DESIGN AND OPTIMISATION OF A MOTION CUEING ALGORITHM FOR A TRUCK SIMULATOR

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ABSTRACT

This paper describes the design and optimisation of a motion cueing algorithm for a truck simulator. However, the optimisation process described here can be applied for other simulators, in particular ground vehicle simulators. With the washout filter being the most common solution in simulation technology applications, the main idea of the optimisation procedure presented in this paper is the use of numerical tools to determine suitable washout algorithm parameters while respecting all kinematic and dynamical limitations of the motion platform including the perceptual thresholds of the vestibular system. These limitations are covered by a detailed mathematical model of the whole motion cuing system also described here. Washout algorithm consists of many different parameters the impact of which on the quality of motion cueing has not been clearly identified yet or is difficult to deduce. Therefore, the setup is often based on the programmer's experience. This article describes a method of optimising these parameters by means of a genetic algorithm. The optimisation criterion, expressed in the form of a fitness function, is the highest fidelity of motion cueing.

INTRODUCTION

Motion cueing is an essential part of most professional training and research simulators. In 2011, a new project, supported by the Technology Agency of the Czech Republic, was commenced in order to develop a new type of a truck simulator intended primarily for emergency situation training and follow-up research (http://www.vyprask.eu). Emergency situations require an especially high level of fidelity of motion cueing, as drivers often react purely instinctively in such circumstances and motion effects are the first indicator of an emergency or erroneous vehicle behaviour, such as a punctured tyre etc. Simulation fidelity is therefore the cornerstone of the project.
The truck simulator shown in Figure 1 below is a development version using a hydraulic motion platform with six degrees of freedom (hexapod). Known primarily from flight simulators, this type of mechanical system combines the highest degree of movement flexibility with exceptional robustness and rigidity, thus requiring no stabilising frames. Recently, hydraulic cylinders would often be replaced with electromechanical actuators (a description of the characteristics and comparison of both actuator types are provided in (Thöndel 2011)). A hydraulic system was used for the truck simulator project because it is cheaper and easier to maintain in operation.

Figure 1: Truck Simulator Mounted on a Motion Platform.

As the core component of the motion cueing algorithm, the washout filter converts data provided by the mathematical-physical vehicle dynamics model (acceleration) to the motion of the platform. Various modified or enhanced versions of the basic washout filter structure have been described in international literature; all of them, however, feature a set of parameters that have to be configured with respect to the type of motion platform used to make sure that the kinematic and dynamic limits are observed.
The setting up of these parameters is a rather lengthy iterative process, with the programmers often having to rely on their feelings and experience. The ways of setting up the parameters together with objective methods of assessing simulation quality are the most discussed topics in this area. The following text shows how this process can be automated, to a certain extent, and how the optimum parameters for fitness function can be determined.

FUNDAMENTALS OF MOTION CUEING

The fundamental principle of motion cueing is the reproduction of motion effects perceived by the human vestibular system. These include linear and angular acceleration.
The principles of motion cueing are shown in the block diagram below (Figure 2).

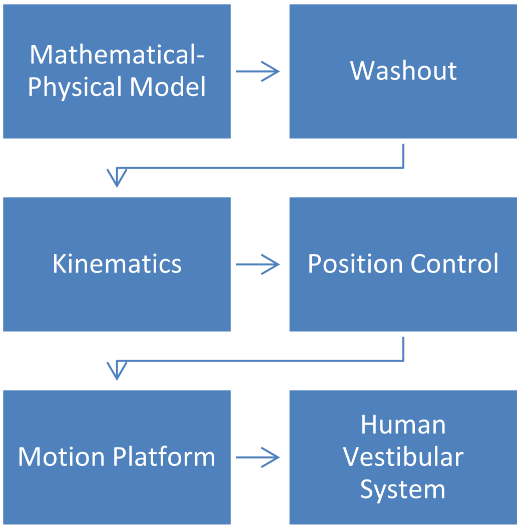

Figure 2: Motion Simulation Block Diagram.

