Motion Cueing Algorithm Online Parameter Switching in a Blink of an Eye – A Time-Variant Approach

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Abstract – *The development and evaluation of human centered driver assistance systems is one major research focus within the automotive domain of the Institute of Transportation Systems (TS) at the German Aerospace Center (DLR). To investigate the impact of new driver assistance systems on driver behavior different research facilities from simulations to real car environments are used. One research facility at TS is the dynamic driving simulator with a hexapod structure. Using dynamic driving simulators to reproduce real car motion is a major challenge as the workspace is limited. Within this paper a method of state adaption is presented. This method enables a discrete switching of high-pass filter corner frequencies within one single simulation time step. Thereby discontinuities of the filter output signal as well as in the derivatives of the output signal are avoidable. Thus it is possible to adapt corner frequencies of high-pass filters of a Motion Cueing Algorithm (MCA) according to the current driving situation. The article starts with a description of the MCA currently used for the motion rendering at TS. Afterwards the state adaption method is described including the challenges for adapting this method to the current MCA structure. In the end the new structure for the time-variant MCA as well as the boundary conditions for corner frequency switching and the test results of the new time-variant approach using the state adaption method are outlined.*

Motivation and Introduction

Research activities at the Institute of Transportation Systems (TS) at the German Aerospace Center (DLR) focus on increasing safety and efficiency of traffic. In particular, this includes development and evaluation of assistance and automation systems within the automotive domain. To evaluate the impact of new driver assistance systems on driver behavior different research facilities are used. One research facility is the dynamic driving simulator with a hexapod structure. Using such motion simulators the representation of real car motion within the limited simulator workspace is a major challenge.

Nomenclature

$\underline{a}_{FDD}$	$\left[\frac{m}{s^2}\right]$	vector of translational accelerations calculated by the vehicle dynamics model
$a_n(t)$	$[\ ]$	coefficients of the linear time-variant high-pass filter
$\underline{a}_{Sim}$	$\left[\frac{m}{s^2}\right]$	vector of high-pass filtered translational accelerations commanded by the MCA
a_y	$\left[\frac{m}{s^2}\right]$	translational acceleration in y-direction
HP	$[\ ]$	time-variant third order high-pass filter in the translational path of the MCA
HP_a	$[\ ]$	first order high-pass filter in the translational path of the MCA
HP_{WO}	$[\ ]$	second order high-pass filter in the translational path of the MCA
L_{IS}	$[\ ]$	transformation matrix from vehicle fixed to inertial coordinate frame
L_{SI}	$[\ ]$	transformation matrix from inertial to vehicle fixed coordinate frame
s_y	$[m]$	position in y-direction
$\underline{sc}_a$	$[\ ]$	vector of scaling factors for the input accelerations of the MCA
t_{switch}	$[s]$	time when the MCA parameter set is switched
$u(t)$	$[\ ]$	input signal of the high-pass filter
v_y	$\left[\frac{m}{s}\right]$	translational velocity in y-direction
$\underline{x}(t)$	$[\ ]$	state vector of the high-pass filter
$y(t)$	$[\ ]$	output signal of the high-pass filter
ϕ_{tilt}	$[\circ]$	rotation angle for the rotation around x-axis for the tilt path
$\omega_{x,tilt}$	$\left[\frac{\circ}{s}\right]$	angular velocity for the rotation around x-axis for the tilt path
$\dot{\omega}_{x,tilt}$	$\left[\frac{\circ}{s^2}\right]$	angular acceleration for the rotation around x-axis for the tilt path

To improve the motion rendering new and refined Motion Cueing Algorithms (MCA) which map the real car motion to the limited simulator workspace are necessary. Commonly the main elements of these algorithms are scaling blocks, frequency filters and limiters. Usually the parameters of these elements are fixed during a simulator ride. But as outlined in [1, 2, 3] a discrete switching of these parameters according to the current driving situation e.g. city, rural and highway driving could be advantageous. These sets of parameters have to be determined a priori and are used when the respective driving situation occur. The following paper provides a method to discontinuously switch the coefficients of high-pass filters within one single discrete simulation time step. Furthermore the occurring challenges regarding the fast-tilt-coordination (FTC) algorithm [1], which is used for the motion rendering at TS, are presented.

