State-of-the-Art Driving Simulators, a Literature Survey

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Nomenclature

$\phi$ Roll
$\psi$ Pith
$\theta$ Yaw
$x$ Surge
$y$ Sway
$z$ Yaw
ADAS Advanced Driver Assistance System
CWF Classical Washout Filter
DOF Degree of Freedom
DSC Driving Simulator Conference
FB Fixed Base
FS Fixed Screen
Heave Translational motion defined positively in the opposite direction of the gravitational field, z-direction in Figure 1.
hi-fi High fidelity
HMD Head Mounted Display
HMI Human Machine Interface
IVIS In-Vehicle Information System
MCA Motion Cueing Algorithm
MSC Motion Simulator Conference
Pitch Rotational motion around y-axis in Figure 1
Roll Rotational motion around x-axis in Figure 1
Surge Motion in longitudinal direction of the vehicle, x-direction in Figure 1
Sway Motion in lateral direction of the vehicle, y-direction in Figure 1
Yaw Rotational motion around the z-axis in Figure 1
Figure 1: Degrees of Freedom (DOF)
Chapter 1

Motion Simulation

1.1 Introduction

Driving simulation is a type of motion simulation that is currently undergoing an enormous change as the demand for more advanced and sophisticated driving simulators increases, the past decades. This survey focusses to get insight to the current state-of-the-art of driving simulation and simulators. Motorcycle, bicycle and train simulators are not considered.

The driving simulator has a broad range of applications: in the purpose of the simulation as well as the used type of simulator. One can find driving simulators at driving schools, psychological research centres, amusement parks, car manufacturers etc. This survey will make a subdivision in fidelity.

First attention is paid to motion simulation in general and everything that contributes to it. What is motion simulation? How does motion cueing work?

Only motion based driving simulators are considered in this survey. Motion simulators without actuated motion are referred to as mid-level simulators [2] and consist of a car in front of a fixed screen.

Terminology and acronyms used throughout this report can be found in the Nomenclature at page iii.

1.2 History

Motion simulation started with flight simulation in the beginning of the 20th century. Flight training school “Antoinette” developed the first flight simulator [3]. In 1948 Gough developed a parallel manipulator for the purpose of testing tires. It was not until 1962 when D. Stewart reintroduced the parallel 6DOF (degree of freedom) system consisting of two platforms and 6 actuators [4]. The so called Stewart platform was very well received in the world of motion simulation. It is a relatively compact design, comprising 6DOF-actuation and allowing relatively large payloads [5].

The first driving simulator designs consisted of few actuated DOF’s. 3DOF Designs were built bij Volkswagen (early 1970s) and the Swedish Road and Traffic Research Institute VTI, who were inspired by the Volkswagen design [6].

Mazda [7] has build a 4DOF actuated simulator in 1985, inspired by Volkswagen. That same year, the first 6DOF actuated simulator comes from Daimler-Benz [8]. Throughout the 90s, several 6DOF actuated were built (FORD [9], JARI, BMW, Renault, WIVV, Nissan [10]).

At the North American Driving Simulation Conference(DSC) in 2003, the University of Iowa amazed the world of motion simulation with their National Advanced Driving Simulator (NADS-1) [11]. It
Figure 1.1: Antoinette

Figure 1.2: Stewart Platform, or Hexapod

was the largest so far and consisted of a turntable, mounted on a hexapod, which was actuated in $x$- and $y$-direction using an xy-table. A complete car was fitted inside the dome. Several car and truck simulators were built in the beginning of the 21st century (SimuSys, Mark III, TUTOR, Katech, SimCar, UoLDS, see Chapter 2) and some were upgraded (FORD, VTI-III, BMW, MARS Renault ULTIMATE, see Chapter 2). It was not until 2007, when the Toyota Motor Corporation came with a design, which exceeded the NADS-1 in size. Whether the Toyota Simulator also exceeded the NADS-1 in fidelity is an interesting issue (Chapter 3).

There is still no consensus on which motion system design suits the demands of a realistic driving simulator best. Therefore first motion cueing will be introduced and the purpose of driving simulators will be explained, before getting to driving simulators.

