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Predictive Control of Motion Platform in Driving Simulator

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Abstract: In the recent years driving simulators are effectively used for vehicle system development, human factor studies and as a tool for driving training in a safe controlled environment. This paper describes a platform control for 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 and a motion platform. The platform consists in motorised rail, is used to simulate the longitudinal accelerations. We focus here on the implementation of the generalized predictive control developed by D.W.Clarke, on the motion platform of this driving simulator. Several tests were performed to study the performance of the system. Some results are shown.

Key words: Driving simulator, motion platform, washout, generalized predictive control, simulation

INTRODUCTION

A driving simulator is a virtual reality tool that gives a driver impression that he drives a real vehicle by predicting vehicle motion caused by driver input and feeding back corresponding visual, motion, audio and proprioceptive cues to the driver. 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[1-4].

Because of the impossibility to reproduce the actual vehicle accelerations on a driving simulator, illusion of inertial effect have 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[5]. In the transient acceleration case, the platform is linearly moved in the same acceleration direction and come back when the acceleration is continuous[5-7]. 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[2,7].

The motion platforms were firstly used in flight simulator to generate the correct accelerations cues, attitudes and vibrations to the flight compartment to provide an extra degree of realism for the pilots using them. The concept was applied much later to movement restitution on automobile driving simulators[2,7,8].

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[7]. In this presentation we will show the motion platformwe 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

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Fig.1 The Driving simulator architecture

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, a low-cost motion platform is designed and built which is able to animate the simulator's cab with a longitudinal movement.

PLATFORM DESCRIPTION AND MODELLING

The longitudinal motion platform is driven by a single d.c.motor. It can move in front or back direction (acceleration or deceleration operation).

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 a 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 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.

The mechanical equation of the actuator pulling the cabin is:

$$T_{a1} = J_{al}\frac{d\omega_{a1}}{dt} + f_{a1}\omega_{a1} + \frac{T_{al1}}{N1} \qquad (2)$$

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.m^2, ù is the rotational speed in rad/sec, f is the rotational armature friction in N.m.sec/rad, and N_1 the reduction factor. Where the torque T_{a1} and the back emf e are given by:

$$T_{a1} = k_{t1}i, \qquad e = k_{e1}\omega_{a1} \qquad (3)$$

I : armature current;
ω_{a1} : rotational velocity;
k_{t1},k_{e1} : constants

We have now two more components: the balls screw- nut transmission mechanism and the cabin's set. The cabin's set slides on a mechanical guide-way under an external applied force F_{x1} in Newton according to the $\vec{x}$ axis. The governing equation is:

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

M (the total cabin's mass (kg)) = m_c+m_t where m_c is the known empty cabin's mass and m_t is the estimated operator's mass.

The balls screw-nut pulling mechanism is driven by the external torque T_{s1}, indeed:

$$T_{s1} = J_{s1}\frac{d\omega_s}{dt} + f_{s1} + T_{sl1} \qquad (5)$$

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_{sl1} 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_{sl1} and F_{x1}. In fact the load torque T_{sl1} is transformed through the linkage to the axial force F_{x1} by the following equation:

$$T_{t1} = \frac{p_1}{2\pi\eta}F_{x1} \qquad (6)$$

Now, Eq. 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_{sl1}. Indeed, the actuator load torque is in fact the applied screw torque and thus $T_{s11} = T_{al1}$ and Eq. 2 becomes:

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

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:

$$x = \frac{p_1}{2\prod}\omega_{s1} \quad (9)$$

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:

$$k_{t1}i = (\frac{2\pi N_1}{p_1}J_{al} + \frac{2\pi}{p_1 N_1}J_{sl} + \frac{p_1}{2\pi\eta N_1}M)\frac{d\dot{x}}{dt} + (\frac{2\pi N_1}{p_1}f_{a1} + \frac{2\pi}{p_1 N_1}f_{sl} + \frac{p_1}{2\pi\eta N_1}fx1)\dot{x} \quad (11)$$

Since:

$$u = R_1 i + L_1\frac{di}{dt} + \frac{2\pi N_1 k_{e1}}{p_1}\dot{x} \quad (12)$$

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):

$$\frac{X}{U} = \frac{1}{s}\frac{k_{t1}}{(j_1 s + f_1)(L_1 s + R_1) + \frac{2\pi}{p_1}N\ k_{e1}k_{t1}} \quad (13)$$

GENERALIZED PREDICTIVE CONTROL

Predictive control is now widely used in industry and a large number of implementation algorithms has been presented in literature such as Generalized Predictive Control-GPC[1]. Most of these control algorithms use an explicit process model to predict the future behaviour of a plant and because of this, the term Model Predictive Control-MPC is often utilized.