Challenges of the Time-Variant FTC Algorithm

The FTC Algorithm

Figure 1 represents the block diagram of the initial FTC structure, which is currently used for motion rendering at TS. The main difference compared to the classical MCA approach [4, 5] is the ideal filter structure which is introduced and discussed in detail by Fischer [1]. There studies proving the validity of the FTC concept were done.

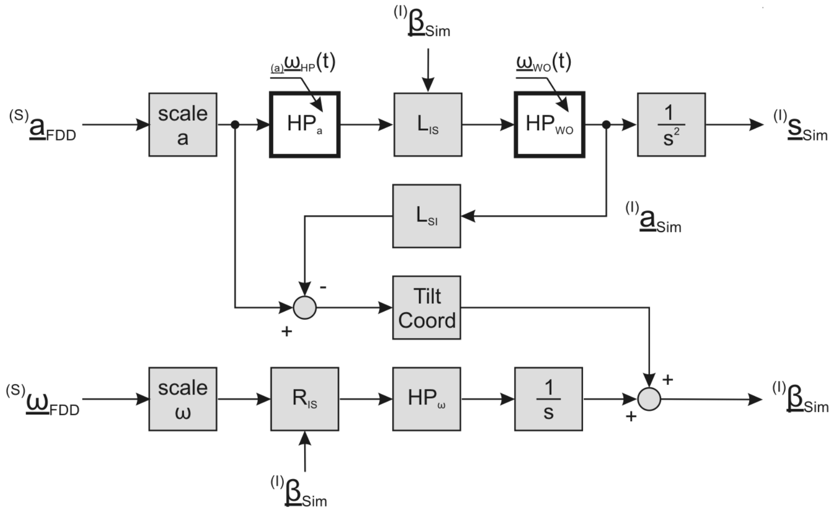

Figure 1. Block diagram of the initial FTC structure

The ideal filter structure is represented by the subtraction of the transformed output signal $L_{SI} \cdot {}^{(I)}\underline{a}_{Sim}$ of the two high-pass filters (HP_a and HP_{WO}) and the scaled input acceleration $\underline{sc}_a \cdot {}^{(S)}\underline{a}_{FDD}$. In the upper path of Figure 1 the high frequent signal components of $\underline{sc}_a \cdot {}^{(S)}\underline{a}_{FDD}$ are extracted and presented by a linear movement of the simulator platform. Through the ideal filter structure it can be ensured that no signal components of the scaled input acceleration $\underline{sc}_a \cdot^{(S)} \underline{a}_{FDD}$ get lost caused e.g. by an additional low-pass filter in the tilt coordination path. Thus all parts of the scaled input acceleration, which are not presented by a linear movement of the motion platform, are presented by a tilt movement.

Switching Effects of Time-Variant High-Pass Filters

Regarding the high-pass filters within the FTC (see Figure 1, white blocks with bold line) according to the discrete online parameter switching of their coefficients $a_n(t)\ (n \in \mathrm{Z}, n \geq 0)$ undesired switching effects occur. These effects can be explained by considering the time-variant state space description of common high-pass filters. From the linear time-invariant transfer function

$$H(s) = \frac{s^n}{s^n + a_{n-1} \cdot s^{n-1} + ... + a_1 \cdot s + a_0} \tag{1}$$

the state equation (2) and output equation (3) of the state space description can be derived. There the coefficients of the high-pass filter $a_n(t)$ are considered as time-variant.

$$\begin{bmatrix} \dot{x}(t) \\ \ddot{x}(t) \\ . \\ . \\ \overset{n}{x}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & . & . & 0 \\ 0 & 0 & 1 & . & & 0 \\ . & . & . & & . & . \\ . & . & . & & & 1 \\ -a_0(t) & -a_1(t) & . & . & . & -a_{n-1}(t) \end{bmatrix} \cdot \begin{bmatrix} x(t) \\ \dot{x}(t) \\ . \\ . \\ \overset{n-1}{x}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ . \\ . \\ 0 \\ 1 \end{bmatrix} u(t) \tag{2}$$

$$y(t) = \begin{bmatrix} -a_0(t) & -a_1(t) & . & . & . & . & -a_{n-1}(t) \end{bmatrix} \cdot \begin{bmatrix} x(t) \\ \dot{x}(t) \\ . \\ . \\ \overset{n-1}{x}(t) \end{bmatrix} + u(t) \tag{3}$$

When considering the output equation (3) at a certain time t_{switch} with the input signal $u(t_{switch})$ and the state vector $\underline{x}(t_{switch})$ it is evident that – if one or more of the coefficients $a_m(t)\ (m \in \mathrm{Z}, 0 \leq m \leq n)$ are changing discontinuously – there will be a discontinuity in the output signal $y(t)$. To avoid these discontinuities the method of state adaption is presented in the next section.

