Proceedings of the 1998 IEEE
International Conference on Robotics & Automation
Leuven, Belgium • May 1998

A Driving Simulator as a Virtual Reality Tool

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ABSTRACT

Driving simulators are used effectively for vehicle system development, human factor study, and other purposes by enabling to reproduce actual driving conditions in a safe and tightly controlled environment. This paper describes a driving simulator developed for design and evaluation of full-scale driving simulators and for driver-vehicle interaction study. The simulator consists of a real-time vehicle simulation system, a visual and audio system, a motion system, a control force loading system, and an experiment console. The real-time vehicle simulation system supervises overall operation of the simulator and also simulates dynamic motion of realistic vehicle models in real-time. The economical visual system generates high fidelity driving scenes that are displayed on a screen by a projector. The motion system generates realistic motion cue using a six degree-of-freedom Stewart platform driven hydraulically. The control force loading system acts as an interface between a driver and the simulator. The experiment console monitors the status of the simulator in operation and also collects and manages experimental data.

Keywords: Driving Simulator, Real-Time Vehicle Simulation, Visual/Audio System, Motion System, Control Force Loading System, System Integration

INTRODUCTION

A driving simulator is a virtual reality tool that gives a driver on board impression that he/she drives an actual vehicle by predicting vehicle motion caused by driver input and feeding back corresponding visual, motion, audio and proprioceptive cues to the driver. The simulator normally consists of several subsystems as follows: a real-time vehicle simulation system performing real-time simulation of vehicle dynamics; motion, visual and audio systems reproducing vehicle motion, driving environment scenes and noise sensed by a driver during driving; a control force loading system acting as an interface between the driver and the simulator; an operator console for monitoring system operation; and system integration managing information and data transfer among subsystems and synchronization. The driving simulators have been used effectively for vehicle system development, safety improvement and human factor study.

The driving simulators, having their roots on flight simulators applied since the early 1900s, have begun to appear in primitive forms in the 1970s [1,2]. With the advent of computer technologies, Daimler-Benz in Germany launched a high fidelity driving simulator in the early 1980s [3], which created wide interests throughout the world. Since then, many automotive makers and research institutions have developed and applied their own simulators that meet application purposes and target performance [4-6]. Recently, construction of the state-of-the-art National Advanced Driving Simulator (NADS) [7] in the United States has begun and will be completed in 1999.

Many factors should be carefully considered in developing and applying full-scale driving simulators effectively, such as construction costs, application areas and target performance. A prototype simulator, down-scaled, yet consisting of all the necessary subsystems can be used effectively for evaluation of the factors mentioned above and design of the full-scale simulators. The objective of this study is thus to develop an economical and effective driving simulator as a virtual reality tool and apply it to design and evaluation of full-scale simulators and driver-vehicle interaction study. This paper describes mainly the development of the simulator.

SIMULATION COMPONENTS

The essence of interactive driving simulation is the cuing feedback that a driver receives based on control responses, input commands, and disturbances. The realism of the simulation then depends on the basic fidelity of the cuing, and the relationship between the driver's control responses and the response of the cuing devices.

Figure 1 illustrates various components that control and generate visual, motion, control loading, instrument, and auditory display feedback cues to a driver in driving simulation. Driver control inputs to the vehicle dynamics generate vehicle positions, velocities, accelerations, and orientations that then provide inputs to the various feedback cuing pathways. In driver-driving simulator closed-loop operation, the driver receives visual and motion feedback of vehicle motion related with the driver's inputs, and proprioceptive feedback of steering torques as influenced by vehicle motions and steering system characteristics. These feedback cues must be accurate and realistic enough to ensure high fidelity. They must also be received by the driver without significant delay over what would be experienced in a real vehicle, otherwise the effective vehicle dynamics will be degraded, resulting in reduced fidelity and validity.

SYSTEM CONFIGURATION

Figure 2 shows a basic concept and configuration of the driving simulator developed in this study. The simulator is controlled and operated in a network of four personal computers connected by Ethernet.