The first block, the mathematical-physical model, generates information about the dynamical behaviour of the simulated vehicle. In the next step, this data (translational and angular acceleration) is transformed, in the "Washout" block, to the position of the motion platform. The position of the motion platform is subsequently transformed to the position of individual actuators. This process takes place in the "Kinematics", block where the inverse kinematics transformation of the motion platform is solved. The position of the linear actuators is controlled by a position controller. The last link in the chain is the person perceiving the motion of the platform; the diagram thus includes also a block representing the human vestibular system.
In order to analyse and optimise the system, all of the above blocks have to be defined and modelled.

MATHEMATICAL MODEL OF MOTION CUEING

This section describes the mathematical models of the different blocks shown in Figure 2. The models were implemented using the MATLAB/Simulink system.

Mathematical-physical model of the vehicle

The mathematical-physical model for the truck simulator project described above was designed based on the vehicle's known parameters provided by the manufacturer; a few additional parameters were determined by measurement.
(Negele 2007) provides a list of measured acceleration ranges by axes for automobiles and different drive modes.
For the subsequent analysis and optimisation of the washout algorithm the vehicle model has been replaced with a linear acceleration generator and values from the range of ±4 m/s^2, as measured in average passenger car drivers (Negele 2007).

Washout algorithm

As already explained, the washout algorithm transforms the data provided by the mathematical-physical model to the position of the motion platform, while respecting the kinematic and dynamical limits of the motion platform and features of the human vestibular system. Technical literature provides many different algorithm structures, including the following main washout filter types (see e.g. (Jamson 2010), (Telban et al. 2000)):

- The classical washout filter is the oldest and still most used algorithm type, as it has a fairly straightforward structure and provides good results.
- The adaptive washout filter is an enhancement of the previous structure, allowing an automatic parameter reconfiguration based on the status (position) of the motion platform. This ensures better coverage of the kinematic range.
- The optimal washout filter is a further enhancement of the adaptive algorithm, providing optimum automatic filter parameter reconfiguration according to a defined criterion.
- The predictive washout filter (MPC) is a rather new and still rarely used structure. In addition to being new, the solution has high computing power requirements. The structure is based on reference trajectory (acceleration) predictions determined with a suitable model (Fang and Kemeny 2012).

All of the above have certain common features: acceleration data is first scaled to make sure that the value does not exceed the allowed kinematic and physiological limits and the input signal is divided into high-frequency and low-frequency components. The high-frequency component is transformed, via double integration, to the translational position and the low-frequency component to the rotational position of the platform.
The main difference between the different algorithm types is the approach to the setting up of the parameters. Clearly, the correct parameter configuration is an essential requirement for a proper functioning of the algorithm and the process is far from being obvious, always remaining a bit of a puzzle, as confirmed for instance by (Jamson 2010): "the simulation engineer is still faced with the daunting task of selecting the ideal set of parameters to tune the motion system to achieve the highest level of fidelity for the driving task in question", or (Barbagli et al. 2000) "the utility of a given scheme can be vastly improved or degraded by the choice of parameters used".
In addition, another interesting aspect is the scaling of the input signal (acceleration). Assuming that the kinematic range of the motion platform is large enough, a scale factor of 1 may seem as a logical decision. Nevertheless, experience, corroborated by various studies, shows that people perceive motion effects more strongly when sitting in a motion simulator than in a real vehicle (Jamson 2010). Therefore, with a scale factor of 1 the platform's motion would be perceived as too strong.

The truck simulator described here features a standard washout filter version, adjusted to make it suitable for the intended purpose. The block diagram of the modified algorithm is given in Figure 3. A description of the modifications is provided below.

