Low cost motion platform for driving simulator

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Abstract

Nowadays, driving simulators are interactive virtual reality tools which take a considerable place in the human factors studies. The difficulty or impossibility to reproduce in reality some road situations mainly for risk and reproducibility reasons increases the interest of this tool. Nevertheless, the validation of the experiments carried out on driving simulator is closely related to embedding realism of the driver in the simulated world. Thus, the wish to increase the validity field of such tool requires more and more the integration of the haptic and kinesthetic feedback. The design of these devices which allow "sufficient" embedding is still a research topic.

In this article, we present the design of a low cost motion platform which allow the restitution of 2 DOF weak movement. This overall system is considered as a two independent systems linked mechanically. The first system consists in motorised rail for the longitudinal movement while the second system consists in motorised seat allowing either pitch movement of this one or just back seat inclination.

I. Introduction:

Some tasks, which are easily achieved in an actual driving situation (lane shift or queuing for instance), become tedious when the driver has to accomplish them using a driving simulator, primarily when it is a static one. The lack of sensory stimuli (haptic, kinaesthetic), prevent the driver from an adequate control of the virtual vehicle. In order to drive a virtual vehicle, the driver need to be provided with sufficient information which allows him to control the car as easily as it is the case in most of real situations. Depending on the hardware architecture of each simulator, the feedback strategies might be different, due to the very fact that the control is based on sensory-motor activity.

Some studies aiming to highlight the relevance of kinesthsic perception in simulator controllability clearly showed that longitudinal and lateral acceleration significantly reduce the simulator control variability [4][5][6].

Accurate restitution of accelerations observed on an actual vehicle is impossible to achieve on a driving simulator, whatever motion platform performance used (as acceleration restitution during a braking manoeuvre can demand a platform shift of around 100 metres) [1]. Due to this impossibility, illusion of inertial effect has to be for the driver. Such illusion rests on acquired knowledge of the human perceptive system. In the case of continuous accelerations the illusion is generally produced by tilting the driver forward or backward. Such tilt can be interpreted by his/her vestibular system, as either a positive or negative acceleration, depending on the direction of the tilt [2][7]. In the transient acceleration case, the platform is linearly moved in the same acceleration direction and come back when the acceleration is continuous [2][7]. The implementation of this technique depends strongly on the architecture of the motion platform, the limits of its workspace and its band-width capacity as well as on the dynamic characteristics of the actuators used to move the platform [1].

The first designed motion platforms were intended for movement restitution for flight simulators. The concept was applied much later to movement restitution on automobile driving simulators [1][6].

The designers of the first driving simulators which, integrated motion platforms derived from technology used for flight simulators were confronted with a whole of problems linked to the great differences between driving a car and flying a plane:

- The dynamics of a vehicle are indeed different from those of an airplane; and the 6 DOF acceleration variations in a vehicle are more frequent and sometimes more brutal than those observed in airplane (in particular in a curve, changing lanes or braking).
- Driving a vehicle takes place in traffic that can sometimes create very complex situations. The driver is thus more called upon for the control of his vehicle than is an airplane pilot (handling interactions and, notably, car following driving).
- The sensory information used for driving a vehicle is greater (and sometimes different) that used for flying an airplane.

All these constraints have led designers to imagine another architecture by seeking as often as possible to supply the driver with stimuli that are as close as possible to those existing in actual situations. Let us recall that the reproduction of physical phenomena is impossible and that these architectures seek to produce the best possible illusion. The most sophisticated solutions bring into play hybrid architectures (X-Y, 6 axis + yaw) and their costs reach upwards of 100 million dollars (Nads, USA). These simulators seek to process all possible driving situations. They are, however, not always able to accurately reproduce braking manoeuvres accurately.

Another driving simulation approach is possible. This approach is founded on the design of partial simulators, intended for certain studies or applications (e.g. a particular driving task study) [8]. For these simulators, and concerning movement restitution, the goal is to produce a sufficient illusion in order to make possible the achievement of the task. By sufficient illusion, we mean an illusion that allows the driver to carry out the task by using the same strategies as those he/she would have employed in a actual situation. This last point is essential to guarantee transferability of results acquired on a simulator to real situations.

In this presentation we will show the motion platform we designed for a driving simulator whose objective is the study of “normal” driving situations (e.g. outside of sliding or harsh braking situations). We will focus on the most common driving situation: car following driving. Our objective is not to resituate acceleration in a realistic physical way, but rather to study the minimal inertial effect from which the subject extracts the necessary information to carry out the driving task in a manner comparable to a real driving situation.