Over the past decades the use of hydraulic actuation has been replaced by electric servo technology in many industrial applications [12]. This development is also noticeable in driving simulators. The improvements in electric motor performance have been enabled by the development of new high energy product magnetic materials, advancements in low cogging, low torque ripple sinusoidal designs and the availability of high resolution optical encoders [12].

1.3 What is Motion Simulation?

Simulation is defined as an imitation of some real thing, state of affairs, or process [13]. Motion simulation is all about perception. The human body has two inputs for motion perception: inertial stimulants on the body and environmental motion with respect to the body. The inertial stimulation stems from the gravitational force and the external forces and moments on the body [14]. The vestibular system, located in the inner ear (left and right), is the prominent sense that provides the perceptual system with information about linear and angular inertial accelerations of the body. The prominent sense of speed of the human body is obtained through the visual system. Sense of speed is also acquired through the acoustic system.

Motion cueing describes the presentation of visual, acoustic, vestibular and haptic information (cues) with the aim to resemble real movements in virtual environments [10]. The most popular way of motion cueing is the Classical Washout Filter (CWF). The principle of the Classical Washout Algorithm is shown in Figure 1.3. Only the high-frequency components of the translational and rotational accelerations are reproduced by the simulator. This is required to keep the simulator motion within the capabilities of the system. The visual system will provide the low-frequency information. For
the longitudinal and lateral acceleration, tilt coordination is used to mimic the sensation of sustained acceleration [15]. Tilt coordination cannot be used for sustained heave motion.

![Classical Washout Filter](image)

Figure 1.3: Classical Washout Filter [1]

An extensive survey about motion perception is carried out by Van der Steen [14], where a model of self-motion perception is presented. A driver should feel the same accelerations as he visually perceives. This is true to a certain extent. Threshold values determine an indifference zone. These values vary as a function of DOF, frequency and workload [15], but are determined to be typically at an angular velocity of ±3°/s and a maximum acceleration of ±0.6 m/s² [17]. Staying within this zone and therefore below these values, allows the motion system to move without the occupant noticing it.

1.3.1 The Need for Motion

When people play computer games or watch movies on large or multiple screens they already feel as if they are part of the virtual world they are looking at. They sense the motion that is represented on the screen. Then why is it required to have a large and expensive motion system to excite this virtual world accordingly?

Discussion in the late 70s arose about the need for motion in simulation. The anti-motion position consisted of Jacobs and Roscoe, 1975; Woodruff, Smith, Fuller, and Weyer, 1976; Gray and Fuller, 1977; Martin and Waag, 1978; Pohlmann and Reed, 1978 [18]. P.W. Caro [19] notes that the anti-motion position is not supported by evidence. McCauley concludes in his report [18] that motion contributes to the performance of the pilot, particularly for experienced pilots and that it is possible that motion cues may be beneficial for flight training in unstable aircraft and tasks involving disturbance cues, although the evidence is weak.

There are several reasons why a motion system is important in simulation, outlined by Piatkiewitz [15] and Advani [20]. The main reason is to prevent simulator sickness. Symptoms of simulator sickness result from a difference in the latency of the visual and motion system and false cues. Therefore the motion latency should be less or equal to the visual latency [21] and false cues should be avoided [15].

A driver uses his sensory inputs to obtain the required input to base his decisions on. The bandwidth of the required input signal should be in accordance to the driver’s task [15]. For cognitive decision, e.g. when to turn on the screen wipers or direction indicator, relatively low frequency information is sufficient. When cornering on a busy road, high frequency information is required.

The presence of motion increases the workload of the driver. Accelerational cues and high frequency motion add a feeling of realism. High frequency motion can be used to simulate special events like road rumble.
Automobile manufacturers also benefit from the use of a motion based driving simulator, especially in the early development phase of the car [22]. Evaluation of manoeuvres like lane change, slalom and braking in turn are determined by subjective sensation, which is not available in computer models. Use of a motion system contributes in early decision-making in the design phase and allows integration of suppliers in this phase. A variety of subjective evaluations, e.g. thresholds and aging effects, can be systematically analyzed.

