Control Design for a Motion Cueing on Driving Simulator

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Abstract. A Linear Quadratic Regulator (LQR) has been designed to simulate the pitch and roll vehicle dynamics of a platform which is connected to the real time simulation environment of Dynacar. The motion cueing algorithm translates the movement of the simulated vehicle to the platform using three rotary actuators, by satisfying all actuation boundaries. Experimental results illustrate that the LQR motion cueing algorithm performs satisfactory the tracking control at low frequencies, close to the resonance frequencies of the pitch and roll motion.

1. Introduction
In general, a driving simulator can be designed for different applications: entertainment, research and advanced training. To achieve a real assessment, the simulators deliver motion cues to the driver; whose fidelity depends on the degrees of freedom of the platform. These kind of systems are called also motion cueing systems and their main objective is joint the physical motion of the simulated vehicle with the real-time image generation system, i.e. the motion cueing system allows the drivers the perception and control of the vehicle motion, [1], such that the driver feels being inside the vehicle.

Recently, the interest of designing and control the motion cueings has been increased for automotive engineers, particularly in the research field to test Advanced Driver Assistance Systems (ADAS), In-Vehicle Information Systems (IVIS), and the effects of noise and vibrations on driver performance, [2]. The key parts of a motion cueing system are the driving simulator and the tracking control algorithm.

The realism of simulation depends strongly on the fidelity of the motion platform and the perception of motion by the human driver, [3]. In [4] is validated that the human vestibular system located in head is dominant in the human motion sensation for rotational and linear movements. The physical validation of a motion cueing is usually at small displacements [1] and useful to estimate frequencies of resonance of roll, pitch or heave [5]. Typically, the driving simulator consists of a seat, a vehicle dynamics model interacting with a driver through a steering wheel and pedals with haptic feedback, a sound feedback, a set of screens with a visual engine reproducing the vehicle dynamics results of the driver manoeuvre in the simulation, and, in some cases, translational and rotational actuators for the motion cueing system.

The motion cueing algorithms are mainly classified by the fidelity of the simulation level and its application. At a low-level simulator, the driver sits in a car seat, which is fixed to the ground. The driver looks to a screen, which is fixed too. The screen is designed such that the view angle is as large possible. The driver operates a set of driving actuators such as
the accelerator, braking system and the wheel steering system in order to receive visual cues corresponding to the actual driving situation. In some types of applications, it is desirable to provide a motion and haptic restitution to improve the simulation fidelity. Therefore, the driving simulators use a moving platform to restitute in a limited and constrained workspace, sufficient motion cues similar as much as possible to the real motion feeling in a vehicle [1][6][7][8]. Low level simulators can include the longitudinal axis motion in only one axis while the mid and high level simulators include more motion axis [9]. Table 1 presents the main features of different level driving simulators.

Table 1. Driving simulators complexity with Entertainment (E), Training (T), and Research (R) applications.

| Level  | Components                              | Feedback                     | Degrees of freedom | Applications |
|--------|-----------------------------------------|------------------------------|-------------------|--------------|
| Low    | Large screens, steering wheel, pedals, one linear actuator | Force, Sound, Longitudinal motion | 0, 1 (x, y, or z axis) | E, T         |
| Mid    | plus at least one linear actuator        | Force, Sound, Longitudinal and rotational motions | 2 or 3      | E, T, R     |
| High   | plus at least four more linear actuators | Same as mid                  | 6                 | T, R         |

A three Degrees of Freedom (3 DoF) system is designed to mimic the main vehicle rotational dynamics such as the roll and pitch motions. This system causes a sensation of acceleration through rotation around the longitudinal, lateral an vertical axis, by keeping a tilt angle (typically 45 degrees) and considering the gravity. The tilt limitation in this system prevents a sensation of acceleration over 0.707 g’s [9]. This paper is focused in developing a tracking controller for a 3 DoF driving simulator.

The control algorithm for motion cueing systems is called washout filtering with classical, optimal and predictive approaches [1][4], proportional-integral-derivative washout filtering [6], and optimal and model predictive control [7][8][5] among others. The classical washout filtering is the most common because of the simplicity of implementation and fair simulation results [9], but limited to the design of specific high-pass and low-pass filters whose parameters are usually empirically obtained. On the other hand, the design of an optimal cueing algorithm such as an LQR approach ensures the tracking control in a operating zone of the actuators.

