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# Dynamic and Efficiency Study Applied to Automotive Vehicles

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**Abstract.** This paper addresses a simulation system based on an Electromechanical Stewart Platform (ESP) used to analyze a vehicle driving dynamic, allowing to emulate forces and accelerations that passengers or cargo are subject to. The ESP interacts with a driving simulation platform, where the drivers' action on wheel and pedals are used as input on the driving simulation software. The software is being built to provide the correspondent movement to the ESP, and visual feedback on the driver behavior. The inclusion of virtual reality into the system will enhance the physical effect felt by the user, resulting in a more realistic driving simulator when compared with the conventional ones. This system can be an efficient, flexible, agile, and sustainable solution to provide driver training, for professional drivers, providing initial training on the vehicle motion behavior, as well as for continuous training, by including information on energy use and emission outcomes.

**Keywords:** Stewart platform, virtual reality, driving simulators, comfort

## 1 Introduction

The existing driving simulators allow a visual perception of the road and driving conditions, however usually they do not provide feedback from the resulting longitudinal and lateral accelerations that occur in real vehicles. The inclusion of a 6 degrees-of-freedom simulation platform provides a realistic sensorial perception of the automotive vehicle dynamic behavior to the user.

The possibility to include this type of platform adds a layer on the perceptive dynamics of the vehicle on the driving simulator. This is of particular interest for heavy-duty vehicle drivers training. For bus drivers, riding comfort is of major importance since some of the passengers are standing and not seated. Therefore, the

vehicle dynamics applied in the six degrees-of-freedom (6 DOF) platform contributes to training on undesirable driving behaviors on the perspective of passenger comfort. Moreover, real-time driving consumption can be included in the simulator, allowing to evaluate real-time undesired driver behaviors, the vehicle movement, and its energy impact.

## **2 Relationship with Technological Innovation for Digitalization and Virtualization**

The proposed simulation system encompasses the interconnection between hardware and software developed to provide a realistic sensorial effect to the user. The hardware is defined by an ESP, with 6 DOF, which actuators are induction motors with mechanical movement conversion from rotation to linear displacement, driven by electronic power converters. The software allows the incorporation of vehicle dynamics, according with drivers' actions on wheels and pedals, used as software inputs. The realistic enhancement of the proposed simulator, when compared with conventional simulators, is attained by a conjunction between movements provided by drivers' actions on the ESP and a corresponding image that gives visual feedback on driver behavior, such as warnings on hard acceleration, deceleration, or excessive fuel usage, for example. Including virtual reality into this system contributes for increasing the simulator flexibility, making it more agile and efficient in classroom drivers training, namely for professional drivers. Even in a continuous training context, the proposed simulator contributes for drivers and system efficiency improvement, by including information and data of used energy, such as fuel, and the emissions. It is also important to underline that with this approach the driver can integrate the relations between his actions on the vehicle, that are traduced in vehicle dynamics and, in real-time, receive indicators on energy, emissions outcomes and, with the 6 DOF ESP, also feedback on comfort. This innovative approach allows to provide complete training under classroom.

## **3 Related Literature**

First simulators were developed to be applied in aerospace industry as flight simulators and have approximately 7 decades of existence. Automobile driving simulators first developments are dated from de early 1980's. Nowadays there are several driving simulators that can range from a simple structure and low-cost, to high-level structure based on expensive parallel manipulators, used for different applications, such as drivers' behavior analysis, vehicles technology study, safety study and drivers' training [1]. Some well-known simulators are high-level systems and result from intensive research and development work, such as NADS, TUTOR [2], Simulator III [3] and others [4], [5] developed by universities or research institutions.

Driving behavior studies includes the assessment of passengers' comfort, the road profile, and conditions [6], driving performance and economic driving techniques [7], improvement of driving safety and warning systems [8].

The energy and emission impacts associated to vehicle dynamics can be assessed using the Vehicle Specific Power (VSP) methodology [9]. This method is widely used for light and heavy-duty vehicles and allows to evaluate energy and environmental impacts of specific vehicles in specific routes, under any driving condition, based on a combination of speed, acceleration, and road grade [10] which can be obtained from a driving simulator.