To do this, we have designed and built a low-cost motion platform equipped with two degrees of freedom. This makes it possible to animate the simulator’s cab with a longitudinal movement, on the one hand, and with a weak pitch movement from the driver’s seat or a weak tilt of the back of this seat, on the other hand.

II. Platform Description and Modelling :

To model the driving simulator motion, the overall system is considered as a two independent systems mechanically linked: the rotating driving seat and the longitudinal motion platform. Each of them is driven by a single actuator. The motion platform undergoes translational motions according to one direction (front and back) which correspond to driver's acceleration and deceleration. The overall system's design allows to have a simple linear model of the motion. Model's mathematical refinements can be achieved if the controller performances are not satisfactory.

II.1 The linear motion platform:

The motion base supports the cabin consisting of the seat, the vehicle board and the driver. Because the rotations of the seat are slow and low in amplitude, its induced inertia is negligible comparing to the total mass of the cabin's set. The linear motion of the cabin's set is made thanks to a balls screw/nut transmission mechanism driven by an DC actuator. The technological design was made in order to reduce, even eliminate, mechanical flaws such as backlash, mechanical play, static and dynamic friction, and to be able to design good quality acceleration and jerk based controllers. The followings equations describe the systems components.

The actuator's electric equation is:

$$u - e = R_1 + L_1 \frac{di}{dt} \qquad (1)$$

where u is the armature applied voltage in Volt, e is the voltage generated by the back electromotive force in Volt, R_1 is the actuator resistance in Ohms, L_1 is the armature inductance in Henry and i is the armature current in Amperes, $\frac{dx}{dy}$ states for the derivative of function x according to variable y, and t is the time in seconds.

The mechanical equation of the actuator pulling the cabin is:

$$T_{a1} = J_{a1} \frac{d\omega_{a1}}{dt} + f_{a1}\omega_{a1} + \frac{T_l}{N_1} \qquad (2)$$

where the indexes a and l state respectively for actuator and load, T is the torque in N.m, J is the rotational inertia in kg.m², ω is the rotational speed in rad/sec, f is the rotational armature friction in N.m.sec/rad, and N_1 the reduction factor. It is standard to relate the torque T_{a1} developed in the rotor in terms of the armature current i and a constant K_{t1}, and to express the generated voltage as a results of the shaft rotational velocity ω_{a1} and the back emf e, that is:

$$T_a = k_{t1} i \ \ (4) \qquad \text{with} \qquad e = k_{e1}\omega_{a1} \ \ (3)$$

We have now two more components: the balls screw-nut transmission mechanism and the cabin's set. The last is considered as a whole having a mass M sliding on a mechanical guide-way under an external applied force F_x in Newton (the total cabin's mass (kg) $M = m_c + m_t$ where m_c is the known empty cabin's mass and m_t is the estimated operator's mass). The guide-way induces friction during motion. The whole set slides according to the $\vec{x}$ axis, then x denotes the cabin's position, it is also used as an index for cabin's related variable, and $\dot{x}$ is the cabin's speed. The governing equation is:

$$M \frac{d\dot{x}}{dt} + f_x \dot{x} = F_{x1} \qquad (4)$$

The balls screw-nut pulling mechanism is driven by the external torque Ts, indeed:

$$T_{s1} = J_{s1}\frac{d\omega_s}{dt} + f_{s1}\omega_{s1} + T_{t1} \quad (5)$$

where, J_s is the ball screw-nut mechanism's inertia, f_{s1} is the friction forces due to balls redistribution and their interaction with the pulling system, this friction is supposed to be very small when the screw-nut is pre-load, and T_{t1} is the torque induced by the load (through the linkage). Now it is time to link the three systems. First, linking the pulling mechanism to the cabin's set is made through the variables T_{t1} and F_{x1}. In fact the load torque T_{t1} is transformed through the linkage to the axial force F_x by the following equation:

$$T_{t1} = \frac{p_1}{2\pi\eta}F_{X1} \quad (6)$$

Now, equation (5) can be written as:

$$T_{s1} = J_{s1}\frac{d\omega_{s1}}{dt} + f_{s1}\omega_{s1} + \frac{p_1}{2\pi\eta}(M\frac{d\dot{x}}{dt} + f_{x1}\dot{x}) \quad (7)$$