In this paper, an LQR cueing algorithm is proposed to control the driving simulator of three degrees of freedom specially the tracking to the roll and pitch vehicle dynamics. The goal of this simulator is to validate ADAS including the biometrics systems and autonomous vehicle assessment as well as the transportation of finish goods. The proposed controller is described in section 2. Section 3 describes the Vehicle Dynamics Simulator (VDS) and the hardware platform. The results and discussion are shown in Section 4. Conclusion ends this paper in Section 5. Table 2 describes the used variables.
where the vertical suspension force at each corner ($F_{s_i}$) are obtained from the tire lateral and longitudinal forces ($F_{l_i}$ and $F_{t_i}$). The vehicle dynamics that reproduces the vertical, longitudinal, lateral, and rotational dynamics of the chassis and wheels in the virtual simulation is given by [10]:

\[ \begin{aligned}
\dot{x} &= \frac{m}{m} \ddot{x} + \frac{r}{m} \dddot{x} \\
\dot{y} &= \frac{m}{m} \ddot{y} + \frac{r}{m} \dddot{y} \\
\dot{z} &= \frac{m}{m} \ddot{z} + \frac{r}{m} \dddot{z} \\
\theta &= \text{degrees Roll angle} \\
\phi &= \text{degrees Pitch angle} \\
\psi &= \text{degrees Yaw angle} \\
u &= V \text{ Command for } \theta_d \text{ and } \phi_d \\
M_{1,2,3} &= \text{Electric motor 1, 2 and 3}
\end{aligned} \]

### Table 2. Variables.

| Variable | Units | Description |
|----------|-------|-------------|
| $\ddot{x}$ | $\text{m}$ | Longitudinal acceleration |
| $\ddot{y}$ | $\text{m}$ | Lateral acceleration |
| $\ddot{z}$ | $\text{m}$ | Vertical acceleration |
| $\theta$ | degrees | Roll angle |
| $\phi$ | degrees | Pitch angle |
| $\psi$ | degrees | Yaw angle |
| $u$ | $V$ | Command for $\theta_d$ and $\phi_d$ |
| $M_{1,2,3}$ | - | Electric motor 1, 2 and 3 |

### 2. LQR-based Motion Cueing

The washout filter design strategy based on the LQR structure is presented in this section. The objective of the optimal washout filter is to obtain a linear transfer matrix $W$ that minimizes a quadratic cost function involving the tracking error and the driving simulator output (actuator manipulations) by considering the physical constraints of the platform.

The proposed controlled output for tracking is given by:

\[ y = [\ddot{x} \; \ddot{y} \; \ddot{z} \; \theta \; \phi]^T \]  

(1)

where all variables are measured from the simulator platform. Such that the control tracking error is given by:

\[ e = y_m - y \]

(2)

where $y_m$ is a vector that contains the simulated vehicle variables corresponding to the measured ones. The vehicle dynamics that reproduces the vertical, longitudinal, lateral, and rotational dynamics of the chassis and wheels in the virtual simulation is given by [10]:

\[ \begin{aligned}
m\ddot{x} &= (F_{tx} + F_{tz}) \cos(\delta) + F_{tx} + F_{tz} - (F_{ty} + F_{t_y}) \sin(\delta) + m\ddot{y} \\
m\ddot{y} &= (F_{ty} + F_{t_y}) \cos(\delta) + F_{ty} + F_{t_y} + (F_{tx} + F_{tz}) \sin(\delta) + m\ddot{x} \\
m\ddot{z} &= -(F_{s_1} + F_{s_2} + F_{s_3} + F_{s_4}) \\
m_{us_i} \ddot{u}_{us_i} &= F_{s_i} - F_{t_{zi}} \\
I_x \ddot{\theta}_s &= (F_{s_1} - F_{s_2}) t_f + (F_{s_2} - F_{s_3}) t_r + m h \ddot{y} + (I_{yy} - I_{zz}) \ddot{\psi} \\
I_y \ddot{\phi}_{s} &= (F_{s_1} + F_{s_2}) t_f - (F_{s_2} + F_{s_3}) t_r + m h \ddot{x} + (I_{zz} - I_{xx}) \ddot{\psi} \\
I_z \ddot{\psi}_{s} &= (F_{s_1} + F_{s_2}) t_f \cos(\delta) - (F_{s_2} + F_{s_3}) t_r + (F_{t_{x_i}} + F_{t_{z_i}}) t_f \sin(\delta) + (I_{xx} - I_{yy}) \ddot{\psi} \\
\end{aligned} \]

(3)

where the vertical suspension force at each corner ($F_{s_i}$, with $i = 1, \ldots, 4$) is composed by the spring (stiffness $k_{s_i}$) and damper (coefficient $c_{s_i}$), as:

\[ F_{s_i} = k_{s_i} (z_{s_i} - z_{us_i}) + c_{s_i} (\dot{z}_{s_i} - \dot{z}_{us_i}) \]

(4)

the tire lateral and longitudinal forces ($F_{l_i}$ and $F_{t_i}$), that depends on the throttle and brake, are obtained from the Pacejka formula; while the tire vertical force, with stiffness $k_{t_i}$, is given by:

\[ F_{t_i} = k_{t_i} (z_{us_i} - z_{r_i}) \]

