vehicle and its behavior over time. Further, a driving simulator study implies requirements from the study, earlier mentioned as the essential characteristics for the intended usage, and provides requirements on the model. This section gives a presentation of different techniques for modelling of such essential characteristics.

In a moving base driving simulator it is important to present realistic dynamic behavior of the driven vehicle to the driver. This is typically done by implementing a mathematical software representation of the physical model of the driven vehicle, which describes the vehicle dynamics. The driver interface in a driving simulator is commonly similar to an actual vehicle with a steering wheel and accelerator and brake pedals, although different experimental settings can be freely tested within a simulator. The driver interface provides input to the physical model which uses these inputs to calculate vehicle responses, such as accelerations and velocities. The calculated motions by the physical model of the vehicle will be fed back to the driver in a moving base simulator. To do so specific strategies that consider the physical limitations of the moving base are required, which are called motion queueing. Also worth noting is that input to the physical model is not only the driver input, but also the surrounding world, e.g. slope and curvature of the road. Thus, for a total experience in a moving base driving simulator it is necessary to consider the whole chain, a driver in a certain driving scenario providing inputs, a physical model generating a dynamics response from the inputs, and realization of motion by motion cueing. A limitation in this work is that it does not include an investigation into the area of motion cueing. The reason for this is that the area is too vast to be included, considering the time constraints. However, different vehicles with different dynamic performances are expected to benefit from using different motion cueing algorithms or calibrations.

Physical modelling of the vehicle will typically use a representation of differential algebraic equations (DAE) combined with discrete events, e.g. when a driver changes gear. Modelling such systems can be done in several ways using many different tools. One straightforward method would be to use a procedural programming language, such as Fortran or C/C++, and let an engineer design how the equations will be solved by implementing a

Table 1.1: A one tank system implemented in C++ and Modelica omitting routines for initialization and set and get input and/or output.

Modelica	`model tank`
	`  input Real Q_in "flow in";`
	`  output Real Q_out "flow out";`
	`  parameter Real A "tank area";`
	`  Real h "water level";`
	`equation`
	`  Q_in - Q_out = A * der(h);`
	`end tank;`

C++	`class tank {`
	`public:`
	`    updateLevelExplicitEuler(double dt)`
	`        { h = h + dt*(Q_in - Q_out)/A; }`
	`private:`
	`    double Q_in;     //flow in`
	`    double Q_out;    //flow out`
	`    const double A;  //tank area`
	`    double h;        //water level`
	`}`

solver for the DAE system. Another approach would be to use a tool that provides a graphical user interface where the engineer can specify the flow of information in an input/output manner, an example of such a tool is Simulink from MathWorks. Here the task for the engineer is simpler since the solver is provided in Simulink. However, in such an approach the direction of information flow is embedded into the model which can be a drawback. Thus, one further approach is to reduce the manual work by letting the engineer write the equations directly and let the compiler sort the equations automatically, then using a numerical solver for solving the resulting system, e.g. DASSL which is a numerical solver for implicit systems of differential and algebraic equations (Petzold 1982). An example of a language to handle this type of modelling is the equation based language Modelica, see e.g. (Fritzson 2004) or (Modelica Association 2012). Modelica lets the modeler write acausal models and also includes a graphical user interface with a rich standard library of components. Modelica supports object-orientation, where a large model may be built from components, giving a high level of reusability. To give an example of the described modelling methods consider Table 1.1 where two implementations are presented, one in C++ and one in Modelica. For the modelled system in C++ the model will only solve for `h` while for the Modelica model the system could be changed by the compiler to be solved for e.g. `Q_out` if `h` were given depending on how the engineer uses the model. Relieving the developer of practical details such as implementing a solver for the DAE makes the acausal modelling attractive, but one drawback has been the difficulty in debugging such systems.

