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Driving Simulation

1.1. Objectives of driving simulation

When driving a vehicle (either a four-wheeled or a two-wheeled vehicle), there are a variety of sources of information that enable the driver to follow a given lane and to control their vehicle. The objective of a driving simulation is therefore to provide the illusion of self-movement via a virtual vehicle, in accordance with real-time information, excluding control blocks (such as a motorcycle's handlebars, accelerator and braking system). This illusion is a complex phenomenon that involves the proprioceptive sensors of the human being, especially the visual, kinesthetic and vestibular systems.

Designing a driving simulator is a compromise between how faithful the perceptual representation will be and the global cost of the proposed architecture. While the design of automobile simulators is a highly active field of research, motorcycle driving simulation remains in its infancy, there being very few prototypes in the world. Because of balance issues, the problem of immersion is even more complex for a two-wheeled vehicle rider.

A driving simulator is a tool that recreates, in an artificial context, the driving situation of a vehicle. The number of simulator users has been ever increasing. However, depending on their needs and the respective discipline, their requirements in terms of performance and simulation realism are different. Thus, the primary objective of vehicle manufacturers is to test the vehicle–driver interaction in order to assess its impact on new driving devices being integrated in the vehicle and the reaction of these devices to different operations performed by the driver. Nowadays, technological innovations considerably alter the driving of the real vehicle. The new advanced driver assistance systems (ARAS), such as electronic stability program (ESP), information systems such as global positioning system (GPS), and finally X-by Wire systems – all make driving a very different task from what it used to be several years ago. Therefore, before incorporating a system into a real vehicle, the vehicle manufacturers are obliged to carry out tests in order to make sure the system makes a positive contribution to the driving process. It is therefore important to have rapid prototyping systems in order to optimize the duration of the development phase on the one hand, and to predict and correct the problems that may arise when driving the real vehicle on the other hand. Vehicular driving simulators are the ideal tools for implementing such tests.

Although this objective can never be fully achieved, manufacturers try to faithfully reproduce, on the simulator, the environment that the driver will face in real life. Their objective is to enable the driver to experience the majority of the sensations perceived in a real vehicle. Thus, the simulator cabin is generally based on the cockpit of a real vehicle. Devices with effort feedback or haptic feedback are coupled with certain piloting tools, such as the steering wheel and the pedals (brake and clutch), so as to provide the driver with a haptic simulation, similar to the one they would experience in a real vehicle. One or several screens reproduce the virtual scene, most often covering a broad visibility for the driver. An audio feedback simulating the traffic, the engine speed, the noise of the wind, as well as other indicators of the speed of the vehicle are also rendered in 3D. The mobile platforms are considered to be one of the most important elements that can improve the realism of the simulation. They are meant to replicate, as faithfully as possible given the working space of the platform, the inertial effects of the simulated vehicle. Therefore, they enable the drivers to better perceive the dynamic of the vehicle (i.e. the inertial effects) and, consequently, to exert better control over the vehicle.

1.2. A short history of driving simulators

Driving a vehicle requires that different elementary tasks are fulfilled in order to place the vehicle on a particular trajectory or take it to the desired state. It is therefore necessary to have information regarding the different states of the vehicle. This information is acquired by multiple human sensory receptors, and is then combined and merged together in order to interpret and analyze the current driving conditions and come up with appropriate decisions.

Starting from this discussion, we can understand that the multiplication of informational feedback is very important for creating an acceptable illusion. During the design phase, it is necessary to consider the different characteristics of the perceptual systems for recreating a coherent virtual environment and to study the different compromises for reducing sensory conflicts and trying to protect the user from simulator sickness.

According to the literature, there are about a hundred simulators in the world. Whether they are academic, industrial or commercial, several institutions have started to build their own prototypes for different aims. Generally, the simulators are classified depending on their mechanical architecture, which, on its own, gives us a rough idea of the complexity and the objectives pursued.