Linking the pulling ball screw-nut mechanism to the actuator is made through the variables T_{s1} and T_{t1}. Indeed, the actuator load torque is in fact the applied screw torque and thus $T_{s1} = T_{t1}$ and equation (2) becomes:

$$\begin{aligned} T_{a1} &= J_{a1}\frac{d\omega_{s1}}{dt} + f_{a1}\omega_{a1} + \\ &\frac{1}{N_1}[J_{s1}\frac{d\omega_{s1}}{dt} + f_{s1} + \frac{p_1}{2\pi\eta}(M\frac{d\dot{x}}{dt} + f_{x1}\dot{x})] \end{aligned} \quad (8)$$

Now we can work this equation either in the cabin Cartesian space x or the actuator joint space, this can be done simply by the equation linking the rotational speed to the Cartesian's one:

$$\dot{x} = \frac{\omega_{a1}}{N_1} \quad (9)$$

and the one linking the actuator speed to the screw pulling system's one through the reduction factor N_1, that is:

$$\omega_{s1} = \frac{\omega_{a1}}{N_1} \quad (10)$$

Finally we obtain the following equation considering the cabin's motion space:

$$\begin{aligned} k_{t1}i &= (\frac{2\pi N_1}{p_1}J_{a1} + \frac{2\pi}{p_1N_1}J_{s1} + \frac{p_1}{2\pi\eta N_1}M)\frac{d\dot{x}}{dt} + \\ &(\frac{2\pi N_1}{p_1}f_{a1} + \frac{2\pi}{p_1N_1}f_{s1} + \frac{p_1}{2\pi\eta N_1}f_{x1})\dot{x} \end{aligned} \quad (11)$$

Since:

$$u = R_1 i + L_1\frac{di}{dt} + \frac{2\pi N_1 k_{e1}}{p1}\dot{x} \quad (12)$$

and using the well known Laplace Transform, we can obtain the transfer functions between the cabin's position $X(s)$ and the voltage command signal $U(s)$, s states for the Laplace variable:

$$\frac{X}{U} = \frac{1}{s}\frac{k_{t1}}{(J_1 + f_1)(L_1 + R_1) + \frac{2\pi}{p_1}N\ k_{e1}k_{t1}} \quad (13)$$

II.2 The rotating seat model:

As previously stated, the driver seat can perform two kinds of small rotational motions: the rotation of the only seat's back and the entire seat rotation. A single actuator with a manual switch performs either the first or the second functionality (i.e. not both at a time). This motion can be coupled to the linear one giving a five possible combinations for experimental investigations of motion feedback strategy during vehicle acceleration and braking.

Using a modelling approach similar to that of the cabin's support platform one, that is: the seat set can be split into three subsystems: the actuator set, the balls screw-nut transmission mechanism, and the seat set (including the driver). In the actuator level, the equation remains the same, and the parameters are taken according to the actuator and the reduction factor. The balls-screw-nut pulling system is also similarly modelled taking.

At the seat level, we are intersected in achieving small rotation angles of either the seat or the seat back, we consider gravity center at a distance ρ from the seat's rotation axis $\vec{y}$. Let l be the distance separating the nut's axis from $\vec{y}$. The forces inducing rotations of the either the seat or the back are: the torque induced by gravity, the one induced by the platform motion, that is F_{x2} and F_{t2}. Let θ be the seat rotation angle, we have:

$$\begin{aligned} &m_t g\rho\sin(\phi+\theta) + F_{t2}l = \\ &J_{t2}\ddot{\theta} + m_t(\ddot{x}\rho\cos(\phi+\theta) + \ddot{\theta}\rho^2) \end{aligned} \quad (14)$$

here, m_t is the estimated seat plus operator mass in kg, g is the gravity in m/s², ϕ is the angle (It is the angle which makes the vector, connecting the point representing the rotation axis and centre of gravity, and the axis X.) between $\vec{g}$ and the line joining $\vec{z}$ to the estimated gravity center G while being normal to $\vec{z}$, J_{t2} is the estimated inertia of the seat and the operator.