State Adaption Method to Switch the Coefficients of Time-Variant High-Pass Filters

The Method of State Adaption

To avoid the described output signal discontinuities as described in the former section the idea is to adapt the states of the transfer system in a way that in the moment of coefficients switching the discontinuity will be transferred to the state space. Thus there will be a discontinuity in the system states $\underline{x}(t)$ but not in the output signal $y(t)$. According to the order of the used high-pass filter this method is not limited to avoid discontinuities in the output signal $y(t)$ but in its derivatives, too. Thus this method is not tied to a type (low pass or high-pass) or a certain order of linear time-variant filters. In Figure 2 the common principle of the state adaption method for the signal flow of the state $x(t)$ and output $y(t)$ signal of a first order high-pass filter is outlined schematically.

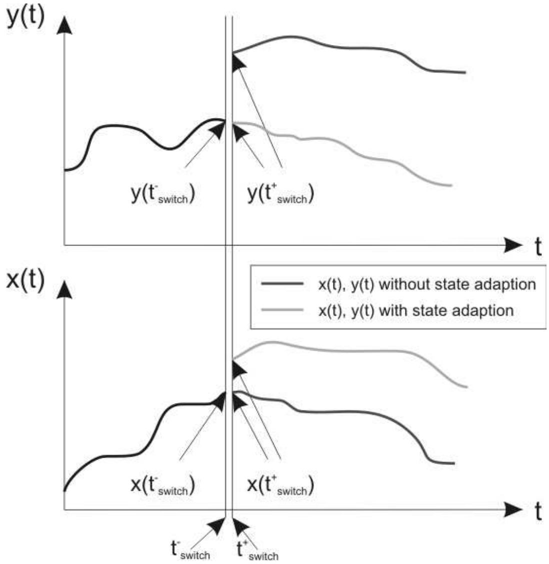

Figure 2. Common principle of the state adaption method

The first step of the state adaption method is the derivation of a system of linear equations based on the output equation (3). There the states of the transfer system are the unknown variables. The order $n\ (n \in \mathrm{Z}, n \geq 0)$ of the used high-pass filter determines the order of the highest derivative of the output signal $\frac{d^{n-1}y}{dt^{n-1}}$ where a discontinuity in the signal flow is avoidable. Within the resulting system of linear equations the current values of the output signal and its derivatives, the new coefficients $a_m(t)$ and the input signal as well as its derivatives are known.

Thus the new states of the time-variant high-pass filter can be calculated to avoid discontinuities in the output signal as well as in the derivatives of the output signal. Because the coefficients of the high-pass filters are piecewise constant its derivatives are zero. So they are not considered in the system of linear equations.

The first equation of the system of linear equations (4) is the output equation of the state space description (3). Considering a high-pass filter with the order $n>1$ the equations of the system can be derived step by step. To derive the second equation the first equation has to be differentiated as shown in equation (4). Caused by the differentiation of the first equation the variable $\overset{(n)}{x}(t)$ occurs in the second equation. This variable has to be replaced by the state equation (2) so that the highest order of the state derivatives is $(n-1)$. If the order of the high-pass is greater than two the second equation of the system of linear equations has to be differentiated and the occurring $\overset{(n)}{x}(t)$ has to be replaced. These steps have to be repeated until the highest order of the output derivative $\frac{d^m y}{dt^m}$ is $(n-1)$.

$$
\begin{aligned}
&I.\ y(t) = -a_0 \cdot x(t) - \ldots - a_{n-1} \cdot \overset{(n-1)}{x}(t) + u(t) \\
&II.\ \frac{dy}{dt} = -a_0 \cdot \frac{dx}{dt} - \ldots - a_{n-1} \cdot \overset{(n)}{x}(t) + \dot{u}(t) \\
&\quad \ldots \quad \ldots
\end{aligned}
\tag{4}
$$

Finally the derived system of linear equations has $(n-1)$ equations including $(n-1)$ unknown state variables. This system of linear equations can be solved by different methods e.g. Gauss-algorithm, Cramer's rule, etc. and as the equations are not linearly dependent there will be a definite solution.