Another important aspect regarding physical modelling of dynamic systems, such as vehicles, is the evolution over time. In this aspect a dynamics model of a vehicle needs to evolve to keep a high level of fidelity over time. If development has been done over several years with a rich history there is a need to handle legacy code. Also, for future use it is good to consider modelling tools which are expected to respond well to changes within a dynamics model such as changing or modifying a submodel. As an example of how legacy code can evolve consider the early usage of moving base driving simulators at VTI where the vehicle dynamics model was programmed in Fortran together with the rest of the simulator software (Nordmark 1984). Limitations in model complexity were at that time the available computing power. Over the more than thirty years of development other programming languages have been introduced into the simulator software with the majority being C and further C++, Simulink, Modelica, and XML with available libraries such as Boost, Qt and Simscape. The result is a heterogeneous simulator system with legacy hardware and software and when engineers implement or add new components the limitations are more due to the required implementation time, since powerful computers are relatively cheap.

In this work the approach has been to use Modelica, which is a modelling language with an emphasis on object oriented modelling and hybrid modelling (continuous and discrete time). Modelica is based on an open standard and has a large tool support. As a counter example consider for example Simulink where the internal description of the model is not freely available and thus the only tool that can handle the model is Simulink itself. As Modelica is a wide-spread language specification there are several different tools available that can transform a model into computable code, thus the user can freely choose tool depending on the application. One free and open source tool for Modelica is OpenModlica developed at Linköping University together with the Open Source Modelica Consortium (Open Source Modelica Consortium 2013). OpenModelica has support for almost the whole standard and the Modelica Standard Library and also has several extra features such as e.g. support for synchronous features, support for compiling Functional Mock-up Units (FMUs) according to the Functional Mock-up Interface (FMI) standard, a graphical user interface, and automatic parallelization with ParModelica.

The abovementioned FMI standard (Blochwitz et al. 2011) enables another way to collaborate using models. FMI is an open standard designed to provide efficient computing and supports both open models and black box models with or without an embedded numerical solver. Given correctly handled connections and a tool that supports the FMI standard an engineer can export and import FMUs into his/her models. Currently, one drawback with the FMI standard is the lack of a master algorithm that simulates several FMUs together since the execution order is important, considering that FMUs are not necessary acausal. The reason for this is that a user can include information into an FMU so that acausal modelling is possible, but it is not required by the standard. Moreover, for a black box FMU such information does not exist.

A further challenge is to run a physical dynamics model in the simulator environment where real-time performance is needed. For Matlab Simulink models a real-time environment called xPC-Target (Mosterman et al. 2005) can be used. Considering a Modelica model there are other approaches for connecting or interfacing the model to a moving base driving simulator environment. One approach is to compile a Modelica model into a Matlab Simulink model and then use an xPC-Target environment. Another solution is to generate C/C++ code and then link it directly into the simulator software kernel. Automatic generation of real-time code to a real-time environment is a convenient but currently costly method for the modeler. Thus, the chosen approach is tightly connected to the application.

1.3 Hardware-In-the-Loop

Hardware-In-the-Loop (HiL) is a method where hardware is interfaced into a software controlled environment/simulation using sensors and actuators. The purpose of introducing HiL can be seen from two perspectives, either the included hardware system is tested or the included hardware system provides extra fidelity to a software simulation. The closer to the final hardware production system the higher the probability is that the HiL system is correctly perceived and evaluated. Note that the hardware system does not need to be a production system but can be a small scale model such as a radio car instead of a car (Brennan and Alleyne 2000) or scaled down electronic components (Petersheim and Brennan 2009) where signals are scaled to resemble a full scale system. HiL is a very general term and the inclusion of hardware does not specify to which degree hardware has been used. For instance, it doesn't distinguish between a simulation that includes vehicle electronic control units (Alles et al. 1992) and when a radio car is included or a case where a complete car powertrain is included as in Paper C. To further specify what is meant by HiL other terms are sometimes used. For example within driving simulation the term human-in-the-loop is used at times. In this thesis such further specifying terms are avoided and instead HiL is used with a thorough description of the set-up. One important difference from other types of simulations is that a HiL simulation has real-time demands due to hardware response times. Thus, it can be difficult to do a simulation faster than real-time e.g. batch simulations and restarting a simulation can be time consuming since hardware needs time to get into a correct initial state.