The driver on board the simulator takes driving action in terms of steering, braking, and accelerating in the given driving scenarios. The driver input is then sensed by the control force loading system and fed back to the real-time dynamic computer through the RS-232C port. Simulation of vehicle dynamics is then performed in real-time to

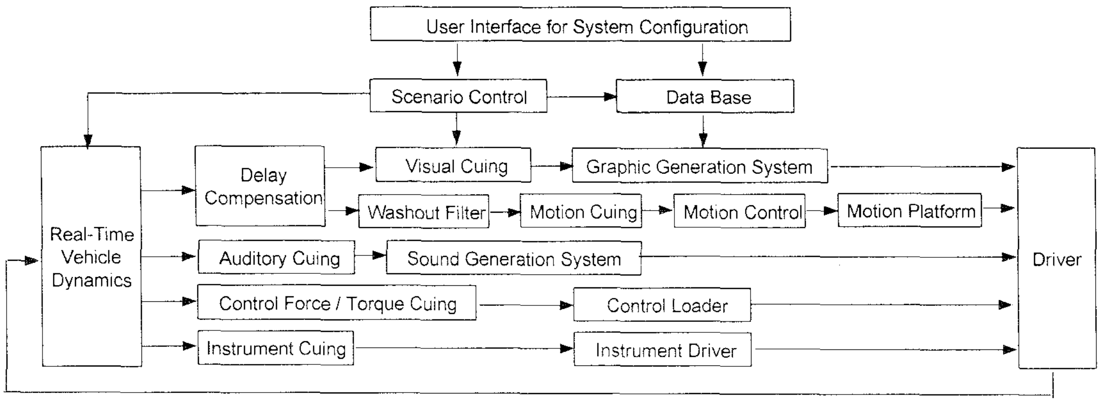

Fig. 1 Interactive Driving Simulation Components

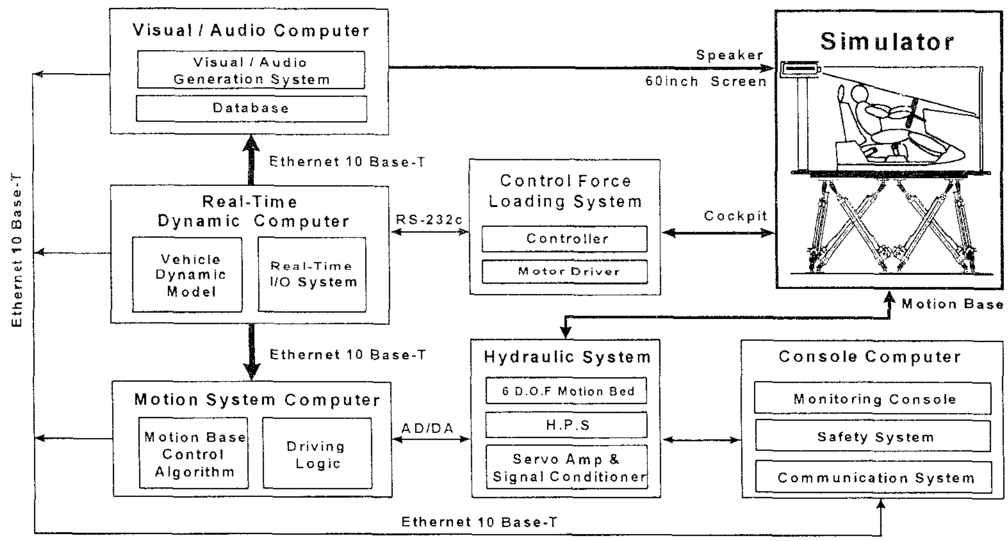

Fig. 2 Driving Simulator Functional Diagram

predict the resultant vehicle motion. The visual and audio computer, with the real-time vehicle simulation output, generates and displays realistic graphic image and noise of driving environment corresponding to driving conditions. The motion system computer runs a drive logic to control a hydraulic system that drives a 6 degree-of-freedom Stewart platform for creating realistic motion cue. The control force loading system, in addition to sensing the driver input, generates realistic reaction forces and torques in the driving mechanism for proprioceptive cue. The monitoring system is also included in the simulator to monitor entire system operation and perform effective fail-safe functions. The driver cab is composed of mainly the driver side of an entire passenger car, along with the actual instrument panels and driving mechanism.