1.2.1. *Fixed-base platforms*

Fixed-base platforms do not have any mechanical movement. The inertial indicators and other dynamic effects are absent and, consequently, no motion reproduction technique is used. The motion sensation is exclusively induced by the convection caused by visual feedback. These simulators are made of an instrumented cabin, and besides the visual projection they are also sometimes equipped with an audio rendering system, along haptic feedback (effort feedback on the steering wheel, vibrating seat, etc.), which creates a driving environment that is sufficiently immersive (Figure 1.1).

a)

b)

Figure 1.1. *Fixed-base simulators: a) Volvo simulator – Sweden [JOH 02]; b) fixed-base simulator of INRETS Arcueil – France [ESP 00]*

Generally, this type of simulator is designed with human factors in mind and used for studies regarding the physical and mental aspects of driving, or aspects related to visual perception. Among these studies, we mainly find problems related to fatigue, medicine intake or other damaging substances (drugs, narcotics, antidepressants, etc.). We also find applications related to the study of road infrastructure, traffic control, intelligent road-vehicle systems and the identification of hazardous situations.

1.2.2. *Platforms with a serial structure*

In this configuration, the cabin is held by a serial structure of mechanical joints, an architecture that is very commonly used in the industrial world in order to carry out automated tasks. The main advantage is a large working space that allows for several maneuvers (e.g. changing lanes) the recreation of the movement on a real scale. The simplicity of the control and the articulation technology used (i.e. no more complex, mechanical joints such as universal joints or spherical joints) make this platform an attractive choice that is well adapted to behavioral studies; these studies need significant transitional accelerations, like in the case of an emergency brake. However, the main inconvenience is the rigidity that decreases with the multiplication of rotational axes because the actuators are held by previous joints, which diminish the precision of the effector. Furthermore, dynamic performances deteriorate when faced with a heavy load and particularly when they are at high speeds.

This serial concept was adopted by several automobile manufacturers for the implementation of home-made simulators. Among them is the VTI 3-DoF simulator, developed by the Swedish National Road and Transportation Research Institute at Linköping, Sweden (Figure 1.2). The simulator can make a broad lateral motion with rolling motion and pitch, all being enhanced by a vibrating table for the simulation of high-frequency motions [WEI 95].

1.2.3. *Platforms with parallel structure*

These platforms are made up of closed cinematic chains whose terminal component that sustains the cabin is supported by several actuators [MER 97]. The most widespread architecture is the 6-DoF hexapode, often referred to as Gough-Stewart platform [STE 65] (Figure 1.3). It displays several advantages in comparison to the serial platform:

Figure 1.2. *Simulator with a VTI serial structure built between 1977 and 1984 – Sweden*

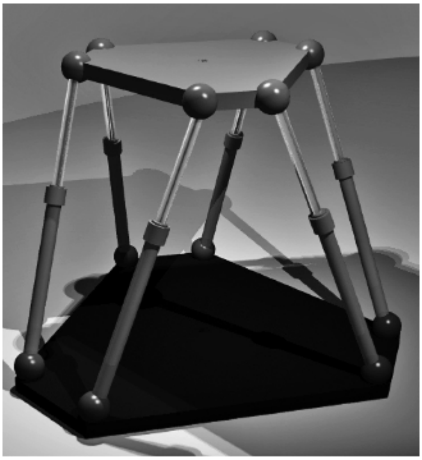

Figure 1.3. *6-DoF Gough–Stewart parallel platform image (source: Wikipedia)*

– The possibility of loading heavier weights. This characteristic has long been used for flight simulators where we must board a real or scaled-down version of a plane cockpit.

– High precision, as the parallel distribution of the mechanical geometry makes the motions less vulnerable to scaling errors.

– A high rigidity, due to the fact that the actuating motors are mounted separately from the various joints.

– A complex dynamic that offers torques, which are very important at significant functioning speeds.

However, some of the major inconveniences of this type of structure are as follows:

– A very narrow motion space in comparison to the one offered by serial structures.

– Given the coupling between the different movement axes, the resulting working space is diminished.

– A complex mechanical design such as this needs a delicate joint technology.

– The control is difficult to implement because of the highly nonlinear behavior, and especially the presence of the singularities, which requires more particular attention.

However, this mechanical architecture has become a reference point for motion cueing mechanisms. It has been hailed as a design standard for flight simulators and is often used for car driving simulators. There having been a preference for this type of technology, the simulators presented here are only a few examples among many others.