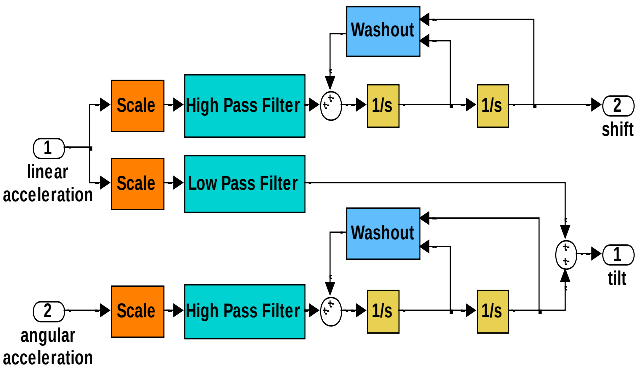

Figure 3: Washout Algorithm – Block Structure.

- The solution uses a non-linear third-order low-pass filter. The filter has the following basic equations:

$$\ddot{\vartheta} + 2\zeta_l\omega_{cl}\dot{\vartheta} + \omega_{cl}^2\vartheta = \omega_{cl}^2 \sin^{-1}\left(\frac{a_x}{g}\right)$$
$$\ddot{\varphi} + 2\zeta_l\omega_{cl}\dot{\varphi} + \omega_{cl}^2\varphi = \omega_{cl}^2 \sin^{-1}\left(\frac{a_y}{g\cos\vartheta}\right) \qquad (1)$$
$$\dot{a}_{fl} + \omega_{cl}a_{fl} = \omega_{cl}a$$

  where ϑ is the forward and backward tilt (pitch), φ is the side-to-side tilt (roll) of the motion platform, the ζ_l and ω_{cl} constants are damping and cut-off frequency of the filter, g is the gravitational acceleration, a_x and a_y are the components of the filtered vector of the translational acceleration a_{fl} and a is the scaled input vector of the translational acceleration
  The filter's unit-step response must not contain overshoots, as these have an extremely negative impact on simulation quality. Because the tilt angles of the platform are relatively small (up to ca. 20°), the results of the analysis of the linear filter variant can be used, in which $\cos\vartheta \cong 1$ and $\sin\varphi \cong \varphi$. In order to make sure that there are no overshoots during unit-step response, the characteristic equation has to have double real roots, i.e. the following must be valid:

$$\zeta_l = 1 \qquad (2)$$

- The scaling function is non-linear.

$$a = a_{max}\tanh\left(\frac{a_{in}}{a_{max}}\right) \qquad (3)$$

  where a_{in} is the input value of translational acceleration generated in the mathematical-physical model and a_{max} is the maximum scaled translational acceleration value. The function has the following properties: $\lim_{x\to\infty}(\tanh x) = 1$, so as to make sure that the scaled value does not exceed a_{max}, $\tanh 1 = 0.76$, i.e. for $a_{in} = a_{max}$ the input value is reduced to 76 %. The remaining 24 % of the range is reserved for $|a_{in}| > |a_{max}|$.
  The behaviour of the scaling function is shown below (Figure 4).

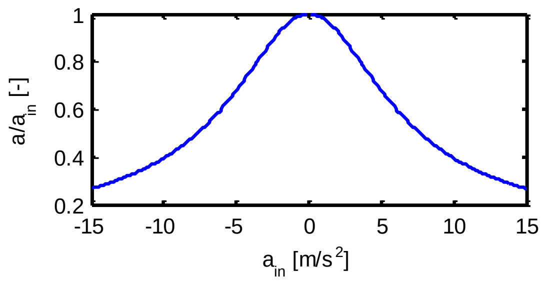

Figure 4: Behaviour of the Scaling Function.

- The high-frequency component consists of two parts:
  A linear first-order high-pass filter, filtering the input acceleration vector *a*

$$\dot{a}_{fh} + \omega_{ch}a_{fh} = \omega_{ch}a \qquad (4)$$

  where a_{fh} is the filtered acceleration vector and ω_{ch} a cut-off frequency.
  The second part is a double integration process (transfer of acceleration to the translational position) and the washout filter, returning the platform to the default/initial position. The formula can be written as

$$\ddot{x} + 2\zeta_w\omega_{cw}\dot{x} + \omega_{cw}^2 x = k\omega_{cw}^2\left(a - a_{fh}\right) \qquad (5)$$

  where x is the translational position vector of the platform and ζ_w, ω_{cw} and k are parameters.
  Again, there must be no overshoots when the platform returns to the default position. After analysing the characteristic equation of the above differential equation the following expression has to be valid:

$$\zeta_w = 1 \qquad (6)$$

- Angular acceleration is transformed in the same way as the high-frequency component of translational acceleration.

