Vehicle Modelling and Washout Filter Tuning for the Chalmers Vehicle Simulator

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Abstract

In this work three washout filters [1][3][4][5] originally developed for NASA airplane simulators are considered for the Chalmers Vehicle Simulator (CVS). The Classical and Optimal washout filters are implemented for real-time use, while the Adaptive washout filter is tested only by off-line simulation.

The washout filter parameters are tuned by optimization algorithms. A Genetic Algorithm is used to find a starting point in the parameter space for the ensuing local optimization where a Riccati Algebraic Solver and the Steepest Descent Method are used. The optimization is performed on a computer simulation model of the CVS, taking standard driving manoeuvres as inputs.

The obtained Classical and Optimal washout filters were tested in real time on the CVS with several "test drivers". During all the tests, the platform never hit the physical boundaries, but moved very close to them, thus using most of the actuator's movement. According to the test drivers' impressions, the washout filters produced realistic driving experience.

Keywords:
Washout filter, vestibular system, tilt coordination, Genetic Algorithms, Riccati Algebraic Solver, steepest descent

1. Introduction

The algorithm that transforms the desired vehicle motion into realizable simulator motion commands is called a washout filter. The washout filter is responsible for:

- keeping the motion platform within its physical boundaries
- stimulating the driver to feel that driving the simulator is close to driving a real car
- returning the platform state to the neutral position
- washing out cues below the driver's perception threshold

The washout filter calculates the reference position (x_s) and angular displacement (β_s) in real time, taking the desired translational acceleration ($a_{desired}$) and angular displacement ($\beta_{desired}$) as an input signal, Figure 1.1.

The problem arises when low frequency high amplitude translational accelerations need to be simulated, because this cannot be achieved by only using the translational movement of the platform. Therefore, a tilt of the platform is used and the gravity emulates the low frequency components of the translational acceleration. In this process the driver should not feel rotation and because of that, the tilt rate is limited beneath the sensitivity threshold for rotation. The high frequency accelerations are simulated by small translational movements the platform can give (approximately 25cm). Even when tilt coordination is applied, very big accelerations cannot be simulated because of the platform limitation. Signals with higher amplitude are scaled and limited to the desired interval so that the platform's actuators do not exceed their limits.

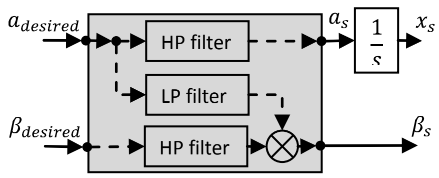

Figure 1.1: Washout filter

The washout filters are optimized by several optimization algorithms. Optimization is prepared offline, in a computer simulation, the desired parameters for the washout filters are found and then the washout filters are implemented for real-time use on the CVS. Optimization algorithms based on both heuristic and functional approaches are used. The Classical washout filter is optimized by Genetic Algorithms (GA), the Optimal washout filter is optimized by both GA and Riccati algebraic solver while the Adaptive washout filter is optimized by GA and Steepest Descent algorithm.

2. The Chalmers Vehicle Simulator

The Chalmers Vehicle Simulator was built by students in 1999 and is constantly being upgraded ever since. The main objective is to provide a simulation environment where new products and ideas related to the car industry can be tested before applying them to an actual car. It consists of a motion platform (Stewart platform) and five computers responsible for the simulation. A quarter of a Volvo car (the part where the driver sits) is mounted on the platform and the visual cues are projected on a screen in front of the driver, Figure 2.1.

Figure 2.1: The Chalmers Vehicle Simulator

3. The Vestibular System

The basic mechanisms with which human beings sense movement are:

- perception through the vestibular system
- visual perception
- perception through distribution of proprioceptors throughout the body

The vestibular system is of our main interest because it senses specific forces which can be easily produced in simulated environment. It is located in the inner ear (Figure 3.1) and consists of semicircular canals and otoliths organs.

