# Predictive Actuation of a Driving Simulator

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**Abstract.** Testing of virtual cars in multi-modal virtual environment is an important step in the validation process of new concepts and technologies. A driving simulator with realistic interaction, operating environment and feedback eliminates the difficulties of road test, but allows the understanding of driving behavior, testing driver assistant systems and for traffic research. A static driving simulator is lacking the required displacement and acceleration feedback, but a hexapod motion system can reproduce some of these. The objective of this paper is to present a predictive actuation algorithm for controlling the position of a driving simulator in order to maximize the sensation of displacement and acceleration of the driver. Several driving scenarios are considered and for each an ideal starting point of the motion platform is computed. In case the driver is in the process of approaching a road segment from one the analyzed scenarios, the predictive actuation module will try to move the driver of the simulation platform from the current position towards the ideal position within the perceptibility thresholds.

**Keywords:** Driving simulator · Prediction of sensation · Stewart platform

## 1 State of the Art – Driving Simulators

Driving simulators have a wide range of applications, from entertainment to advanced trainings, or research regarding driver behavior, human-machine interface, effect of tiredness and drugs [1], vehicle design [2]. A very good driving simulators list in chronological order can be found in [1], where can be seen the improvements along the years in this domain.

The performance of a driving simulator is defined by the Motion Cueing Algorithm (MCA) [3], which is a system of filters that takes into account the limits of the simulator as well as the threshold of driver's motion perception to reproduce simulated vehicle acceleration [4]. The most common approaches are the following: classical washout, adaptive washout, optimal control and Model Predictive Control [5]. The classical washout has short processing time, fast computation, stability and it is based on empirically determined high and low pass filters. The drawback of this approach is that does not take into account the vestibular system [6]. To overcome the disadvantages that this method presents, adaptive washout (a classical filter with variable gain) and optimal washout (based on optimal control theory) are used [2]. As mentioned previously,


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another technique is Model Predictive Control (MPC) which uses a process model and a future reference trajectory to improve the control signal [7].

Stewart platform has certain physical limitations, thus cueing algorithms are used to yield the same sensation rather than to duplicate the motion [8]. In this sense, it is considered the pre-positioning in motion cueing. Since the main motions in a car are acceleration, braking and/or turning, the main focus is on surge, sway and yaw direction [9]. One example of this pre-positioning was developed by PSA-Peugeot-Citroen in SHERPA simulator. This pre-positioning is based on vehicle speed for longitudinal movements and road database information for the lateral movements. Depending on these two information, at each time step is computed an estimated needed linear stroke (for the following curve) and together with the estimated time-to-next-curve, the pre-positioning signal is generated [10]. Another example of pre-positioning is described by Cornelius Weiss in [11], where he developed a hybrid system that switches between several subsystems which are connected through a certain rule. Relying on states and variables, the switching rules can be time-driven, event-driven or path dependent. A later study presented in [9] uses two algorithms; for longitudinal and lateral pre-positioning. The algorithm that gives the longitudinal pre-positioning is based on the idea that a possible maximum and minimum acceleration of the vehicle is calculated, at any given velocity of the vehicle. The lateral pre-positioning is given by an algorithm which has as input the current longitudinal velocity and the curvature at a given time in front of the vehicle.

Linear and rotational accelerations, as well as the orientation of the head are perceived by the vestibular system in the inner ear. The perceptibility thresholds value are 0.3 deg/$s^2$ for angular acceleration, 3–5 deg/s for angular velocity and 0.1 m/$s^2$ for translational acceleration [12].

## 2 The Simulator Motion Platform

The driving simulator is composed by a hexapod motion system (Stewart platform), actuated by six synchronous motors with permanent magnets, the driver's seat, steering wheel, pedals, and a big-screen display.

The Stewart platform can impose on the driver's seat displacements in three direction (surge, sway and heave) and three rotations (roll, pitch and yaw) along a fixed reference frame and has the following limitation regarding displacement (space covered), maximum velocity and acceleration:

- Surge: −0.38 … +0.38 m, 0.5 m/s, 0.6 g,
- Sway: −0.38 … +0.38 m, 0.5 m/s, 0.6 g,
- Heave: 0 … −0.45 m, 0.3 m/s, 0.6 g,
- Roll: −0.5 … +0.5 rad, 30 deg/s, 500 deg/$s^2$,
- Pitch: −0.5 … +0.57 rad, 30 deg/s, 500 deg/$s^2$,
- Yaw: −0.5 … +0.5 rad, 40 deg/s, 400 deg/$s^2$.