Kinematic transformation

During the kinematic transformation stage, the (angular and translational) position of the platform obtained by means of the washout algorithm is transformed to the position of each hydraulic actuator. The process uses a well-known calculation algorithm based on a transformation matrix projecting points defined in the coordinate system of the movable platform part to the coordinate system of the static part. In its basic form, the kinematic transformation equation can be written as:

$$h = |T \cdot C \cdot p_u - p_d| - h_0 \qquad (7)$$

where h is the position of the actuator, T the transformation matrix from the coordinate system of the upper (movable) frame to the lower (static) frame, C the transformation

matrix shifting the centre of rotation, p_u the position of the upper actuator joint expressed in the coordinate system of the upper (movable) frame, p_d is the position of the lower actuator joint expressed in the coordinate system of the lower (static) frame and h_0 is the default (i.e. fully contracted) actuator length.
The centre of rotation should ideally be situated in the same position as the driver's head (where the vestibular system is located). However, shifting the centre of rotation from the geometric centre of the upper movable frame results in a decrease in the platform's maximum kinematic ranges. It is therefore necessary to find a compromise between simulation fidelity and simulation range.

Position control of linear actuators

The method of controlling the position of the linear actuators depends on the class and type of the actuators used. The mathematical model used for washout filter parameters optimization employs a standard PID controller, which corresponds with the practical implementation of the hydraulic cylinders used.

Motion platform with the simulator cab

The kinematic and dynamic model of the motion platform, including the simulator cab, has been developed and implemented using the SimMechanics tool, a part of the MATLAB/Simulink. The application works with multi body systems (MBS) but offers a significant advantage compared to standard MBS modelling: mathematical models are created automatically by the application, with the user only having to define the properties and geometry of the bodies and the links between them (Grepl 2007).
The following graphics (Figure 5) shows a model visualisation of the motion platform with the simulator cab.

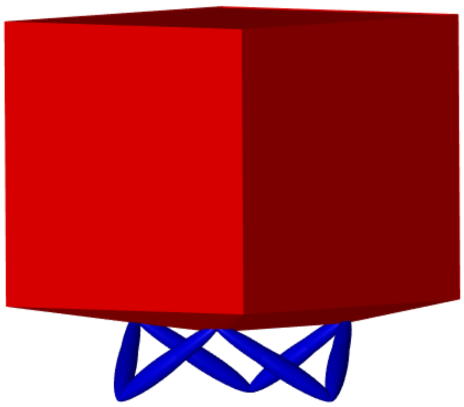

Figure 5: Model Visualisation of the Motion Platform with the Simulator Cab.

The model was verified by measuring on a real motion platform. The result is shown below (Figure 6).

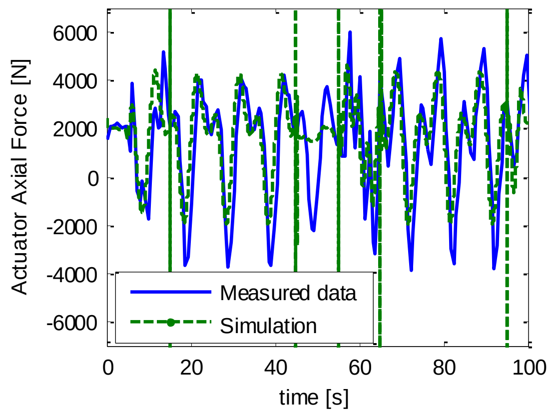

Figure 6: Verification of the Mathematical Model of the Motion Platform.