Since this equation relates to the screw mechanism through the variable F_{t2} (the induced screw's axial force), we will express equation (14) in function of F_{t2} that is:

$$\begin{aligned} F_{t2} &= \frac{J_{t2}}{l}\ddot{\theta} + \frac{m_t}{l}(\ddot{x}\rho\cos(\phi+\theta) + \\ &\ddot{\theta}\rho^2 - g\rho\sin(\phi+\theta)) \end{aligned} \quad (15)$$

As we can notice, this equation is non-linear, thus we gather the non-linear terms into the function

$$f(\theta,\ddot{x}) = \ddot{x}\rho\cos(\phi+\theta) \tag{16}$$

Since the screw speed relates the induced linear motion by $\omega_{s2} = \frac{2\pi}{p_2} l\dot{\theta}$, when x covers an arc around $\vec{y}$ by a ray of l, then x related θ by $x = \frac{1}{\theta}$, so $\dot{x} = \frac{1}{\dot{\theta}}$. Consequently, we may relay the screw rotation speed/acceleration to the seat angular speed/acceleration by:

$$\omega_{s2} = \frac{2\pi}{p_2} l\dot{\theta} \tag{17}$$

Now, replacing each item, in a similar way to the motion platform, modelling gives :

$$k_{t2} i = \left(\frac{2\pi l N_2}{p_2} J_{a2} + \frac{2\pi l}{p_2 N_2} J_{s2} + \frac{p_2}{2\pi\eta N_2}(J_{t2} + m_t \rho^2)\right)\ddot{\theta} + \left(\frac{2\pi l N_2}{p_2} f_{a2} + \frac{2\pi l}{p_2 N_2} f_{s2}\right)\dot{\theta} + \frac{p_2}{2\pi\eta l N_2} m_t g \sin(\phi+\theta) - \frac{p_2}{2\pi\eta l N_2} m_t f(\theta, x) \tag{18}$$

The obtained equations are non-linear. Preliminary considerations concern the seat's rotation angle. Because we want to feedback vehicle motion during acceleration and braking situation in a reduced space, because of the small angle of the rotation of the seat (-4°< θ < 4°). One can make the well known approximations: $\sin(\theta) \approx \theta$ in radians, and $\cos(\theta) \approx 1$, then: the equation (14) can turns to

$$f(\theta,\ddot{x}) = \frac{m_t}{l}\rho\ddot{x}\cos(\phi)\theta \tag{19}$$

If there is no motion then F_{x2}=0 ($\ddot{x} = 0$) and the overall equation is linearized in the neighbourhood of 4°< θ <4°, otherwise the equation is still non-linear because F_{x2} varies according to time and the non-linear term $\ddot{x}$. θ which can be linearized with feedback linearisation approach.

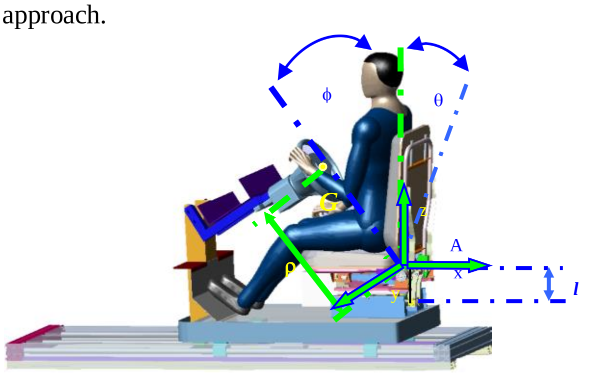
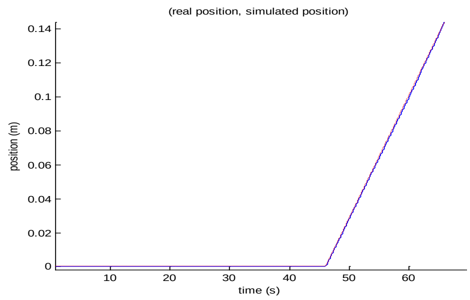


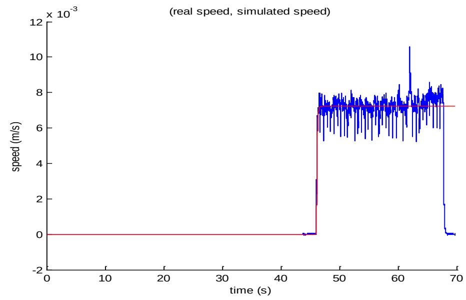
Figure (1) moving platform

III. Longitudinal dynamic model validation:

In order to validate the platform's longitudinal dynamic in open loop, we simultaneously stimulated the simulated dynamic model as well as the actual platform with a step voltage. We have also recorded their speed and position response signals. Results are as follows :