The components of the driving simulator are presented in Fig. 1. The driver's actions together with the road curvature and profile are controlling the dynamic simulation module. In the simulation, the driver's seat accelerations are measured in a fixed reference frame. These are transformed with the MCA into the displacement and rotation commands of the hexapod motion platform.

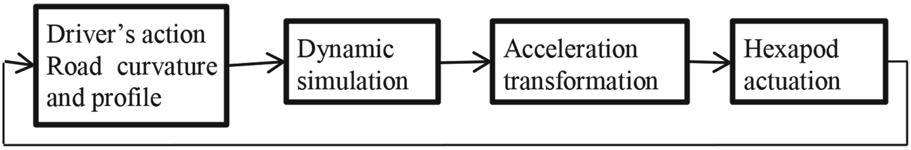


**Fig. 1.** The components of the driving simulator.

In order to reproduce as close as possible the motion of the simulated vehicle to a real vehicle, different kinds of MCA can be used. In our approach (presented in Sect. 4) the road is decomposed into segment (see Sect. 3) and for each characteristic segment the desired displacement and rotation of the motion platform is obtained.

Intuitively, for acceleration, the motion platform would move the driver from neutral point forward in order to get the sensation of the seat pushing against his back. The same situation but opposite in sign is for deceleration, and for turning, the platform moves the seat in such a way the driver will feel the lateral push due to his inertia.

In order to confine in the limitation regarding displacement of the motion platform, each of the driving scenarios along the considered segment will have an ideal starting point of the platform. In case the road on which the car is moving can be anticipated and the driving scenario can be included into one of the considered type, then the ideal point of the motion platform is also known. The predictive actuation module is trying to move the driver of the simulation platform from the current position towards the ideal position within the perceptibility thresholds of the linear and rotational accelerations and velocities. This predictive module is moving the driver when the car is on straight road and no sudden change in acceleration is present.

## 3 Driving Scenarios and Ideal Starting Positions of the Platform

Either called traffic scenarios [13], tasks [14], maneuvers [15], or simply scenarios, all papers mentioned above take into consideration general road conditions, like straight road, curve, lane change, bumper [16], or critical, dangerous situations that a driver might feel while driving [13].

In this paper, the multi-body model of the car has input parameters as dimension, number of passengers, acceleration/deceleration, steering wheel angle etc. set in LMS Driving Dynamics, which uses LMS Virtual.Lab for computation and visualization of results. The full scenario is composed by driving the virtual car along a curved road with obstacles. It is divided into several smaller segments, each representing one acceleration/deceleration/turning/constant velocity. For each of these segments are measured and recorded the angular velocities and linear accelerations of the driver's seat (further integrated to obtain displacement and tilt angles of driving simulator).

Segments include:

- 4 accelerations: low acceleration—1.2 m/s$^2$, low-medium acceleration—1.736 m/s$^2$, medium acceleration—2 m/s$^2$ and high acceleration—2.77 m/s$^2$;
- 4 decelerations: 100 to 50, 50 to 25, 100 to 0 and 50 to 0 km/h—with a rate of 0.4 g;
- 2 constant velocities: at 25 and 50 km/h;
- 6 turnings: big, medium, small turning radii both to the left and to the right with different velocities.

Figures 2 and 3 are presenting the linear accelerations and the roll/pitch angles during a right turning maneuver of 120° executed in 4 s at the speed of 25 km/h.

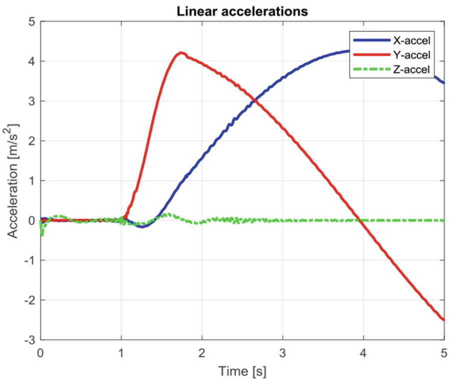


**Fig. 2.** Linear acceleration during small turning radius.

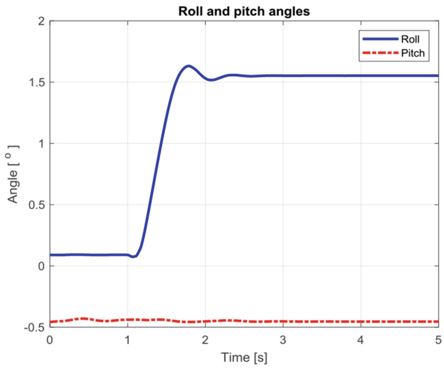


**Fig. 3.** Roll and pitch angles during small turning radius.

The measured accelerations and velocities are to be reproduced by the driving simulator. They are filtered and converted by integration through the MCA into position command of the moving platform.