1.4 Areas of use

Driving simulators are found in various areas of use; from entertainment to research and advanced training. This survey presents a subdivision in fidelity: low-level, mid-level and high-level fidelity. These simulator types are defined as follows.

At a low-level simulator, the driver sits in a car seat, preferably inside a car, which is fixed to the ground. This is called a fixed base (FB) simulator. The driver looks to a screen, which is fixed too (FS). The screen is designed such that it the view angle is as large possible. This can be done using multiple screens, but preferably using a large convex screen. Steering wheels and pedals are often equipped with force feedback and sound system takes care of the audio feedback.

The mid-level driving simulator consists of a car, which is accelerated in one degree of freedom (DOF). The screen can be fixed (FS) or can move along with the car. Force feedback is applied to the steering wheel and a sound system takes care of the audio feedback. The actuated DOF at a 1DOF simulator is often a y-sled, x-sled or a yaw-table.

A high-level driving simulator actuates the payload in at least 6DOF’s. The payload might be accelerated in additional DOF’s (introducing redundant DOF’s), e.g. to allow longer planar excursions. The payload consists often of a dome with a car’s interior) inside of it and graphics projected such that a view angle of at least $220^\circ$ is covered. The largest driving simulators consist of dome on a turntable, mounted on a hexapod, which is fixed to an xy-table.

As an alternative to FS, some simulators use a head-mounted display (HMD). HMD’s are found in a number of simulation research applications [23].
1.4.1 Entertainment

Many simulators exist in entertainment industries and comprise mainly fixed screen simulators with 0 or 1 actuated DOF. Figures 1.4–1.6 show some of these simulators. The benefit of the lower-level simulators should not be underestimated as technical development, driven by the military and entertainments industries, will ensure continual progress towards even higher fidelity systems [24]. This also includes video games, which have the largest market share in entertainment. The increase of processing power contributes to more realistic simulators in recent years [13].

1.4.2 Research

Driving simulators are used at research facilities for many purposes. The driving simulator has a broad range of applications, from studies concerning driver behaviour, the human-machine interface (HMI) and the effects of tiredness and drugs to projects concerning environmental issues, road and landscape design, tunnel design, the reactions of the body, drivers with reduced functionality and new subsystems in vehicles [25], [26].

In addition to studying driver training issues, driving simulators allow researchers to study driver behaviour under conditions in which it would be illegal and/or unethical to place drivers. For instance, studies of driver distraction would be dangerous and unethical (because of the inability to obtain informed consent from other drivers) to do on the road. A lot of fixed base simulators are used in research and offer an alternative for research groups that do not require a hi-fi motion system. This type of simulator is cheaper in purchase, as well as in usage and maintenance.

Vehicle manufacturers operate driving simulators mainly to design the interior or to test Advanced Driver Assistance Systems (ADAS). With the increasing use of various in-vehicle information systems (IVIS) such as satellite navigation systems, cell phones, DVD players and e-mail systems [21], simulators are playing an important role in assessing the safety and utility of such devices.

The effects of noise and vibrations on driver performance are examples of other areas that may be studied using the simulator [22]. One exciting area is how the new technology influences driving, for example the use of mobile telephones [26].

Simulators have also been used for road planning [23], e.g., in order to determine the positioning of road signs and for reasons of aesthetic design.

In the driving simulator it is possible to recreate any traffic situation as many times as you want, in an efficient, risk-free and cost-effective manner. One scenario may involve driving through the

Figure 1.6

Figure 1.7: SHERPA
countryside and suddenly being confronted by a large animal leaping out in front of the car. Another scenario could be in a city environment, with dense traffic, where cars unexpectedly cross the roadway. A certain scenario can also be recreated under different preconditions, to study, for example, the differences between driving with and without time pressure.