A photograph of the simulator in operation is shown in Figure 3.

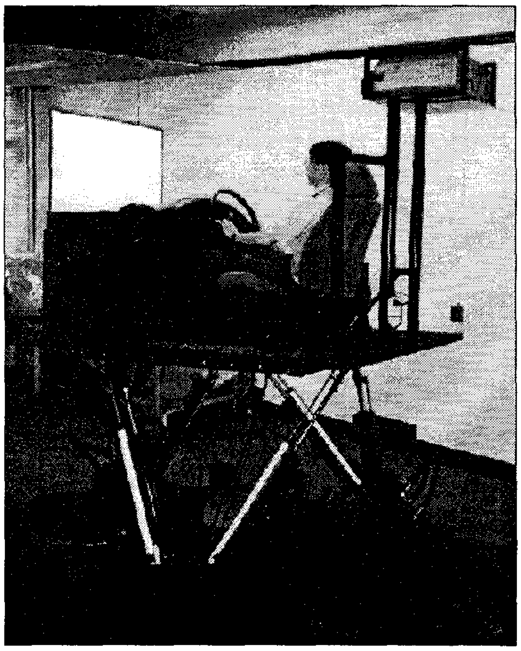

Fig. 3 Driving Simulator in Operation

REAL-TIME VEHICLE SIMULATION SYSTEM - The real-time vehicle simulation system is a key element of the driving simulator because accurate prediction of vehicle motion with respect to driver input is essential. Three factors that are correlated each other must be considered for performing real-time vehicle simulation: vehicle modeling, real-time simulation and a real-time computer.

Vehicle models used in the driving simulator must satisfy contradicting conditions of realism and real-time. In order to predict vehicle motion caused by various driving action of the driver on board the simulator, the vehicle models should include, in addition to basic chassis and suspensions, subsystems such as an engine, a power train, a steering system and a brake system. The models should also have flexible expandability. The modular vehicle modeling approach has been adopted in this study for systematic development of the vehicle models.

For chassis and suspension motion, both a 16 DOF lumped mass model and a 14 DOF multibody model with front Macpherson and rear trailing arm suspensions have been developed. Based on a simple linear relationship between the accelerator pedal angle and the throttle valve angle, the input to the engine model has been determined according to driving action. The engine speed and torque have been computed using a simple engine model based on the reference 8. A power train model, consisting of a static torque converter and an automatic transmission model with a transmission map, has been used to compute driving torque that will be included in tire rolling dynamics. For the brake system, a quasi-static model has been used to compute brake pressure in relation to the brake pedal angle, without considering hydraulic system dynamics. The steering system has also been simplified to account for a rack and pinion type.

Several real-time integration methods such as Euler, Heun and Adams methods have been used for real-time simulation. In selecting the right integration method, several factors must be considered including accuracy, stability, phase, delay, and execution time. Based on results from several numerical experiments, the Adams method has been selected for this purpose [9]. The zero or low speed conditions occurring during various maneuvers, including starting after stop, high speed driving, braking and complete stop, cause undefined longitudinal slip and, as a result, difficulty in simulation. This problem has been solved by following the approach taken by Bernard [10].

A personal computer equipped with dual-Pentium pro processors has been set up as a real-time computer in this study. The execution time of the lumped mass and the multibody models on the computer is less than 2 and 6 msec per step, respectively. For more complex and realistic vehicle models, the parallel processing technology is being considered for efficient parallel execution of the vehicle models based on parallelism identified in independent kinematic chains using shared memory multiprocessors [11].

VISUAL AND AUDIO SYSTEM - Since visual cue is most significant in controlling and maneuvering a vehicle during driving, the key element for ensuring high fidelity in driving simulation is a visual system. Processing of high resolution graphics in the visual system is essential for the driver to have realistic driving feel and react to driving environment precisely. The visual system is divided into two parts for computer image generation and display. Figure 4 shows a functional diagram of the visual/audio system in this study.