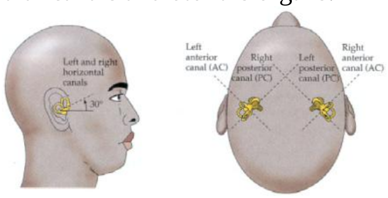

Figure 3.1: Location of the vestibular system [6]

The semicircular canals can be represented as an over-damped torsion-pendulum model with the transfer function given in Figure 3.2. Semicircular canals are good sensor for rotation in the frequency band $(02 \div 10) rad/s$.

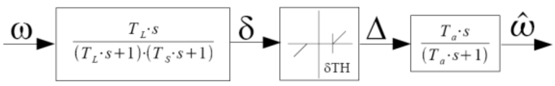

Figure 3.2: Transfer function for the semicircular canals [2]

Otoliths are good sensors of specific force (3.1) in the frequency band $(0.2 \div 2) rad/s$.

$$f\left[\frac{m}{s^2}\right] = a - g \qquad (3.1)$$

where g is the gravity and a is sensed acceleration.

The interesting thing about the otoliths is the fact that the gravity is sensed in the same way as linear acceleration. This feature opens the opportunity to use gravitational force, by tilting the platform, for simulating low-frequency linear accelerations.

The mathematical model of the otoliths is given in Figure 3.3.

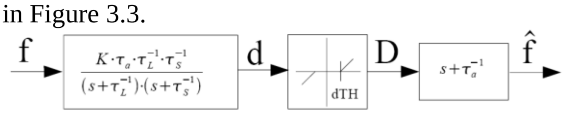

Figure 3.3: Transfer function for the otoliths [2]

4. Motion Cuing

The motion cuing deals with the basic problem in this research: how to create a simulated movement, as realistic as possible, by keeping in mind not to exceed the lengths of the actuators. Its general framework is given in Figure 4.1:

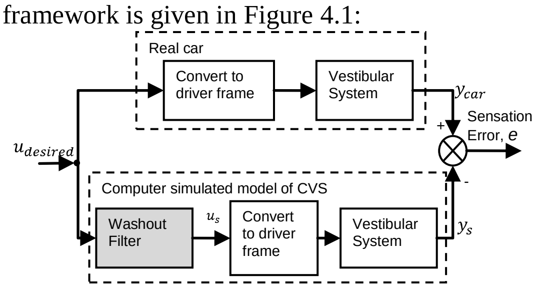

Figure 4.1: General framework of motion cuing

where $u_{desired} = \begin{bmatrix} a_{sesired} \\ \beta_{desired} \end{bmatrix}$ is the input signal and y_{car}, y_s is the sensed signal in the car and in the simulator respectively.

The sensation error e in Figure 4.1 is a measure of the experienced difference between driving the CVS and a real car.

4.1. Tilt Coordination

The sustained translational acceleration is sensed by the driver as a long term change in the magnitude and direction of the specific force. Generally, this cannot be simulated due to the limits of the platform which can barely move 25cm. Yet, it is possible to reproduce the same feeling by tilting the platform so that the driver feels the force of gravity as translational acceleration. Tilting the platform should be done with small rate of change of the angular displacement so that the driver does not feel rotation.

$$a_s = \begin{bmatrix} g\sin(\theta_s) \\ -g\cos(\theta_s)\sin(\phi_s) \\ -g\cos(\theta_s)\cos(\phi_s) \end{bmatrix}; \beta_s = \begin{bmatrix} \theta_s \\ \phi_s \\ \psi_s \end{bmatrix} \qquad (4.1)$$

Because the angles are always smaller than 20°, the sustained acceleration can be simulated using the tilt coordination matrix *TC*:

$$\begin{bmatrix} a_s^x \\ a_s^y \\ a_s^z \end{bmatrix} = TC^{-1} \begin{bmatrix} \theta_s \\ \phi_s \\ \psi_s \end{bmatrix}; TC \approx \begin{bmatrix} 0 & -\frac{1}{g} & 0 \\ \frac{1}{g} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (4.2)$$

Tilt coordination can be only applied on surge and sway acceleration, Figure 4.2.