1.4.3 Training

Driving simulators are being increasingly used for training drivers all over the world. Research has shown that driving simulators are proven to be excellent practical and effective educational tools to impart safe driving training techniques for all drivers. They can be economical in cases where the alternative (real object) is much more expensive. An advantage is the reduction of risk as the driver is often put in a complex scenario, which might be hazardous when applied in a non-virtual environment, i.e., real environment. Another advantage is the ability to monitor students and that they can be advised as they practice. There are various types of driving simulators that are being used as training simulators, like train simulators, truck simulators, bus simulator, car simulator, etc.

Figure 1.8: UoLDS

Figure 1.9: VTI-III
Chapter 2

Driving Simulators

This section will discuss some of the most high-level fidelity, human-in-the-loop, moving base driving simulators. The simulators are presented in a chronological order.

A lot of low-level FB/FS simulators exist in psychological research. Most of them are described by Inrets [29]. The development of 6DOF/FS simulators started in 1999 with a design of Renault, [30], but still 6DOF/FS simulators are built.

- The very FTM Truck-simulator [31] at the Munich Technical University (2004)
- SHERPA, built by LIMA [32]
- The Pennsylvania Department of Transportation uses a Truck Driving Simulator [33] at their Vehicle Simulation Research Center (VSRC) very recently a truck simulator;
- and many others are listed [29].

Unless the 6DOF/FS is considered a high-level simulator, it won’t be further discussed, in order to focus on the more sophisticated simulators.

**Volkswagen** The first driving simulator was built by Volkswagen [34] in the early 70s. It concerned a car on a 3DOF motion system. The motions were driven by a turntable (yaw) and a roll and pitch mechanism. A single, flat screen is mounted in front of the driver sitting on its seat at a platform. No further car interior is created at the platform.

*Figure 2.1: IFAS (1984)*

*Figure 2.2: MARS (2004)*
**IFAS** In 1984 IFAS [35], former IKK, produced a 1DOF simulator with the visuals projected in a box in front of the driver. The actuated DOF was a hydraulically driven y-sled (Figure 2.1). The simulator is still used at the University of the German Armed Forces in Hamburg.

IFAS extended their simulator with 6DOF’s in 2004 with the MARS Driving Simulator [36] at Helmut Schmidt University. A y-sled is present in the new design, but has a hexapod mounted on top of it (Figure 2.2).

**VTI** The Swedish Road and Traffic Research Institute VTI is an active player in the world of driving simulation and swear by a y-sled in their designs. They started in 1984 with the VTI-I [34], a 4DOF simulator. A half car with a screen fixed in front of it on a motion platform is to be accelerated in roll, pitch and yaw, on a y-sled (sway).

A the end of the 1980s VTI rebuilds their VTI-I to the VTI-II, by request of the Swedish insurance company Trygg Hansa who requires a truck simulator, which has a higher payload than the passenger car simulator [37].

In 2004 this design is upgraded to the VTI-III [6]. The VTI-III (Figure 1.9) is increased in size and equipped with a vibration table, allowing high frequent road rumbles to be experienced by the driver.

**Daimler-Benz** The initial “Daimler-Benz” Driving Simulator was first introduced at 1985 [8] and was the first driving simulator to be driven in 6DOF. An hydraulic hexapod, which was a special design for this simulator, realized the largest motion envelope at that time. A car or truck cabin is situated inside a dome on which 6 CRT projectors display a 180° field of view.

In 1993 the simulator was upgraded to the “Advanced Driving Simulator” [22]. The main difference to the previous design was the extension of the motion system in lateral direction. Another hydraulic cylinder realized a 5.6 m excursion in lateral direction (sway). This modification the quality of the simulator was improved considerably [8].

**Mazda** Mazda introduced their 4DOF driving simulator in 1985 to decrease the number of traffic accidents, which grew rapidly with the spread of motorization [7]. The design is very similar to the VTI simulators.

**Ford** Ford introduces the Virttex [9] in 1994, a dome on a hydraulic hexapod. The Virttex is renewed in 2001 [9] (Figure 2.4).