The visual systems in the full-scale driving simulators normally utilize very expensive high-end workstations

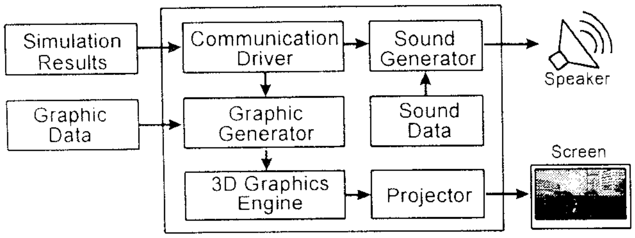

Fig. 4 Visual/Audio System Functional Diagram

with dedicated graphic cards and graphic software to generate high fidelity visual image. In this study, an economical, yet very efficient visual system computer has been set up with a personal computer with a Pentium pro processor and a Glint 500TX+*Delta* 3D graphic accelerator [12]. Visual image generation software has been developed using OpenGL 1.1, and objects have been modeled using VRML 1.0. A visual database has also been developed for storing and managing model, object and terrain data systematically.

A system configuration file in ASCII format has been utilized for defining driving scenarios and measuring performance easily. A typical driving scene with texture map generated by the visual system is shown in Figure 5. Fog and night effects can be imposed on the same scenario easily. For display of generated driving scenes, a single channel projection system has been developed having 42

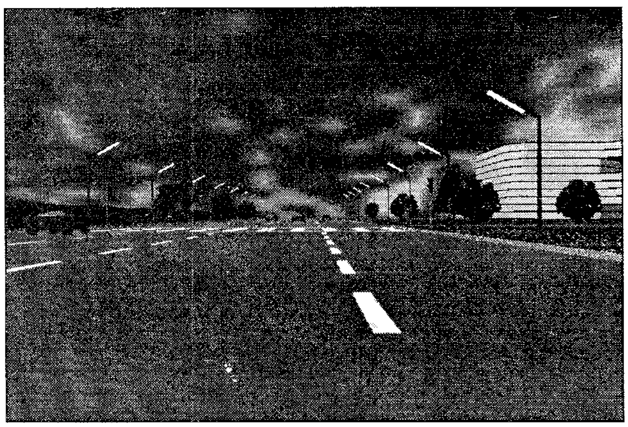

Fig. 5. Typical Driving Scene with Texture Map

and 32 degrees of horizontal and vertical field of views, respectively.

An audio system is an important addition to fidelity enhancement of the driving simulator. In this study, an audio system has been set up with a Sound Blaster AWE32 sound card and speakers. A sound database has been constructed to store and manage tire, engine and driving environment noise. The MIDI function of the sound card has then been used to combine and play appropriate noise in coordination with driving conditions.

MOTION SYSTEM - Reproducing ride and handling characteristics of a vehicle that a driver feels through chassis linear accelerations and angular velocities is an important element for enhancing simulator fidelity. However, a care should be taken not to cause conflicting effects among subsystems and induce simulator sickness, due to high sensitivity of the motion system.

The kinematic structure of the motion system should be considered first in developing the motion system. A widely used 6 DOF Stewart platform, driven hydraulically, has been chosen to be the motion platform in this study. Target performance and motion envelope of the motion system have been defined with reference to MIL-STD-1558 specification for flight simulators, as shown in Table 1. Based on the target performance, motion envelope and driving scenarios, a hydraulic circuit and its elements including actuators, servovalves, and other components have been designed. The lower part in Figure 3 shows the motion system developed in this study.

Table 1. Motion Platform Requirements

	Surge(X)	Sway(Y)	Heave(Z)	Roll	Yaw	Pitch
Displacement	±250mm	±250mm	±250mm	±20°	±20°	±25°
Velocity	±0.6m/s	±0.6m/s	±0.6m/s	±60°/s	±60°/s	±60°/s
Acceleration	±1.0g	±1.0g	±1.0g	±60°/s²	±60°/s²	±60°/s²

A drive logic of the motion system for generating realistic motion cue includes an washout algorithm, inverse kinematic analysis, and a control algorithm, as organized in Figure 6. The washout algorithm recovers motion cue that is realizable within the motion envelope