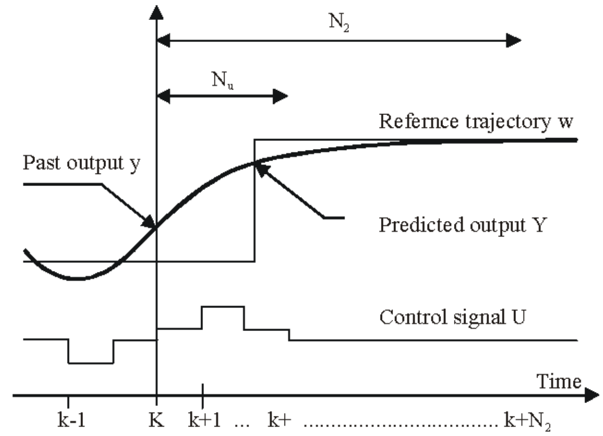

Fig. 2: Generalized predictive control strategy principle

The most important advantage of the MPC technologies comes from the process model itself which allows the controller to deal with an exact replica of the real process dynamics, implying a much better control quality[1,6,9]. Also, the constraints with respect to input and output signals are directly considered in the control calculation, resulting in very rare or even no constraints violation. The inclusion of the constraints is feature that most clearly distinguishes MPC from other process control techniques. Another important characteristic, which contributes to the success of the MPC technology, is that the MPC algorithms consider plant behaviour over a future horizon in time. Thus, the effects of both feed forward and feedback disturbances can be anticipated and eliminated.

Consider the following locally linearized controlled autoregressive and moving average (CARIMA) time discrete model :

$$A(q^{-1})y(k) = B(q^{-1})u(k-1)+e(k)/\Delta \quad (14)$$

Where u(t), y(t) and e(t) are respectively the control input, the controlled variable, and uncorrelated random sequence at time k; q^{-1} is the backward shift operator, Δ is the differencing operator ($\Delta = 1-q^{-1}$); and $A(q^{-1})$, $B(q^{-1})$ are the polynomials obtained by instantaneous linearization method:

$$A(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-2} + \ldots + a_n q^{-n}$$
$$B(q^{-1}) = b_0 + b_1 q^{-1} + b_2 q^{-2} + \ldots + b_m q^{-m} \quad (15)$$

The objective of the generalized predictive control strategy is to minimize a cost function based on error between the predicted output of the process and the reference trajectory. The cost function is minimized in order to obtain the optimal control input that is applied to the linear plant. The cost function has the following quadratic form:

$$J=\sum_{i=N_1}^{N_2}\left[\hat{y}(k+j)-r(k+j)\right]^2+\rho\sum_{i=1}^{N_2}\Delta u^2(k+j-1) \quad (16)$$

N1: the minimum prediction horizon;
N2: the maximum prediction horizon;
j: the order of the predictor;
r: the reference trajectory;
ρ: weight factor;
Δ: the differnentiation operator

Thus, the goal is to drive the future outputs y(k+j) close to r(k+j). For N1 = 1 and N2 = 2, the prediction vector:

$$\hat{Y}=[\hat{y}(k+1),\hat{y}(k+2),...,\hat{y}k+N)]^T \text{ is given by} \quad (17)$$
$$\hat{Y}=G\Delta U+F$$

Where $\Delta U = [\Delta u(k), \Delta u(k+1), ..., \Delta u(k+N-1)]^T$

G is an N*N lower triangular matrix and $F = [f(k+1), f(k+2), ..., f(k+N)]^T$ are the predictions of the output by assuming that future control increments are all zero.

Then, the control law is given by:

$$\Delta U = (G^TG+\lambda I)^{-1} G^T(R-F) \quad (18)$$

Where $R = [r(k+1), r(k+2), ..., r(k+N)]^T$

If after a certain horizon N_u, control horizon, the increments are assumed to be zero:

$$\Delta u(k+j-1) = 0,\ 1 \le N_u < j \le N_2$$

The control law becomes:

$$\Delta U = (G_1^TG_1+\lambda I)^{-1}G_1^T(R-F)$$

$$G_1=\begin{bmatrix} g_0,0,...,0,..........,0 \\ g_1,g_0,...,0,........,0 \\ .,.....,.....,.......,.....,0 \\ g_{N-1},g_{N-2},g_{N-N_u} \end{bmatrix} \quad (20)$$

and the matrix $(G_1^TG_1+\lambda 1)$ is $N_u{*}N_u$.
The coefficients of the matrixG1 can be obtained from polynomials G_j given by

$$G_j = E_j B \quad (21)$$

and E_j results from the recursive solution of the Diophantine equation:

$$1 = E_j(q^{-1})A(q^{-1})\Delta+q^{-1}F_j(q^{-1})$$

$\deg(E_j) = j\text{-}1$, $\deg(F_j) = n$

As the cost function used in GPC is quadratic then quadratic programming (QP) techniques are well suited for solving the problem of constraints on the control signal, the output signal or on the increments of the control signal.