1.2.3.1. *Chalmers simulator*

Located in the Machines and Vehicle Systems Department at Chalmers University in Gothenburg, this simulator is more specifically designed for the development of vehicles [AND 07]. This is a simulator of average complexity with a mobile platform of ±20 cm of linear movement and ±20° of rotation (Figure 1.4). The model of the vehicle allows 15-DoF simulation, implemented in Matlab/Simulink on a dSPACE TMS320C31 map of Texas Instruments, with 60 MFlops of computing power.

Figure 1.4. *Parallel platform simulator at the Chalmers University – Sweden*

1.2.3.2. *Renault simulator*

Renault, one of the French manufacturers that has acknowledged the importance of driving simulation in the cycle of vehicle development and prototyping, has several prototypes itself. One of its simulators, especially exploited for studies in ergonomics and human factors, looks like a Stewart platform with 6-DoF, which offers a working space of ± 22 cm in motion and $\pm 15°$ in rotation, and accelerations and maximum speeds respectively capped at ± 0.5 g and 0.4 m/s in linear movement, and $300°/s^2$ and $30°/s$ in angular movement (Figure 1.5).

The movement of the platform has a frequency response of low-pass type of a bandwidth of 3 Hz, which is technically enough to reproduce the majority of transitional accelerations of a real vehicle [REY 00a]. Furthermore, a real Renault Clio cabin is mounted on the mobile platform, whose main commands (steering wheel, brake, clutch and accelerator) are equipped with haptic feedback.

The simulation software is based on the SCANeR-II platform, a multitask [DAG 05] and real-time application. The distribution between the different modules is made via a universal datagram protocol (UDP) communication protocol between the server and the different customer processes. The movement (washout cueing algorithms and effort feedback) is implemented on the same machine as that of the dynamic model of the vehicle, via a shared memory. The model of the virtual vehicle is calculated by the MADA software, derived from the ARHMM mode, based on a multi-body approach, allowing us to calculate 250 internal variables in real time at a frequency of 100 Hz.

Figure 1.5. *Renault dynamic simulator – France*

1.2.3.3. *VIRTTEX simulator*

The VIRtual Test Track EXperiment (VIRTTEX) simulator is located at the Ford Research Laboratory at Dearborn, USA [GRA 01]. VIRTTEX is a high-level driving simulator built at the beginning of the year 2000. The movement system consists of a large 6-DoF, supporting a dome of 1,360 kg (Figure 1.6) and offering a broad linear movement of ±1.6 m and a response time of 15 ms. The bandwidth of the simulator is higher than 13 Hz with a transport delay of 80 ms [ART 01]. VIRTTEX was implemented for three research axes regarding, more specifically, road safety, vehicle dynamics and driving behavior.

Figure 1.6. *Gough–Stewart platform simulator of the VIRTTEX – USA*

1.2.4. *Hybrid structured platforms*

We must combine the advantages of the two previous architectures. By combining different technical tricks, hybrid structures display complex and intricate open and closed cinematic chains. However, certain solutions, such as the one consisting of building a parallel platform on an XY table, seem to become a standard in the field of driving simulation. Thus, we can afford a generous working space with a strong dynamic.

1.2.4.1. *ULTIMATE simulator*

A driving simulator with a hybrid structure was built within a European project (Eureka) lead by Renault at the Technical Simulation Centre (Figure 1.7). This is a 6-DoF Gough–Stewart platform whose base can move on XY rails with a maximum, longitudinal and lateral movement of 6 m$\times$6 m [DAG 04].

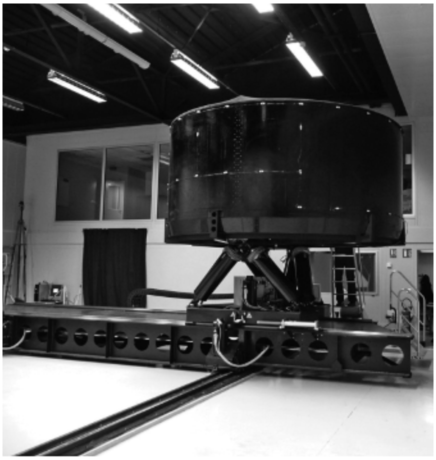

Figure 1.7. *Hybrid architecture of the ULTIMATE simulator by Renault – France*

1.2.4.2. *Daimler-Chrysler simulator*

The simulator is made of a dome mounted on a 6-DoF mobile platform offering a maximum linear acceleration of 1.2 g and a bandwidth of 3 Hz [KÄD 95a]. Furthermore, the mobile platform can also move laterally on a rail via a hydraulic actuator, thus facilitating a maximum lateral motion of ±3.8 m (Figure 1.8). The maximum lateral acceleration is of 0.7 g with a bandwidth of 5 Hz.