Figure(2)



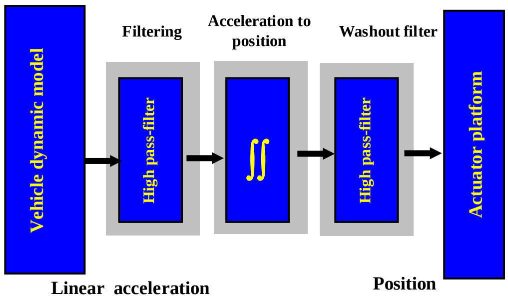
Figure(3)

The step stimulation response of the two systems, simulated and real, coincides exactly in position. In addition, the speed of the two systems, simulated and real, coincide in transition output speed and they have the same static gain permanent output speed. The noise signal of the real system sees to it that two signals do not overlap during this phase.

IV. Movement restitution algorithm :

In order to give to the driver the illusion of feeling the inertial effects of the simulated vehicle, the platform is powered by a classic Washout algorithm. A Washout algorithm aims to resituate transitory accelerations, within the cinematic, mechanical and dynamic limits of the platform (workspace, robustness, band-width, etc.). Transitory acceleration is obtained by filtering the simulated acceleration signal through a high-pass filter in order to isolate the high frequency component. In this way, the signal collected has a non-zero acceleration in the acceleration variation phase and a zero acceleration in the continuous acceleration phase.

The selection of the high-pass filter time constant takes place according to the maximum platform dimension. Indeed, this constant is as small as the platform course is reduced. After having filtered the acceleration, the signal produced is integrated twice in order to obtain the desired position profile. This is filtered by high-pass filter. This second filter is integrated with the sole aim of bringing the platform back to its neutral position in order to allow the generation the following acceleration. This is commonly referred to as “washout”. It is important to emphasize that the time constant of the second filter must be chosen as to allow the platform to return to its initial position without crossing the vestibular system’s movement perception threshold. If not, the subject will perceive a contradiction between the visual and vestibular stimulation.



Figure(4) Washout restitution movement algorithm

IV.1 Washout algorithm results :

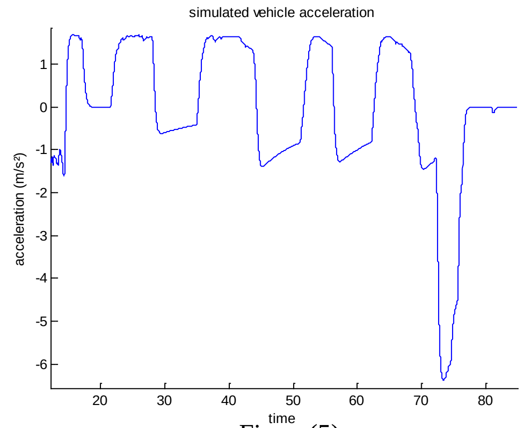
The mini-simulator mounted on the mobile platform is derived from work carried out jointly between INRETS and Faros. This mini-simulator is equipped with generic dashboard, safety belt, hand brake, acceleration pedal, brake pedal etc.. The steering wheel is equipped with haptic feedback. Virtual scene-rendering is carried out on screens or monitors (up to 360° according to the configuration). The simulator uses INRETS SIM² software. Traffic simulation, 3D sound rendering and scenarios administrator are computed by INRETS ARCHISIM software. The vehicle model used comes from the CNRS CEPA research laboratory.

A driver placed on the steering wheel of this simulator can cover a virtual route by interacting with a simulated environment. Scenarios, described in text form, make it possible to place the driver in pre-defined and reproducible situations. Data which can be carried out during driving concern particularly the drivers’ actions, the movement of the virtual vehicle and the position of the other vehicles).

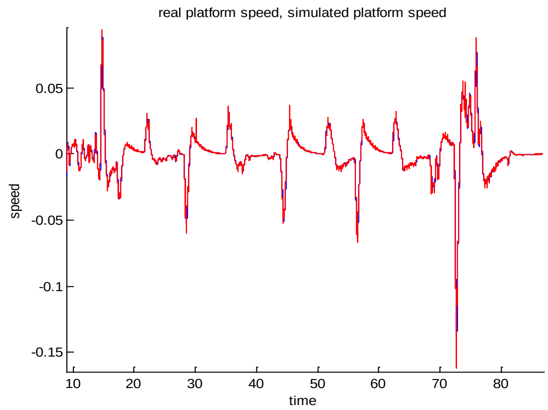
In order to carry out a first evaluation of the mobile platform’s performance in movement restitution, we had a subject drive the simulator.