It has been shown that driver training can contribute to improve eco-driving, by reducing fuel consumption, or non-comfort events, such as hard decelerations, whether by providing real-time feedback or just by classroom eco-driving sessions [11]. However, other studies underline that without real-time feedback, drivers tend to increase the percentage of time in undesirable events [12], [13]. Moreover, acceleration with strong power demand, stop, acceleration with moderate power demand, mostly contribute to energy efficiency and emission outcomes [14]. Also, passenger comfort uses some of these metrics, namely hard acceleration, hard start, hard deceleration, and hard stop [13].

All the parameters required to provide real-time feedback to the driver can be obtained from the simulator and used to build energy, emission, and comfort indicators, as well as providing the vehicle movement using the 6 DOF platform.

The proposed simulator is high-level, portable and less expensive when compared with other existent high-level simulators, offering a dynamic response in line with the drivers' sensorial perceptions and allowing to develop studies on driving efficiency. In addition, the proposed system shows promising results in what concerns to the interface between human and virtual environment, achieved by the synchronization between the platform and the human sensorial effects.

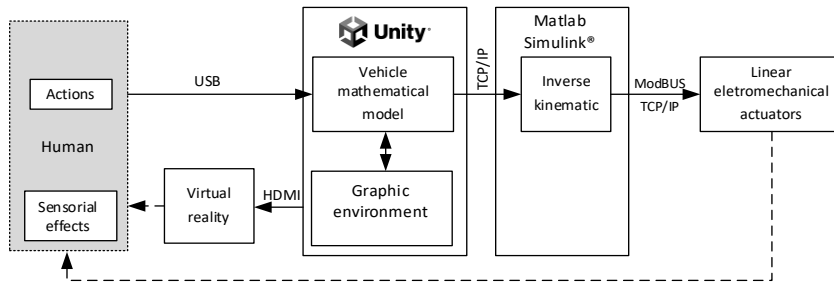
#### 4 System Characterization

To virtualize a vehicle as a driver or passenger, the entire system must be able to transmit sensations identical to a real-world situation. The entire system considers the visual, auditory, tactile and motion perception to offer a complete experience to the user for easy identify discomfort or danger scenarios. Fig. 1 presents an automotive vehicle virtualization scheme.

The system is composed by hardware and software with computational processing in real time using different communication protocols between all the interface components, increasing the complexity of the simulator control, making it essential to reach a synchronization between the visual perception and the movement of the platform according to the vehicle models.

In Fig. 1 Real-time feedback on comfort indicators can be provided using literature data, obtained from real-world bus operation, such as hard acceleration, hard start, hard deceleration, and hard stop [13]. All these indicators can be built based on data provided from the simulator, such as longitudinal speed and acceleration. The system

inputs result from human actions provided by the driver, which receives sensorial effects from the system. This type of indicators based on longitudinal variables is easier for the driver to understand. However, work will be carried to include lateral acceleration indicators, which can also be obtained from the simulation tool, combined with the vehicle mathematical model.



**Fig. 1.** Automotive vehicle virtualization scheme.

In the literature there are multiple ways to implement graphical environments [15]. For the implementation proposed in this study, software *Unity* was used. *Unity* is a cross-platform graphical game engine development software that supports different programming languages and multiple 3D object formats [15]. Herein, the usage of *Unity* in combination with software *Blender* for object drawing allows to produce the graphical environment. An example of the implemented graphic environment is present in Fig. 2.



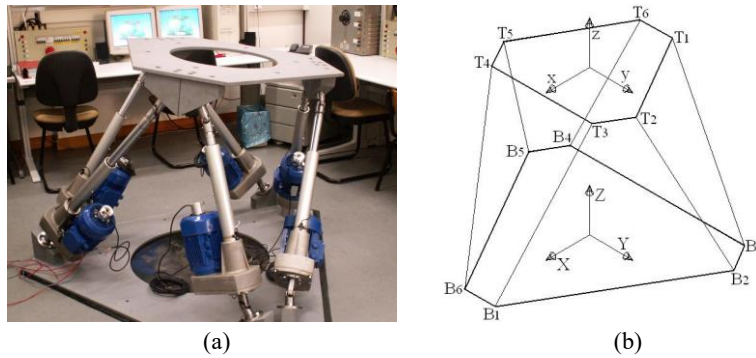
**Fig. 2.** Graphical environment of drivers' view.

The vehicle dynamics is implemented using the models incorporated in the objects from *Unity*, and the *C#* code controls the torque applied to the wheel components. The *Unity* engine will compute all data and calculate the next position of the automotive, updating all the graphics.