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. The washout or cueing system makes the driver thinks he is making a continuous movement when actually the motion is restricted. Then, the commands will drive the platform for the short displacements and will drive it back to its neutral position in order that the workspace limit won't be met and the driver still able to get the sensation of a new acceleration or deceleration operation without he actually realising that it is happened. 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.

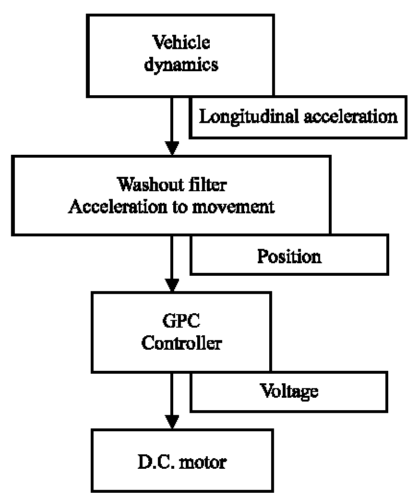

Fig. 3: Motion platform control diagram

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.

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 SIM^2 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.

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. A generalized predictive controller is used for the platform actuator in order to track the desired position.

SIMULATION

The acceleration signal obtained during the subject's driving contains acceleration phases, deceleration and

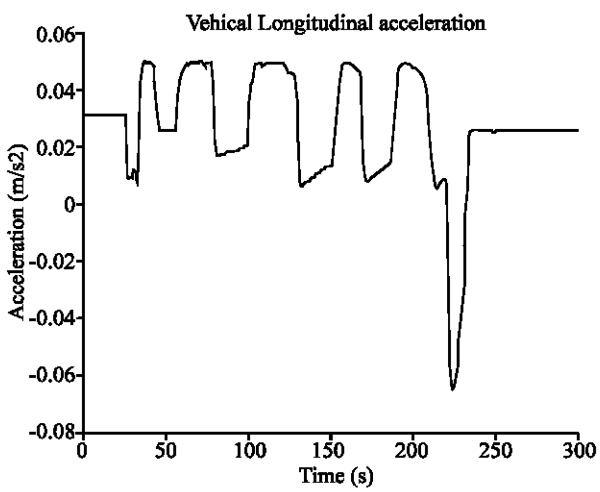

Fig. 4: Vehicle longitidinal accleration with accelerations

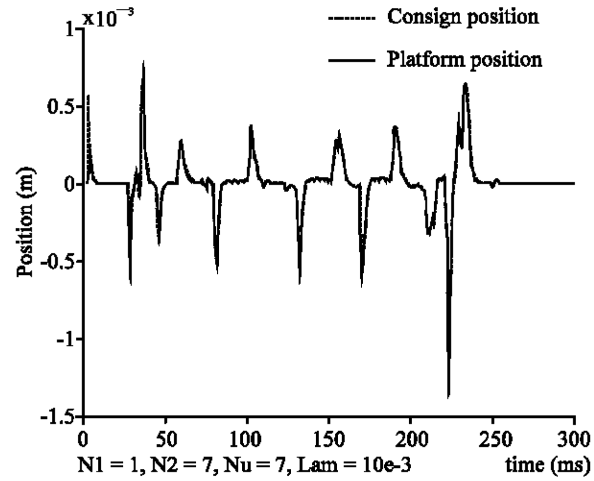

Fig. 5: GPC corrector with the plateform position

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 Acceleartion phase. We noted in Fig. 5 that with a GPC corrector, the plateform position follows exactly the desired postion with the selected design parameters N1 = 1, N2 = 7, Nu = 4, Lam = 10e-3.

CONCLUSIONS

In this study we have presented a mobile platform control 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, we have described the motion cueing algorithm.

The real vehicle move through large distances, while simulator motion base has a restricted range of motion. However, with careful control of motion base a very convincing impression of the real motion can be achieved. To do this, the generalized predictive control is used, in order to drive the acceleration.orfferentiation operator6 platform position more closely to the desired position (the output of the washout filter). The advantage of the generalized predictive control is to be able to drive the process output closely to the reference trajectory with an acceptable control signal by selecting the best choice of the design parameters: the minimum prediction horizon, the maximum prediction horizon, the control horizon and the weight factor. The results obtained are very satisfactory and showed that the GPC control strategy is very efficient for this type of problem. In further works, we have to increase the number of degrees of freedom in order to create other movement perception.

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