The actuator intended for longitudinal movement restitution was powered by the above-described classic Washout algorithm. This algorithm was computed on a control PC which received the acceleration of the simulated vehicle. This is processed by a Washout algorithm in order to obtain a desired position signal. Thanks to a proportional derived corrector (PI) computed on the control machine at a frequency of 1.5kHz, the platform actuator is powered by its power unit in order to track the desired position.

Once again, in order to demonstrate the validity of the model, we stimulated the real platform as well as the simulated model with the same signal delivered by the Washout algorithm. The responses of the two systems to the stimulation signal coincident perfectly in



Figure(5)



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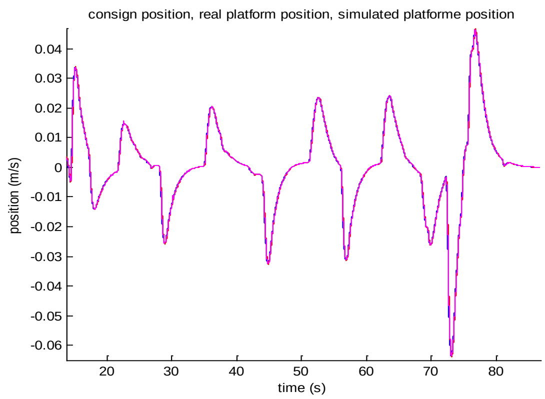

Figure(7)

position as well as in speed, figure (6,7).

The acceleration signal obtained during the subject’s driving contains acceleration phases, deceleration and continuous accelerations phases. Following the processing of this acceleration by the Washout algorithm, this acceleration is transformed into a desired position profile with a tendency to return to the neutral position during the continuous acceleration phase, figure (5,7). We noted in figure (7) that with a PI corrector, the platform position exactly superposed the desired position.

V. Conclusion:

In this article we have presented a mobile platform with two degrees of freedom designed for movement restitution on a driving simulator. This mobile platform was designed in order to be able to test longitudinal acceleration restitution strategies. The objective is to create an optimal strategy for following car driving situations.

After detailed dynamic model of the platform and the results of the individual tests carried out for the validation of this model, we have described the Washout algorithm we have developed.

This basic algorithm was used during an experiment which allowed us an initial verification of the mobile platform's performances.

Our future work will focus on the development of new control strategies for the platform which will aim to favour driver control over the virtual vehicle's acceleration. It will seek to allow the driver to feel the effects of acceleration modulations of the virtual vehicle according to the modulation of the efforts produced on the pedals.

References:

[1] A.Kheddar, Ph. Garrec, "Architectures de plates–formes mobiles pour simulateurs de conduite automobile", CRIIF – 2002.

[2] L. D. Reid, P. R. Grant, "Aerospace Engineering and Research Consultants Limited, November 1991.

[3] G. Reymond, A. Kemeny "Motion cueing in th Reneault Driving Simulator",Vehicle Systme Dynamics, 34 (2000), pp.249-259

[4] G. Reymond, A. Kemeny, J.Droulez, A.Berthoz, "Role of Lateral Acceleration in Curve Driving : Driver Model and Experiments on a Real Vehicle and a Driving Simulator", HUMAN FACTORS, Vol. 43 No. 3, pp. 483-495

[5] G. Reymond, A. Kemeny , J. Droulez, A. Berthoz,"Contribution of motion platform to kinesthetic restitution in a driving simulator. DSC2000, Paris, France, July 1999, pp 33-55.

[6] G.Reymond " contribution respective des stimuli visuels, vestibulaires et proprioceptifs dans la perception du mouvement du conducteur " paris VI *Univesity thsis (in french),* December 21, 2000.

[7] A.kemeny "Simulation et perception du mouvement" DSC 99 'driving simulation conference', Paris, France, Jully 1999, pp33-p55

[8] I. Seigler, A. Kemeny, "Etude sur la pertinence de la restitution physique du mouvement en simulation de conduite en fonction des caractéristiques physiologiques et psychophysiques de la perception du mouvement propre", Jully 2001.