(5)
The sprung mass positions and velocities at each corner are given by:

\[
\begin{align*}
  z_{s1} &= z_s + l_f \sin(\phi) - t_f \sin(\theta) \\
  z_{s3} &= z_s - l_r \sin(\phi) - t_r \sin(\theta)
\end{align*}
\]

\[
\begin{align*}
  \dot{z}_{s1} &= \dot{z}_s + \dot{\phi} l_f \cos(\phi) - \dot{\theta} t_f \cos(\theta) \\
  \dot{z}_{s3} &= \dot{z}_s - \dot{\phi} l_r \cos(\phi) - \dot{\theta} t_r \cos(\theta)
\end{align*}
\]

(6)

All vehicle parameters, including the vehicle mass \(m\), the chassis and unsprung masses \(m_s, m_{us}\), the inertial moments \((I_{xx}, I_{yy}, I_{zz})\) and physical measures \((l_f, l_r, t_r, t_f, h)\) are considered from a generic vehicle model in Dynacar.

In order to ensure the driving simulator constraints and the minimization of the tracking error between the simulated vehicle and the experimental platform, the problem of designing an optimal washout filter is given by:

\[
J = \int_{t_1}^{t_2} (e^T Q e + u^T R u) \, dt
\]

(8)

where \(u\) is the controller output that manipulates the three electric motors, \([t_1, t_2]\) is the residence time horizon of the driving simulator, while \(Q\) and \(R\) are the weighting matrices given by the solution by a Ricatti equation, which gives \(W\) corresponding to the optimal washout filter. The proposed LQR-based motion cueing is schematized in Fig 1.

![Figure 1. Diagram block of the LQR-based motion cueing](image)

3. Vehicle Dynamics Simulator

The VDS consists of a real time vehicle dynamics model system interacting with a driver through a steering system, acceleration system, braking system, as well as a set of three flat screens and a set of speakers. The real time vehicle dynamics model simulation system consists of the Dynacar system, \([11]\), which is a low level driving simulator, and a three DoF platform, Fig. 2.

Figure 3 illustrates the full scheme of the VDS, detailing the main components and describing the interactions between the Dynacar and the 3 DoF platform. The 3 DoF vehicle platform consists of two mechanical frameworks (lower an upper base) separated by an active suspension.
The upper structure holds the driver cabin, and the lower structure holds three crank shaft mechanisms conforming the active suspension as well as a vertical sliding guide, Fig. 4.

A set of actuators and sensors acts and measures the platform dynamics, Fig. 5. Each crankshaft mechanism is governed by an actuator and a sensor. This consists of an alternate current induction electric motor and its electric drive. The motor shaft holds an absolute encoder allowing the angle measurement of the crank. The upper base has one sensor: a gyroscope. It is located under the driver seat. A Real-Time (RT) computer (same as for the Dynacar system) reads the gyroscope and encoder signals. A set of reference signals is delivered from the selected vehicle dynamics model and compared with the measurements. The control algorithm computes in the RT computer the commands for each electric drive. Each electric motor has a frequency variator with a predefined speed control such that controller output is the voltage to the electric motors, and the control input to the platform is the rotational motion caused by the crank shaft mechanisms excited by the speed of the motors. The inner control of the electric motors can be reviewed in detail in [12].

4. Results and Discussion
The validation of LQR-based motion cueing in the VDS consists of a test in Dynacar with random lane changes, and with random braking and accelerating also. The programming of the
control algorithm is done in a MatlabTM environment.

The driver test under random scenario has a frequency contents to explore from 0.5 to 2.0 Hz, close to the frequencies of resonance of the pitch and roll angle. This bandwidth has been obtained from data analysis from Dynacar simulated variables. The ranges of the simulated pitch and roll are $\theta = \{-5.5\}$ degrees and $\phi = \{-8.8\}$ degrees.

Figure 6 presents the tracking performance of the proposed optimal LQR-based washout filter. The results of the washout filtering present high fidelity in the platform motion regarding the simulation in Dynacar, the controlled outputs follow the simulated variables in almost all frequencies of excitation. Qualitatively, Fig. 6 illustrates that the experimental roll angle correctly follows the virtual simulation, even better than the pitch motion. The roll angle dynamics in the Dynacar is well tracked by the platform in amplitude and frequency; however, the pitch motion in the platform has more complications to follow the abrupt changes in the Dynacar simulator, i.e. in some cases these abrupt motions are not tracked by the LQR washout filter such as occurs at $t = 3,500$ ms.
5. Conclusion

An LQR-based motion cueing has been proposed to control a Vehicle Dynamics Simulator of three degrees of freedom. The variables of interest are the pitch and roll angle and simulated in real time according to the Dynacar software. Experimental results show that the LQR washout filter has good tracking to the simulated vehicle variables, specially around the frequencies of resonance of the pitch and roll angle.

Future works will consist on testing active suspension controllers to improve the driver comfort using the developed LQR-based motion cueing on this driving simulator.

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