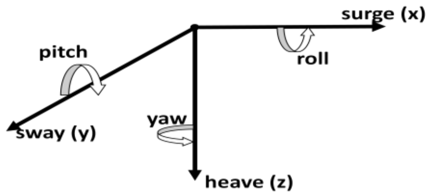

Figure 4.2: Coordinate system

5. Classical Washout Filter (CWF)

The CWF consists of three channels, translational, rotational and coordination, Figure 5.1.

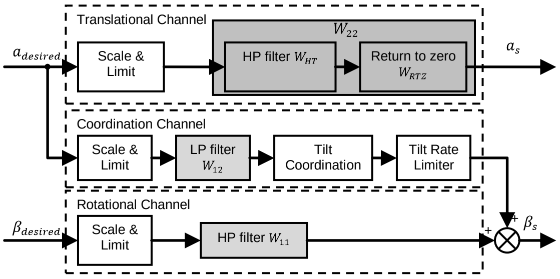

Figure 5.1: Classical washout filter

The translational channel passes high-frequency desired accelerations and it can be represented with the transfer function:

$$W_{22} = W_{HT}W_{RTZ} = \frac{s^2}{s^2 + 2\varsigma_t\omega_t s + \omega_t^2}\frac{s}{s+\omega_b} \quad (5.1)$$

The low-frequency acceleration is produced by passing the desired acceleration through low-pass filter in the coordination channel:

$$W_{12} = \frac{{\omega_c}^2}{s^2 + 2\varsigma_c\omega_c s + \omega_c^2} \quad (5.2)$$

The rotational channel passes high-frequency angular displacement:

$$W_{11} = \frac{s}{s+\omega_r} \quad (5.3)$$

The values for the natural frequencies $\omega_t, \omega_b, \omega_c, \omega_r$ and the relative damping coefficients ς_t, ς_c is optimized with genetic algorithms (GA) [8] by using computer model of the CVS. For each individual in GA a computer simulation is run by using standard driving manoeuvres. The fitness of the individuals is estimated according to:

$$fitness = \begin{cases} \frac{t}{T_{\max}}; \; for \;\; t < T_{\max} \\ 1 + \frac{1}{err}; \; otherwise \end{cases} \quad (5.4)$$

$$err = \sum_{t=0}^{T_{\max}} \left(y_s(t) - y_{car}(t)\right)^2 \quad (5.5)$$

The optimization is run in four separate cases: pitch/surge, roll/sway, yaw and heave which cover different portion of the unknown parameters.

6. Optimal Washout Filter (OWF)

The OWF was designed with four blocks, Figure 6.1:

$$W = \begin{bmatrix} W_{11} & W_{12} \\ W_{21} & W_{22} \end{bmatrix} \quad (6.1)$$

but later it was found out that W_{21} does not contribute to the final solution and was removed.

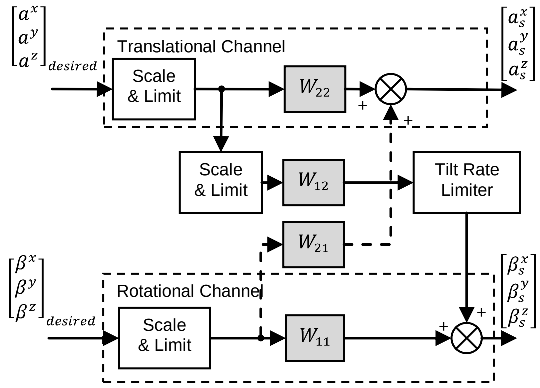

Figure 6.1: Optimal washout filter

The structure and the order of the OWF are derived by including the vestibular system inside its characteristic system of equations. The OWF is optimized by Riccati Algebraic Solver [7][9] using the following cost function:

$$J = E\{e^TQe + u_s^TRu_s + x_d^TR_dx_d\} \quad (6.2)$$

where e is sensation error given in Figure 4.1 and x_d are additional inner state space variables.