The MCA has the following phases:

- Scaling the acceleration with *tanh* function ($a = a_{max} \tanh(a_{in}/a_{max})$) [17].
- Filtering with first order low pass and high pass filter separately for the linear accelerations and angular velocities, and computing the required tilt angles and linear displacements of platform:
  - The high frequency components of the linear accelerations are integrating twice to compute de displacement in x, y and z directions.
  - Low-frequency components of the longitudinal and transversal acceleration, which would drive the platform out of its workspace, are reproduced by the gravitational force, tilting the platform.
  - Roll and pitch angular velocities are integrated and combined with the tilting angles.

The segment of the small turning radius will lead to displacement and rotation of the moving platform presented in Figs. 4 and 5 (the yaw angle is the turning angle form 0° to 120°).

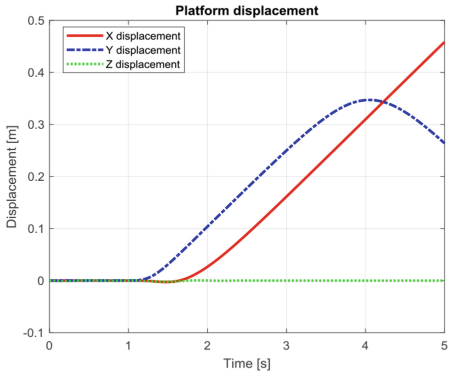


Fig. 4. The imposed displacement of the platform.

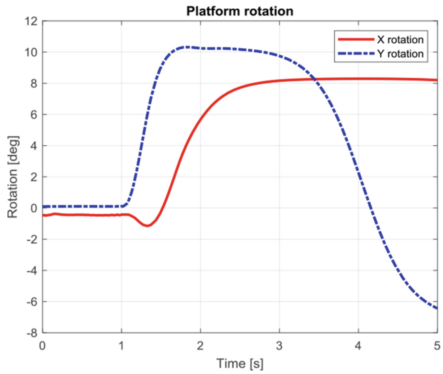


Fig. 5. Roll and pitch angles of the platform.

Due to the limitation of the space covered by the Stewart displacement and the accelerations which can be achieved with the electric motors, the required values cannot be reproduced faithfully. Therefore, ideally is to consider the last point reached by the platform and the future point, where it will be after negotiating the next maneuver. This may be done by using a predictive actuation module (see next Section), in such a way the scenario is previously known, so due to the segment which is going to occur, the platform will be automatically moved to the opposite side (longitudinal and transversal direction) where normally it would reach after the negotiation of the scenario segment.

## 4 The Predictive Actuation Module

The motion platform has limitation achieving the maximum values of the acceleration for the roll, pitch, yaw, heave, surge, sway motion in certain position of the covered space. The developed algorithm is maximizing the efficiency of the driving simulator and will command the platform to assure driving experiences as close as possible to real ones.

The reproduced linear acceleration has two components obtained by tilting and moving the platform. Constant longitudinal and lateral accelerations can be felt by tilting the platform with pitch and roll angles and using the gravity. This is the low frequency component. A constant speed (no acceleration and vibration) can be simulated by visual stimulation.

Each of the considered segments has an ideal starting position. The amplitudes of the displacements in longitudinal and transversal direction are known from the individual simulation of the maneuvers, and ideally the area covered by the displacement should be symmetrical from the neutral position in the middle of the working space of the Stewart platform.

The predictive actuation of the simulator has two components:

- Computing the ideal position for forthcoming event;

- Introducing the washout components to reach the ideal position whenever the vehicle is travelling in straight line and no sudden modification in acceleration is present (accelerating or braking). The washout component is slowly returning the driving simulator to the ideal position, with the speed below the perceptibility thresholds of the user.

## 5 Testing and Validation

For typical passenger cars and maneuvers, the limits of the accelerations are [18] between −6 m/s$^2$ and 4 m/s$^2$ during acceleration and braking, and lateral acceleration of −7 m/s$^2$ and 7 m/s$^2$ for cornering. Depending on the road surface, the vertical acceleration is between −8 m/s$^2$ and 11 m/s$^2$. The dominant frequency range is 0–0.1 Hz for longitudinal, 0–1 Hz for lateral and 0–2 Hz for vertical motion. For roll and pitch motion, the acceleration is smaller than 360 deg/s$^2$ and the dominant frequency is over 3 Hz.