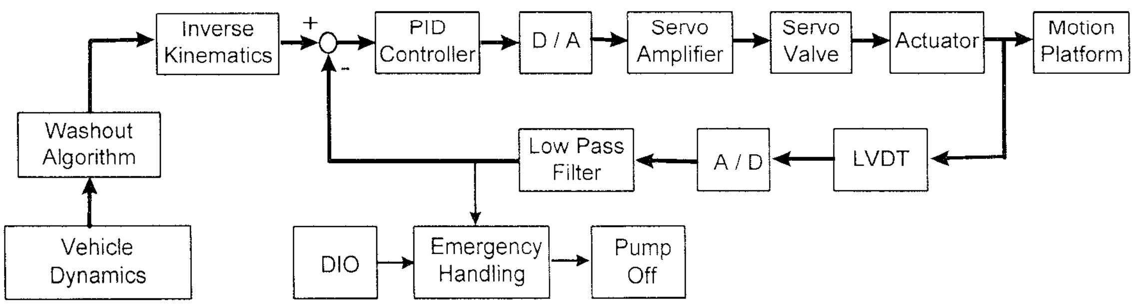

Fig. 6 Motion System Functional Block Diagram

from command cue of vehicle simulation output. A washout algorithm has been developed in this study for software limitation of platform motion based on high-pass filtering, and tilt coordination for generating sustained inertial acceleration required in some maneuvers such as J-turn based on low-pass filtering. Chassis position and orientation information from the washout algorithm has then been converted into actuator lengths by the inverse kinematic analysis. A PID control algorithm has been developed to ensure movement of the motion platform in the right position. The drive software has been developed based on the flexible LabVIEW software [13].

Figure 7 shows a typical response of the motion system in terms of voltages representing actuator lengths. As shown in the figure, the motion system response indicated by the solid line closely follows the driving input from the washout algorithm represented by the dotted line.

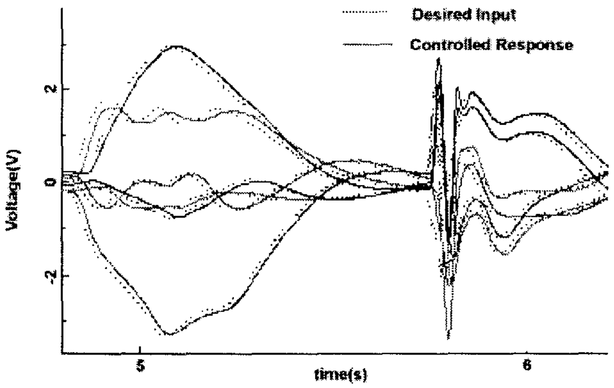

Fig. 7 Typical Motion System Response

CONTROL FORCE LOADING SYSTEM - The control force loading system acts as an interface between the driving simulator and the driver, in that it senses driver input and feeds it back to the real-time vehicle simulation system, displays vehicle operating conditions on instrument panels, and generates reaction forces and torques in the driving mechanism for proprioceptive cue.

The system developed in this study consists of the following components: a controller with five micro-controllers and a communication module for managing data transfer, computing reaction forces and torques, and controlling encoders, motors and lamps; rotary encoders for sensing driver input; and DC geared motors for actuating reaction forces and torques. The driver cab with the control force loading system implemented is shown in Figure 8.

Driver software has been developed using an assembler to control appropriate functions effectively. An algorithm for computing reaction forces and torques have been developed based on the table look-up approach. Use of vehicle dynamics for more accurate and flexible computation is also being implemented.

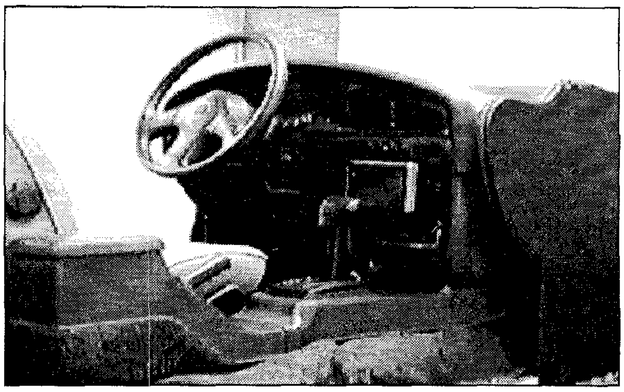

Fig. 8 Driver Cab

SYSTEM INTEGRATION

The system integration technology, managing information and data transfer among subsystems, synchronization, and fail-safe functions, is a key factor in determining the fidelity and performance of the driving simulator. Thus, the method for integrating the subsystems should be carefully considered from the early stages of simulator development.