For a moving base driving simulator the possibility to add hardware into the simulation is rather essential. For instance, consider the usage of a cabin which not only has the steering wheel and pedals but also contains a connection to the internal car CAN bus for in-vehicle buttons. It is advantageous to use a moving base simulator with HiL since it provides faster design cycles as well as providing a better fidelity for the driver without needing a prototype vehicle. However, HiL simulation requires an interface to ensure functionality between the hardware and the software model. This can be specifically tricky if the vehicle model has parts/submodels which are black box models that need to interact with the hardware e.g. when debugging erroneous output from a black box where internal states are unknown.

1.4 Distributed Simulation

Distributed simulation is a technique where different parts of a simulation at physically different locations are connected together over a network. Connecting systems over different networks increases the complexity of the simulation since added communication has to be managed. One major benefit of a distributed simulation is that systems at physically different locations which might not be possible to move can be connected. Thus, a distributed simulation might be the only enabler for performing certain simulation studies requiring specific accurate system set-ups. As an example consider the set-up presented in Paper A where a moving base simulator and chassis dynamometer laboratory are connected to each other. In such a case it is difficult to move either the moving base simulator or the chassis dynamometers. A negative aspect of distributed simulation is that delays are introduced which is an undesired property. The combination of distributed systems with real-time requirements present a particular challenge and techniques have been developed to deal with such set-ups in (Goodell et al. 2006) and (Ersal et al. 2011).

In this work different approaches to create a distributed simulation combined with HiL including moving base driving simulators are investigated. Different simulators have different purposes and different strategies have been tested to see how well different simulators can be combined in the existing literature. But little research exist on distributed simulation combined with moving base driving simulators. At VTI only one study has made a prototype implementation (Vinter 2010). The reason for this can be that the network inside the moving base driving simulator at VTI is contained and thus, when a simulation is started the simulator will be disconnected from the outside world protecting the simulator environment from disturbances. For a distributed simulation, there is a need to have an active connection to the outside world while the simulator is running. This can be sensitive since a moving base simulator have the capacity to present high accelerations to the driver and a higher level of security is needed. One of the few examples of a distributed simulation where connections were made over the internet combining an engine test lab and a moving base driving simulator can be found in (Brudnak et al. 2008). Distributed simulation has been used more in other fields, as an example for military applications High level architecture (HLA) has been used a lot for distributed simulations (Möller et al. 2008).

There can also be different subcomponents of a physical vehicle model which are simulated in a distributed platform. In such a case there is a tighter limit on the time delay that can be tolerated. Considering the update frequency in a driving simulator, the requirements at VTI are rather strict and a common case is a dynamics model update frequency of 1000 Hz, which is needed for providing a good steering feel. Thus, a delay of one millisecond or more in communication would probably make the simulation unreliable and compromise the driver experience and the driver behavior.

1.5 Contributions

Combining HIL simulations and distributed simulations is an underexplored area. With regards to moving base driving simulators existing research is further limited. This thesis work investigates whether simulator fidelity can be maintained or improved with a more flexible and scalable simulator set-up. The contributions in this thesis are primarily presented in three papers. These papers discuss different extensions, both software and hardware, for distributed simulations of moving base driving simulators. There have also been two demonstrations performed of one of the developed distributed driving simulator set-ups.

Below, short introductions to each paper with a short description of the main results are given. The last section presents the performed demonstrations.

1.5.1 Paper A

Paper A presents a distributed co-simulation, connecting the moving base driving simulator Sim III at VTI to a vehicle connected to a chassis dynamometer at Vehicular Systems, Linköping University, a distance of approximately 500 m. The paper presents how a pedal robot with actuators and sensors provides an interface between the driver in the simulator and the car. The fast communication of the platform enables the driver in the moving base driving simulator to drive a production vehicle at Vehicular Systems.

The purpose of this effort was to improve the driver perception of the powertrain in the moving base driving simulator. This first prototype achieved good and promising results and with further potential improvements it was concluded that adequate fidelity could be achieved for a realistic simulator case study. It was also the first time a car in a chassis dynamometer was driven by a driver in a moving base driving simulator.