The dynamic model of the virtual vehicle, called CaSimIR, was developed by Daimler-Chrysler. It is made up of two modules: a file of vehicle parameterization (masses, suspension and motor characteristics) and a module that groups together elementary structure models (motor, tire/road, suspension and steering). CaSimIR facilitates the simulation of a dynamic model of 18–37-DoF, and can include the nonlinear properties of suspensions and the flexibilities of the direction system.

Several experiments were carried out with different ARAS (power steering and active suspension), where their function, efficiency and acceptance were studied.

Figure 1.8. *Daimler-Chrysler simulator – Germany*

1.2.4.3. *NADS simulator*

The project at the origin of this simulator aimed at creating the best possible simulator, with a cost of at least 50 million dollars. It displays massive characteristics, with an XY table of 400 m^2 and a large hexapode. It has a vibrating table that allows us to recreate vibrations of ±0.5 cm going up to 20 Hz (Figure 1.9) [FRE 95, KÄD 95b].

For the dynamic model of the vehicle, NADS uses a multi-body modeling tool similar to ADAMS, called NADSdyna. It is made up of three libraries that define the body, joints and the key elements that are the basis for building different vehicle modules, such as the suspension, the motor and the gearbox. Starting from these modules, validated separately, the motion equations are created and then transformed into a set of differential equations that can be solved with adequate computing techniques.

Figure 1.9. *NADS simulator – Iowa, USA*

The teams that use NADS research human factors [CHE 01] such as the driver's reactions to the state of the road, fatigue, aging, drugs and alcohol, but it is also used for developing safety devices, comfort and for carrying out ergonomic studies.

1.2.4.4. *Toyota simulator*

Having the same architecture as NADS, the Toyota simulator is a hybrid platform made up of two parts (Figure 1.10). On the one hand, we have a hexapode supporting a dome of 7.1 m in diameter that holds a real version of an automobile and is lined on the inside with a screen offering a panoramic view of 360° of the outside environment. On the other hand, an XY table that allows a longitudinal movement of 35 m and a lateral one of 20 m.

Having been completed in 2008, the simulator is mainly meant to:

– analyze driving characteristics. It must detect abnormal behaviors caused by a lack of reflexes (fatigue), the deterioration of sensory faculties (inebriation), etc.;

– implement active safety measures, driving aiding systems and alarm systems, as well as intelligent transportation systems (ITS).

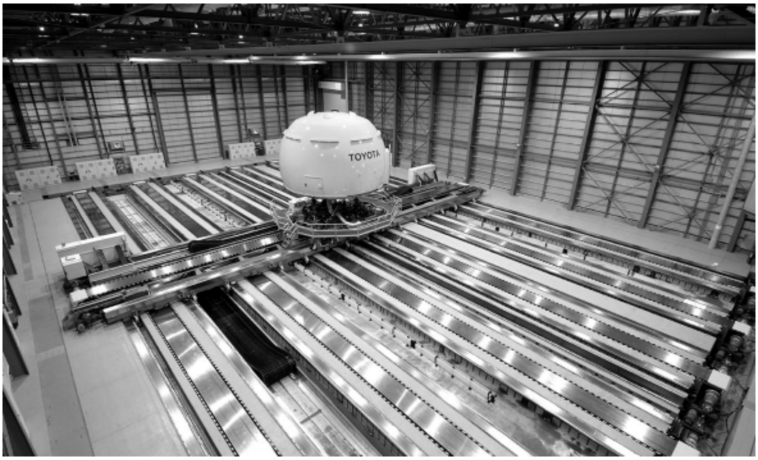

Figure 1.10. *Toyota simulator – Toyota Technical Center at Susono City, Japan*

1.2.5. *"Low-cost" generation*

The use of driving simulators has become increasingly widespread in both private and public institutions. However, while the costs of airplane training and the safety of passengers warrant the investment in high-cost piloting simulators, there is nothing similar to justify a tool for psycho-physical and training purposes. Moreover, the complexity of a simulator is not necessarily an indication of its ability to faithfully render all the motions. For this reason, it is worth proposing targeted, low-cost mobile-based platform solutions mainly for training schools, institutional buildings and other users.