The Windows NT software has been chosen as the operating system of the driving simulator in this study, due to reliability and many convenient features. A software time interrupt function has been added to the basic Windows NT software for real-time operation.

Definition of input/output signal flows among the subsystems is a prerequisite to effective system integration. The signal flow diagram including types and sizes of I/O signals has been carefully prepared at the initial development stage, and then the network communication flow based on Ethernet has been defined. LabVIEW software has been utilized to develop a flexible communication module as shown in Figure 9.

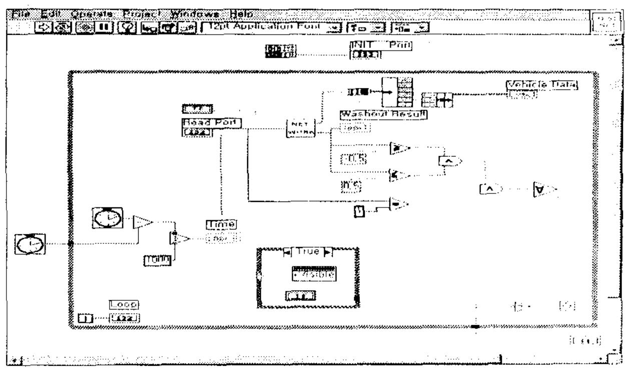

Fig. 9 Network Module Using by LabVIEW

The operation procedure of the simulator includes system initialization, a series of tests for checking normal operability and controllability, and simulation according to driving scenarios. The operation module has also been developed by combining individually developed subsystem modules in LabVIEW and FORTRAN format.

Transport delay is a phenomenon whereby the response of a dynamic element falls behind in time relative to its input. Without including human perception delay and physical vehicle delay occurring in real driving situations, there are three major sources of transport delay in the driving simulator: the vehicle simulation, visual, and motion systems. Real-time vehicle simulation is achieved as mentioned above, and thus delay associated with vehicle dynamics computation remains below the perception threshold of the driver. Transport delay in the visual system includes data acquisition, image processing and display time, and is in the range of 25 and 50 msec depending on the quality of visual images. The delay in the motion system is around 50 msec, including data acquisition, drive logic computation, and motion platform response time. Compensation of transport delay is critical in ensuring the fidelity of the simulator, in that delay degrades system performance, and further system stability. The prediction method based on numerical integration [14] is being applied to compensate for individual delays and guarantee synchronization.

The fail-safe function has also been carefully considered here. The monitoring console, as shown in Figure 10, has been developed to monitor entire system operation periodically and, when emergency occurs, move the motion platform to the neutral position safely.

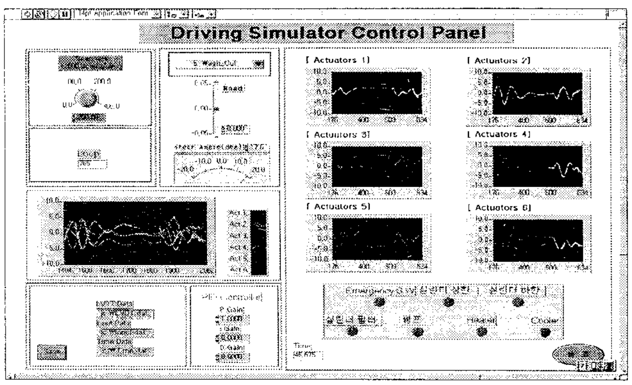

Fig. 10 Monitoring Console for System Safety

CONCLUSIONS

An economical, yet effective driving simulator as a virtual reality tool, consisting of all the necessary components required in full-scale simulators, has been developed. It will be used for design and evaluation of the full-scale simulators and driver-vehicle interaction study. Experiments with the developed simulator are underway and the results will be reported separately.

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