1.5.2 Paper B

The co-simulation set-up described in Paper A requires that both the moving base driving simulator and the chassis dynamometer are available when developing or testing. If the complete co-simulation set-up is not available, but parts of it are, it can still be desirable to make experimentation possible. In this scope, Paper B investigates the potential of using Modelica for physical modeling of subsystems in such a distributed simulation. The objective is to be able to interchange software with hardware-in-the-loop, i.e. using the chassis dynamometer or a model thereof.

The presented Modelica models are evaluated using different solvers and are estimated to have real-time performance given a good run-time environment. The aim to add flexibility to the simulator set-up in Paper A was not entirely met but was seen as a promising work to continue.

1.5.3 Paper C

One further extension to a distributed moving base driving simulator is to use a standard for distributed simulation. In Paper C the usage of the IEEE standard HLA Evolved for moving base driving simulators is investigated. A distributed simulation architecture was designed and implemented, which divides a driving simulator environment into four major entities with well-defined interfaces, using HLA Evolved as the method of communication.

Results showed that original functionality was maintained while increasing flexibility, going from a smaller to a larger simulator, and adding scalability, possibility to add simulators to the same environment. The architecture provides clear interfaces between simulation entities. It was shown that approximately one millisecond overhead latency was added when using HLA, which was considered acceptable for the graphical system but needs more investigation for the interaction between the driver and the vehicle dynamics.

1.5.4 Distributed Simulation Demonstrations

The presented work in Paper C was extended by demonstrations with moving base driving simulators. Results with an active moving base could not be included in Paper C since the network was shut down for security reasons when operating the simulator. This issue for Sim II, Sim III and Sim IV was resolved during the months following the conference where Paper C was presented and two demonstrations were performed, one in Gothenburg and one in Linköping, which showed the complete architecture running. In Figure 1.1 the set-up used during the demonstration in Gothenburg is shown where the connection from Volvo Car Corporation (VCC) to VTI was set via a mobile phone due to VPN issues. The set-up used during the demonstration in Linköping is similar to the one in Gothenburg where instead the Sim IV and the VCC HiL simulators are replaced by Sim III and Sim II.

During both demonstrations, three vehicles, connected to different simulators, were driving within the same simulation scenario. At the demonstration in Gothenburg the vehicles were connected in the following way. One of the vehicles was driven by the driver in Sim IV with the moving base active. Another one was controlled from the VCC HIL simulator, and the last vehicle was driven via a desktop simulator with a gaming steering wheel set-up. The scenario started with the driver in Sim IV driving the leading car and the driver in the VCC HiL driving as a following car. The driver in the VCC HiL could choose to follow the lead vehicle by either driving manually or using

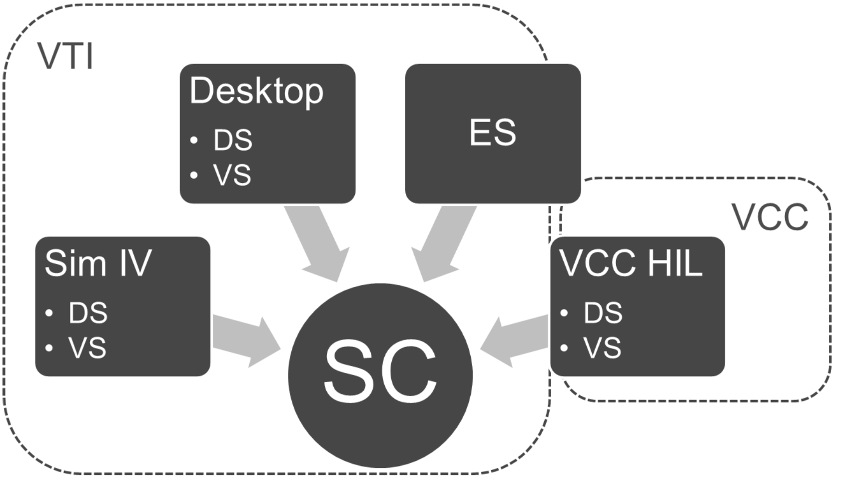

Figure 1.1: Simulator set-up used during demonstration of the developed HLA based simulation architecture in Gothenburg. SC, or Session Control, is controlling the simulation. ES, Environment Simulator, contains the road with its surrounding environment and vehicles. Sim IV, Desktop and VCC HiL are three different simulators.