Vestibular system

The human vestibular system can be characterised with a transfer function, as defined for instance in (Telban et al. 2000). The minimum perceptible threshold values for different motion types are given in the Table 1 ((Groen and Jongkees 1948), (Telban et al. 2000), (Jamson 2010)).
The values show that the human vestibular system is very sensitive. Strictly adhering to these threshold values by, for instance, implementing platform rotation resulting from translational acceleration below these values would allow us to simulate in this way rather long acceleration only (i.e. in the order of several seconds). These thresholds are therefore often exceeded in practice and compromises between response speed and undesirable effects have to be made.
Table 1 gives the threshold values for velocity and acceleration. In practice, however, humans are also sensitive to jerks (the first derivative of acceleration with respect to time), the negative impacts of which ought to be minimised during the optimisation process.

Table 1: Vestibular System Perceptibility Thresholds.

Motion type	**Value**
Angular acceleration	0.3 °/s^2
Angular velocity	3 °/s
Translational acceleration	0.1 m/s^2

OPTIMISATION OF WASHOUT ALGORITHM PARAMETERS

The choice of parameters has a significant impact on the quality of the washout algorithm. The following aspects have to be taken into consideration when looking for the optimum parameters:

- accuracy of reproduction of translational and rotational acceleration,
- kinematic limits of the motion platform,
- dynamical parameters of the motion platform,
- properties of the human vestibular system.

Normally, the parameters are set up and fine-tuned empirically, i.e. based on the programmer's feelings and experience. This section, however, describes a method of

determining the optimum values with a partially automated process.
Earlier in this paper, we have described and modelled the whole motion cueing chain. This model (implemented in the MATLAB/Simulink environment in our case) can be used to verify the properties of the washout filter for a certain set of parameters. Writing the washout filter properties as numerical values provides us with a basis for iterative parameter optimisation. The goal of this process is to find the minimum (or maximum, as the case may be) value for each criterion.
There are many different optimisation tools that can be used to determine the minimum of a fitness function. The process described here uses a genetic algorithm, implemented as part of the Optimization Toolbox application in MATLAB (Bartko 2008).
The genetic algorithm has been selected in this particular instance because it converges to the global minimum quickly even without comprehensive details as to the nature and type of the fitness function (Mařík et al. 2003). Nevertheless, other numerical optimisation tools can be used as well.

Fitness function

The fitness function assigns to each set of parameters a numeric value representing the quality of that specific solution.
The fitness function consists of several components, and its basic form can be written as:

$$J = \int_{0}^{T} \left(q_1 \cdot J_a(t) + q_2 \cdot J_{jerk}(t) + q_3 \cdot J_{ear}(t) \right) dt \qquad (8)$$

where J_a penalises the solution with respect to the deviation between the desired (a) and actually reproduced acceleration (a_{out}).

$$J_a(t) = (a - a_{out})^2 \qquad (9)$$

J_{jerk} reduces positive jerks, i.e. the derivative with respect to time of the acceleration deviation. This criterion eliminates the rippling effect in reproduced acceleration.

$$J_{jerk}(t) = \left(\frac{d(a - a_{out})}{dt} \right)^2, \quad \frac{d(a - a_{out})}{dt} > 0 \qquad (10)$$

J_{ear} is an assessment of the physiological qualities of the washout filter (see Table 1). It penalises the solution if:

1. the tilt speed of the platform resulting from translational acceleration exceeds the vestibular system sensitivity threshold,
2. the acceleration threshold is exceeded when the platform returns to the default (initial) position.

Fitness function minimisation

The following figure (Figure 7) shows the convergence of the algorithm. As can be seen from the figure, the algorithm quickly converges to the optimum value during the first ten iterations (generations). The search is ended after 56 generations. The computing time was 15 min.