The values for the penalty matrices Q, R, R_d is found by GA, then the Riccati Solver finds L (6.3) thus finally producing *W(s)*, Figure 6.2.

$$u_s = Lx + Bu_{desired} \quad (6.3)$$

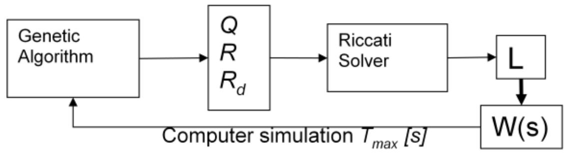

Figure 6.2: Optimization of OWF

7. Results

All three washout filters (CWF, OWF and AWF) were tested in the computer simulation model of the CVS by using different standard manoeuvres.

In Figure 7.1 the WF responses are given for sudden acceleration and brake (ramp to step in positive and negative direction). In Figure 7.2 the

WF responses are given for periodic lane change manoeuvre.

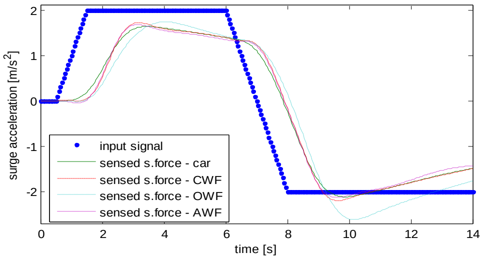

Figure 7.1: WF responses on surge acceleration

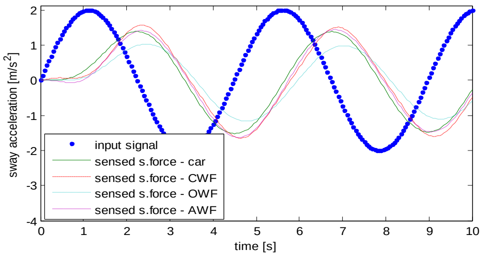

Figure 7.2: WF responses on sway acceleration

8. Discussion

The CWF and OWF were successfully implemented for real-time use on the CVS. But that was not the case with the Adaptive WF (AWF). It happened that the MatlabFcn block used in the Simulink model of AWF does not work in real time and this filter could not be compiled. It is left for future developers to redesign the AWF model.

The WF results given in Figure 7.1 and Figure 7.2 were obtained by a computer simulation model of the CVS. The actual response of the platform was not plotted because at the time this thesis was prepared, the real-time position of the CVS could not be recorded. Instead, the WFs were tested by several test drivers. According to the test drivers' suggestions some of the input signals were rescaled. After the final adjustments their impression was that the washout filters produced realistic driving experiences.

9. Conclusion and Future Work

This work resulted in the development of three washout filters from which two were successfully tested in real time use on the Chalmers Vehicle Simulator. The CWF and AWF gave very close matching to the reference curves, but the OWF produced slightly different results. When the CWF and the OWF were tested in real-time, the test drivers did not feel the difference. However one could repeat the derivation of the system of equations for the OWF without the approximations used in the current model.

The quality of the WF directly depends on the validity of the vestibular model, because they are tuned to respond as close as possible to this model. Improving the vestibular model can produce better results. There already exist models of the vestibular system which are better than those used in this work [1]. One should repeat the experiments by using these new models, which will possibly result in more realistic motion.

Washout filters that use real time tuning can give truly promising results, and this was already shown with the Adaptive WF. Therefore, the development of the Nonlinear WF [1] should be expected from future thesis workers.

A research is recommended for a predictive WF. Using the knowledge about future input signals, one could minimize the delay in the platform response.

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