The ESP consists of a parallel manipulator with 6 legs, each one formed by 2 joints connecting the base to the main element as shown in Fig. 3(a). A universal joint is mounted between the final element and the prismatic joint. From there, another universal joint is connected to the base. This configuration allows rotation movements such as roll, pitch and yaw and translation movements such as heave, surge, and sway. The heave defines the elevation movement allowing emulate vertical accelerations due irregularities in the road. The surge movement defines the forward and the backward translation in longitudinal axis to emulate the starting and the

braking accelerations. The sway defines the lateral translation movement and emulate the accelerations to the left and right. Fig. 3(a) depicts the ESP used in this work and Fig. 3(b) is a representation used to obtain the spatial coordinates.

The roll is the rotational movement along the longitudinal axis and emulates the oscillations due to the vehicle's suspensions. The pitch emulates the orography of the road, and the yaw emulates the direction of the road.



**Fig. 3.** ESP; (a) laboratorial implementation; (b) schematical representation.

Driver sends inputs to the system, such as, steering wheel angle, acceleration, and gear position. The vehicle mathematical model calculates the position of the vehicle in the graphical environment, and *Matlab*<sup>®</sup> provides to the ESP the translational movement ( $p_x$ ,  $p_y$  and  $p_z$ ) and rotational movement ( $\alpha$ ,  $\beta$  and  $\gamma$ ). Equation (1) calculates the inverse kinematics and (2) the coordinates of the joints. Following Fig. 3(b) is possible to obtain the length of each actuator ( $L_1$ ,  $L_2$ ,  $L_3$ ,  $L_4$ ,  $L_5$  and  $L_6$ ) using equation (3). The displacement of the ESP legs is carried out by linear actuators with asynchronous motors and correspondent drivers with position control.

The combination of the 6 DOF movement with a head mounted display (HMD) gives a full immersive environment to the user. *Unity* software was carefully chosen to allow an easily integration of the HMD device, and at the same time, control the hardware in the loop (ESP) by providing data to *Matlab Simulink*<sup>®</sup>, however others open-source software can be used, such as *Octave* or *Python*. Moreover, it is possible with this software and the HMD device to track the position of the user's hands and virtualize it in the virtual steering wheel giving a more realistic environment to the user.

$$T_{BASE}^{TOP} = \begin{bmatrix} \cos \beta \cos \gamma + \sin \alpha \sin \beta \sin \gamma & -\cos \beta \sin \gamma + \sin \alpha \sin \beta \cos \gamma & \cos \alpha \sin \beta & p_x \\ \cos \alpha \sin \gamma & \cos \alpha \cos \gamma & -\sin \alpha & p_y \\ -\sin \beta \cos \gamma + \sin \alpha \sin \beta \sin \gamma & \sin \beta \sin \gamma + \sin \alpha \cos \beta \cos \gamma & \cos \alpha \cos \beta & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} X_{Ti} \\ Y_{Ti} \\ Z_{Ti} \\ 1 \end{bmatrix} = T_{BASE}^{TOP}(p_x, p_y, p_z, \alpha, \beta, \gamma) \begin{bmatrix} x_{Ti} \\ y_{Ti} \\ z_{Ti} \\ 1 \end{bmatrix} \quad (2)$$

$$\begin{aligned} L_1 &= \sqrt{(X_{T3} - X_{B1})^2 + (Y_{T3} - Y_{B1})^2 + (Z_{T3} - Z_{B1})^2} \\ L_2 &= \sqrt{(X_{T2} - X_{B2})^2 + (Y_{T2} - Y_{B2})^2 + (Z_{T2} - Z_{B2})^2} \\ L_3 &= \sqrt{(X_{T1} - X_{B3})^2 + (Y_{T1} - Y_{B3})^2 + (Z_{T1} - Z_{B3})^2} \\ L_4 &= \sqrt{(X_{T6} - X_{B4})^2 + (Y_{T6} - Y_{B4})^2 + (Z_{T6} - Z_{B4})^2} \\ L_5 &= \sqrt{(X_{T5} - X_{B5})^2 + (Y_{T5} - Y_{B5})^2 + (Z_{T5} - Z_{B5})^2} \\ L_6 &= \sqrt{(X_{T4} - X_{B6})^2 + (Y_{T4} - Y_{B6})^2 + (Z_{T4} - Z_{B6})^2} \end{aligned} \quad (3)$$

It is very important that the ESP platform is precisely synchronized with the HMD. As the human body is expecting some accelerations associated to the visual events, the lack of synchronism can provoke some dizziness or motion sickness. To allow that, a bidirectional communication with sampling rate of 60 Hz between *Matlab Simulink*<sup>®</sup> and *Unity* is implemented, being the position of the vehicle in the graphical environment controlled by the pedals and steering wheel controller considering the feedback from the ESP.