The full driving scenario is composed by the following segments:

1. Low-medium acceleration: 1.736 m/s$^2$ (0.177 g) for 8 s (up to 50 km/h).
2. Constant velocity: 50 km/h for 6.5 s.
3. Large turning to the right: 70° steering angle for 5 s at 50 km/h.
4. Constant velocity: 50 km/h for 5 s.
5. Deceleration: 50–25 km/h, 3.92 m/s$^2$ (0.4 g) for 1.76 s.
6. Tight turning to the right: 210° steering angle for 5 s at 25 km/h.
7. Constant velocity: 25 km/h for 7 s.

The measured accelerations of the driver during the full scenario are presented in Fig. 6. After applying the MCA, the resulted tilt angles and displacement of the moving platform are shown in Figs. 7 and 8.

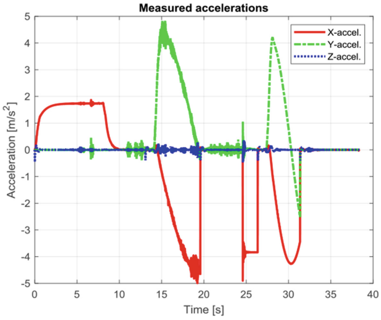


**Fig. 6.** Measured accelerations of the passenger in the simulation.

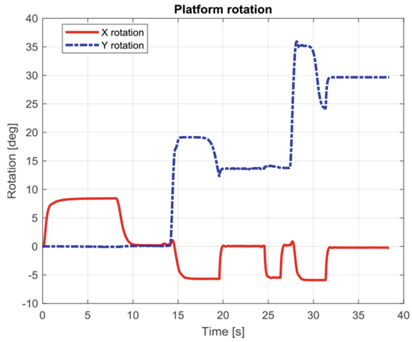


**Fig. 7.** Roll and pitch angles of the platform.

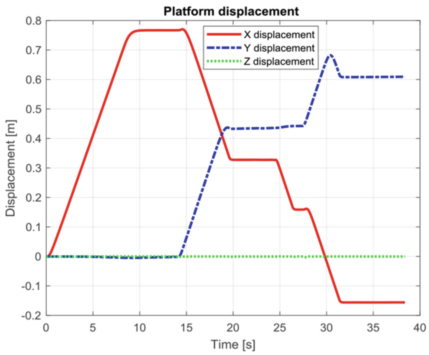


**Fig. 8.** The displacement of the platform without the washout.

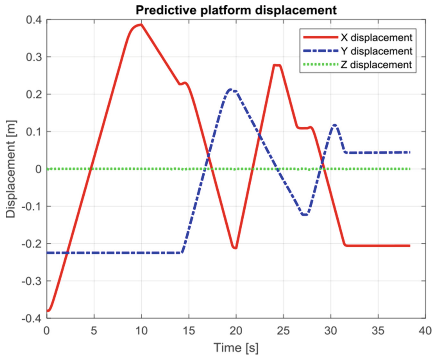


**Fig. 9.** The displacement of the platform with the predictive algorithm.

The predicative algorithm can be applied in this driving scenario, because the car is travelling two times with constant velocities. Also, the predictive algorithm will start the simulation not from the neural position, but from the ideal one. The obtained displacements are presented in Fig. 9.

The predictive actuation has shown better results than using classical washout [4, 6, 11, 15] in terms of improvement of the maneuver segments limit, due to the longer range of movement of the driver's seat. While typical washout pulled back the driver's seat to the neutral position, the predictive algorithm moves the seat further than the neutral point in order to maximize the driver's sensation.

A limitation of the proposed study would be the case when we have several accelerations and decelerations with short time interval between them, thus the platform would not have enough time to move the driver slowly in the desired positions to maximize the driving sensations.

## 6 Conclusions

The presented algorithm can be employed for reproducing sensations of driving vehicles on known and unknown roads, when the vehicle movement can be computed in real-time or recorded data is used as input. A six degree of freedom Stewart motion platform is moving the driver's seat, and the proposed algorithm is commanding the movement in such way that the driving experiment will be as faithful as possible. For typical maneuvers like accelerating, braking, turning with various radii the ideal position of moving platform was computed. In driving scenarios where the car's accelerations can be anticipated with the analyzed maneuvers (the close environment is discovered), the predictive algorithm is pulling back the driver's seat in the ideal position when the vehicle is travelling in straight line and no sudden modification in acceleration is present. This washout component of the motion cueing algorithm has speed below the perceptibility thresholds of the user.

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