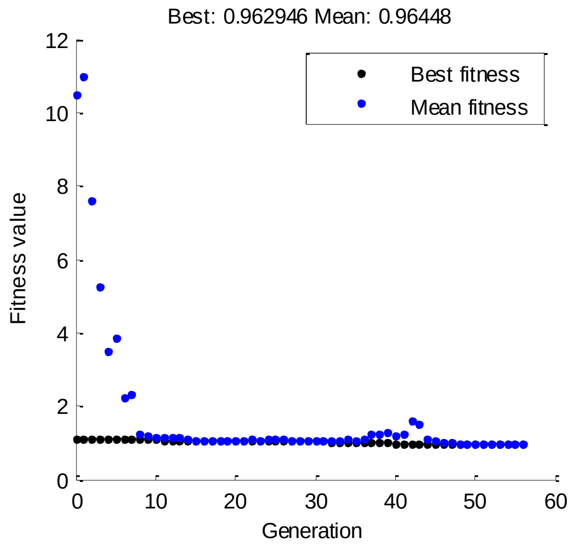

Figure 7: Genetic Algorithm Convergence when Determining the Minimum Fitness Function Value.

The Optimization Toolbox settings is shown on the Figure 8. The function (wf_optim_fce) starts in each iteration step the Simulink model of the motion cueing algorithm described earlier in this paper and returns the value of the fitness function (8).

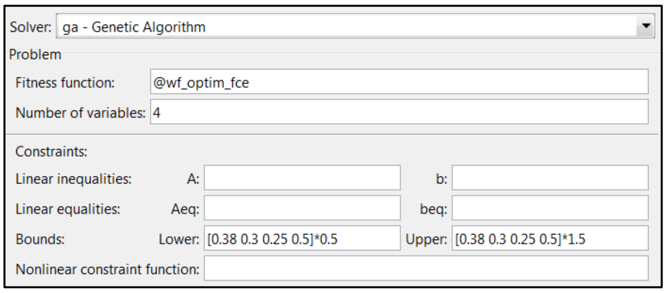

Figure 8: Optimization Toolbox Settings.

OPTIMISATION AND SIMULATION RESULTS

Figure 9 shows the simulation algorithm response to a unit step in input translational acceleration. The reproduced acceleration curve is very similar to that of the input acceleration. The result was verified by measuring by means of an accelerometer on a real truck simulator.

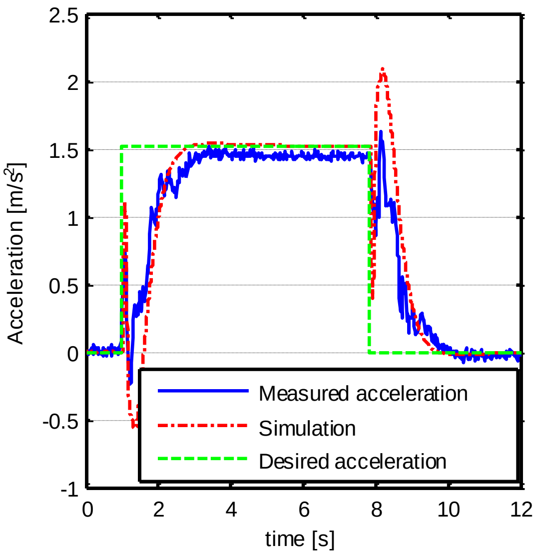

Figure 9: System Response to a Unit Step.

FOLLOW-UP WORK

The follow-up work will deal with validation of the algorithm. Driving tests with professional drivers will be performed in this project stage evaluating the fidelity of the algorithm. Based on these result the algorithm will be further modified.

CONCLUSION

The paper describes the process of optimising washout filter parameters for a truck simulator. The whole simulation chain, comprising of a mathematical-physical model of the vehicle, washout filter, kinematic transformation, linear actuator position control, motion platform and the human vestibular system, was first described and modelled in MATLAB. Subsequently, this model was used for the iterative search for the best washout filter parameters. For this purpose, a genetic algorithm was employed to determine the minimum of the fitness function. Simulation curve for unit step signal is provided in the chart.

AUTHOR BIOGRAPHY

EVŽEN THÖNDEL was born in Prague, Czech Republic, and studied at the Czech Technical University in Prague. In 2004 he acquired a Master's Degree in Technical Cybernetics, followed in 2008 by a Doctor's Degree (Ph.D.) in Electrotechnology and Materials. He has been working at the university as assistant professor after the end of his studies. Since 2009, Evžen has also been employed at Pragolet, working as simulation technology researcher.

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