**BMW** BMW develops a 4 m high, hydraulic hexapod, with a small screen mounted onto the motion platform, together with a full-size car [18]. This system is completely rebuilt in 2003 [18]. The platform is now provided with a dome and the driver enters the simulator through a tunnel/catwalk, to give the driver the idea he enters a car and not a simulator (Figure 2.5).

**JARI, Nissan and WIVW** Other 6DOF, hydraulic simulators are built in this period by JARI (1996) and Nissan (1999). The hexapod of IZVW/WIVW [19] built in 1999 is statically compensated using three additional cylinders (Figure 2.6). The hexapod doesn’t seize the payload at the
bottom, but at the height of the driver’s head. The idea behind this concept is, that it is easier to tilt the payload around the driver’s vestibular system, i.e. inside his head.

**NADS-1** In 2002 the North American Driving Simulator (NADS-1) is presented at the University of Iowa [11]. At that time it is by far the most advanced driving simulator. The NADS-1 [27] is a 9DOF simulator, consisting of an xy-table on which a hexapod travels. On top of the hexapod, a turntable is mounted, which provides yaw-acceleration. A dome, with full-size car inside, rotates on top of the turntable.

**SimuSYS** SimuSYS, developed in 2003 [40], is a relatively small 4DOF simulator, yet it is also relatively high. The stacking of the different subsystems, which actuate a different DOF each, is constructed such that DOF can be actuated independently, but at the expense of simulator height. Therefore an error in the first DOF can be seen again in each following DOF.

**Renault** In 2004 Renault replaced its 6DOF/FS system with a hexapod on an xy-table, called the ULTIMATE [30]. The design of the motion system is carried out by Bosch–Rexroth.

**Tutor** TUTOR is a combined bus and truck simulator [41], for professional driver training. It is developed by Lander Simulation & Training Solutions and Installed at INTA (Spain) in 2004. A similar design is found at the truck simulator Mark III from Transim (2005), which is an upgrade from the FB/FS Mark II. It is used for truck driver training at MPRI (US), to improve driving behaviour and skill.

**Katech, SimCar** In the year 2005 two advanced 6DOF driving simulators were built. Katech introduced the Katech Advanced Automotive Simulator KAAS [42] and at the German Aerospace Institute (DLR) an “inverted” hexapod was built by SimCar [43]. The inverted hexapod holds on to the payload at its top side. This was done to have the rotation point of the simulator at a higher level, as stated at MSC2007. The rotation point of a hexapod, however is virtual and can be placed anywhere within the hexapod’s range by means of coordinate transformation in motion software.
UoLDS  The University of Leeds owns its own UoLDS (Figure 1.8) since 2006 [26] and claims to be one of the world’s most advanced driving simulators in research environment [44]. The research in which the simulator is currently employed, involves intelligent speed adaptation, effects of automated systems on safety and improved driver comprehension on traffic management signing.

Toyota  In 2007 the NADS-1 simulator is exceeded in size by the Toyota Driving Simulator (Figure 2.8), built at Toyota’s Higashifuji Technical Center in Susono City [45]. The design is very similar to the NADS-1, but then larger, and the main difference is found in the turntable. At the Toyota Driving Simulator, the car yaws inside the dome, whereas the NADS-1 yaws the entire dome, with the car inside of it. The simulator will be used for driving tests that are too dangerous to conduct in the real world, such as the effect of drowsiness, fatigue, inebriation, illness and inattentiveness.
Chapter 3

Discussion

There is still no consensus on which motion system design suits the demands of a realistic driving simulator best. Generally every proud owner of a motion simulator claims to have the best simulator suitable for its purpose. This announced issue is a very critical topic and it should be noted that changes in fidelity affect training effectiveness [46]. As it comes to driving simulation one has to wonder what the simulator will be used for [20]. What does the training of research purpose require from a driving simulator? Unfortunately economical and political factors play a role in the simulator design as well and often drastically affect the design. An advanced simulator requires motion, but should be applied very accurately, to prevent false cues [15]. Large excursions, high accelerations and high frequent motions contribute to a realistic perception of motion. Large excursions allows the MCA to use the tilt coordination more gradually.
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