an automatic cruise control (ACC) function in hardware. This demonstrated how a driver in Sim IV could interact with the driver in the VCC HiL simulator including hardware systems. During this part of the scenario the driver in the desktop simulator, controlling the third car, was driving around freely. After the car following part of the scenario the three vehicles were allowed to drive freely together. During the free driving part of the scenario the moving base of Sim IV was turned off so that more participants at the demonstration could try the set-up, as start and stop of the moving base takes time. In Linköping a similar set-up, but without the ACC hardware, was used with the simulators Sim II, Sim III and a desktop simulator.

The demonstrations showed working implementations of distributed simulations including hardware-in-the-loop and fully operational moving base driving simulators. From these demonstrations the following two conclusions could be drawn. Firstly, the simulator systems should be robust since during a simulation all participating simulators need to operate without issues. Here, every added simulator increases the risk of issues and thus adding a non-robust simulator will probably halt the complete simulation often. Secondly, it is important to have good insight into used network topology since hardware equipment at different companies can be protected and hard to reach by e.g. firewalls. For further information about the demonstrations, see (Andersson, Hultgren, et al. 2016).

1.6 Future Work

As discussed in the introduction, with the increasing complexity of vehicles, accurate and versatile modelling and evaluation tools are needed to enable faster development cycles from first sketch to production vehicle. Also, from a national aspect accurate tools are needed as a research platform for achieving a safe and efficient transport system. As an example consider one important topic which is the gradually increasing autonomy in the traffic fleet. A lot of different levels of automation and drivers need to co-exist, which require a substantial technical development. One could then argue that with full autonomy the driver is not needed hence removing the need for driving simulators with drivers in the loop. On the other hand, the purpose of transportation is partially to move people. Thus, in many situations a human will be involved and it is still needed to study human behavior, e.g. regarding comfort. To summarize, it is believed that a moving base driving simulator is an important research tool which should adapt to future needs.

Issues noted in this work identify two directions for future work. One direction would be to create a real-time run-time environment for Modelica models. The run-time environment should be designed with drivers in the loop and contain support for hardware interfaces, e.g. providing access to device drivers for controlling actuators and sensors. Such a run-time environment could focus on Modelica models directly or could be based on open standards for models such as FMI. For recent work on device drivers in Modelica see (Thiele et al. 2017). The model implementation of the chassis dynamometer presented in this thesis has been compiled to a FMU using OpenModelica and it would thus be possible to test with both approaches. One example of usage for the presented work in this thesis could be distributed systems where a Modelica model and the hardware system can be interchanged. Another example is to artificially impose time delays and lost packages, during communication, and investigate how the distributed simulation reacts to such changes.

Another future direction would be to develop a requirement based assessment platform for simulator validity to detect errors, which otherwise can be time consuming and/or hard to detect. In a moving base driving simulator one complicating factor is that a human driver might adapt his/her behavior to compensate for such errors, making the error detection more difficult, as well as including unnatural driving behavior. As an example consider the update rate of the simulator kernel. If the update rate becomes slightly lower, a slow motion effect appears that could possibly change the driver behavior without the simulator operator noticing it. Other examples are errors in vehicle accelerations presented by the moving base, sound feedback and tactile feedback in the steering wheel. The requirements for such an assessment platform needs to be identified and applied to every model and submodel including hardware. If the complete model including communication complies with the requirements, certain simulator performance can be guaranteed. There is an ongoing work by the author in this direction. A method has been established to collect data for a specific vehicle model (Andersson, Kharrazi, et al. 2016). The collected data for one vehicle model has then been used to reason about validity before and during simulation, see (Andersson and Buffoni 2016) and (Andersson and Kharrazi 2016).

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