In this context, a mini-simulator was built, as a result of the collaboration between the French Institute of Transport Science and Technology and the Information Technology, Integrative Biology and Complex Systems Laboratory at the University of Evry-Val d'Essonne in France. It offers a 2-DoF serial architecture holding an instrumented cabin. The platform facilitates an acceleration rendering of approximately 1 g thanks to a longitudinal motion of ±60 cm and to an optimized transmission screw-nut system activated by a Brushless electric motor (Figure 1.11). The seat in the cabin is designed to make small rotations, either of the whole seat (backrest and seat) or only its backrest. These two configurations are possible due to simple and original mechanics described in [MOH 05]. The research work on this simulator has triggered the issue of several prototypes. These consisted of implementing various algorithms and control strategies for this type of platform [NEH 06, NEH 08]. Other studies have tackled the efficiency and quality of the motion rendition as well as subjective comparisons and objectives of the other platforms, mentioned previously.

Figure 1.11. *INRETS/IBISC mini-simulator – France*

The steering wheel of the cabin is equipped with an effort feedback system. The haptic interface is equipped with a motor based on direct current, driven by two electronic boards. The first one is based on an industrial micro-controller for generating the signal pulse width modulation (PWM), while the second is a chopper circuit that delivers the power strength signal toward the steering wheel motor. The current set point is calculated by a quadri-pole formula of the entire cinematic chain, which represents the set “steering wheel-steering column-wheels”.

One first experiment was carried out on the mobile platform, which sought to define the minimum motion configuration that allows for the reproduction of enough inertial indicators, as well as that for a situation of queue driving. Based on the subjective assessments of different drivers, it had been noted that a short motion of the platform combined to the motion of the seat seemed to be the most appreciated configuration for a normal driving situation. However, a long motion seems to be necessary for extreme driving situations that involve acceleration maneuvers and sudden braking [NEI 05].

1.3. Driving simulation objectives

For the car driving trainers, the simulators are tools that were essentially designed to allow drivers to acquire elementary driving reflexes. The trainers therefore think that the realism of the driving process is a significant element for learning how to drive, but the cost of purchasing this tool is a concern they also consider. They are therefore often interested in low-cost simulators that offer a virtual environment that suffices to teach the driver basic driving maneuvers. Another essential aspect for trainers is to be able to establish different possible traffic scenarios, in order to face the driver with driving situations deemed primary for learning. The trainer being often considered as a user, it is deemed essential that the traffic or scenario simulation software be easy enough to use and with it, be able to create the scenarios needed for training.

Researchers that carry out studies on drivers’ behavior are very interested in driving simulators. In-depth experiments carried out for behavioral studies in real situations are often too difficult to implement, as they generally take place in an environment that is less controlled.

Weather conditions and traffic complexity are such that the interaction between the drivers and their environment is practically impossible to reproduce. Moreover, the study of certain dangerous driving situations, such as driving in foggy weather, cannot be carried out because of the risks the subjects may be exposed to. Thus, for reasons of reproducibility, cost and, above all, safety, driving simulators seem unavoidable for certain drivers' behavioral studies. However, the results of the experiments carried out via simulators cannot be validated unless the driver's behavior in the simulator is very close to the behavior he/she displays in real life. The behavior induced by the simulators when facing certain road conditions is not always the same as the behavior in real life. Furthermore, driving tasks, such as the ones related to maintaining a trajectory or even those related to queue driving, are much more difficult to implement on the simulator, even in normal driving conditions. These gaps, that more or less characterize the majority of driving simulators, are mainly due to the inherent limits of simulators, in terms of visual and haptic feedback. In order for the simulators' results to be translatable in reality, it is therefore imperative, for this type of study, that the simulator provides the driver with the stimuli that make the behavior as true to reality as possible.