## 5 Preliminary Experimental Results

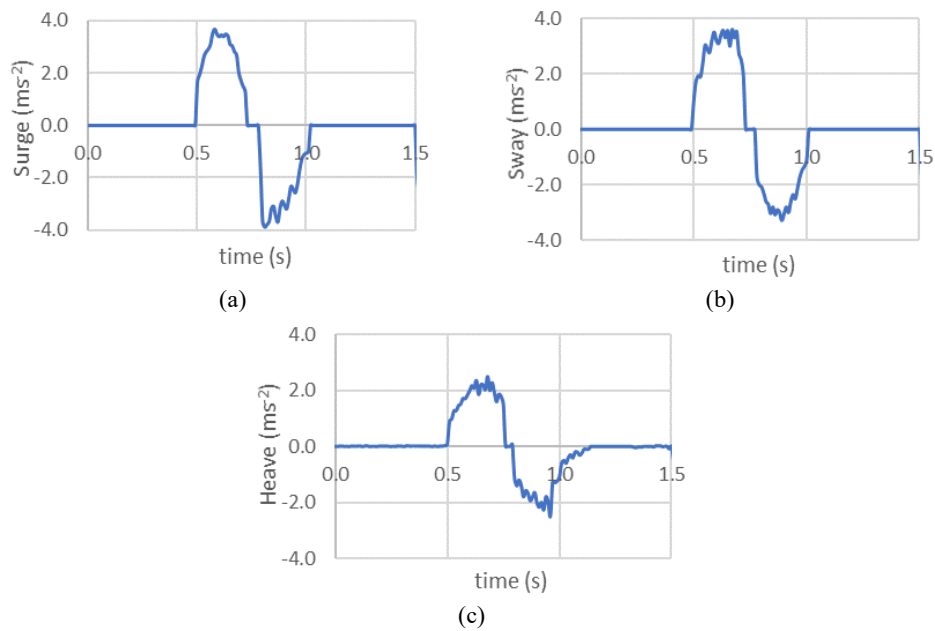
To evaluate the response of the platform and verify the comfort of the driver or passengers, an inertial sensor was installed to check the feedback of the movements according to the mathematical model of the vehicle and the characteristics of the simulated route. With the measurement of lateral (sway), longitudinal (surge) and vertical (heave) acceleration, it is possible to evaluate the perception of the user and to study the limits of comfort, by synchronizing ESP movements and the graphical environment. Being this a preliminary study, only some system responses are here detailed. As an example, in Fig. 4 is depicted the response of the ESP to a surge, sway and heave movement for a positive step of 0.2 meters in relation to the reference stand position.

The limitations of the ESP are determined by measuring the movements and analysing the data, allowing to validate which vehicle models can be used in the simulator for the comfort study. The measurement limits of ESP movement are presented in Table 1. Comparing these results with the limits presents in [13] it can be concluded that the ESP is able to simulate some vehicles such as a bus.



**Table 1.** Measurement limits of ESP movements.

Movement	Limits	Acceleration
Surge	$\pm 0.26$ m	$3.6$ m/s <sup>2</sup>
Sway	$\pm 0.22$ m	$3.5$ m/s <sup>2</sup>
Heave	$\pm 0.30$ m	$2.3$ m/s <sup>2</sup>

**Fig. 4.** Maximum acceleration experimental results: (a) surge; (b) sway; (c) heave.

## 6 Conclusions and Future Work

The proposed simulation system based on the ESP can emulate the dynamics of a passenger bus. Also, it allows to include the visual environment enhancing driver perceptions and analyze passengers comfort experiences accordingly with the road conditions and driver actions.

The experimental setup described provides a useful research tool to study driving comfort in laboratory environment with the ability to measure comfort parameters in real time in different road courses.

Combining the ESP and the graphical environment with head mounted display allows for immersive classroom driver training, also providing feedback on energy, emissions, and comfort indicators.

Future work will focus on the development and refinement of virtual reality graphical scenarios including a variety of daily living events, tune and develop

strategies for synchronization between movements and the graphic environment and study and comparing driving efficiency simulator with real driving situations.

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