The state adaption method, to calculate the new system states, is only to be used in the moment of changing high-pass filter coefficients. In this moment the current output signal and its derivatives, the current input signal and its derivatives and the new coefficients are used to calculate the new state variables. Thus it is possible to switch the filter coefficients within a single discrete simulation time step.

Influence of the State Adaption Method on the Time-Variant FTC Algorithm

In this section the results from the already outlined common method of state adaption are mapped to the FTC algorithm. Considering the block diagram of the FTC algorithm in Figure 1 there are two high-pass filters in the upper path (HP_a and HP_{WO}). There HP_a is a first order high-pass filter and HP_{WO} is a second order high-pass filter. Using the state adaption method separately for both filters will cause points of discontinuity in the angular acceleration signal when the filter coefficients are switched.

Because the highest order of the high-pass filter is two the discontinuities can be avoided for the input signal (accelerations) and the first derivative of the input signal (jerk). This means that in the acceleration signals presented by linear movement of the simulator platform there are no discontinuities. But for the presentation of latent accelerations through the tilt coordination there are discontinuities, because the acceleration signals are transformed to angular values using trigonometric functions. Thus there are no discontinuities in the angular values and the angular velocities but in the angular accelerations. This could be avoided by the new FTC algorithm approach.

In the block diagram of Figure 3 the new structure of the time-variant FTC algorithm is presented. Using the structure of the FTC algorithm presented in Figure 1 discontinuities in the angular acceleration occur in the moment of discrete coefficients switching. To avoid these effects a third order high-pass filter has to be used. Therefore the two high-pass filters in the upper path have to be merged to a third order high-pass filter. This is possible because the time-invariant FTC algorithm almost is a linear time-invariant (LTI) system. Assuming that the time-variant FTC is a piecewise LTI system this method is adaptable. But there is another problem regarding the double integrator in the upper path of the FTC algorithm, because of the discrete switching of parameters by using the state adaption method. In the moment of coefficients switching the wash-out effect of the third order high-pass filter gets lost and the signal flows for the position and velocity signals for linear platform movement are not attracted to the zero position and velocity anymore.

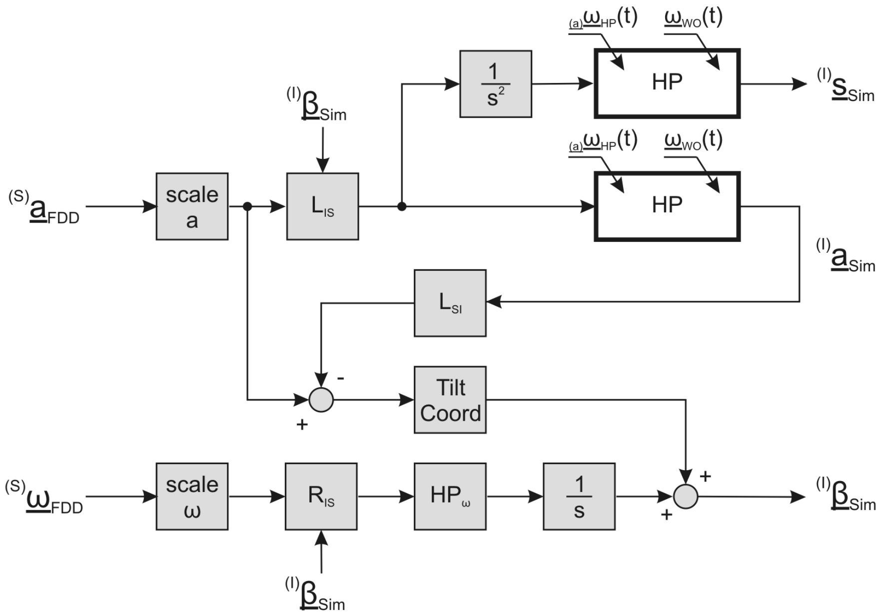

Figure 3. Block diagram of the new structure of time-variant FTC algorithm

In Figure 4 four diagrams are presented dealing with the aforementioned challenges. In the two diagrams on the left side it is shown that the output signals (lateral acceleration and angular velocity of roll movement) of the initial time-variant FTC structure (Figure 1) and the new time-variant FTC structure (Figure 3) are equal for constant filter coefficients. The two plots on the right side present the position and velocity signals in the moment of switching filter coefficients for the initial time-variant FTC structure and the new time-variant FTC structure. In the position signal s_y and the velocity signal v_y it is obvious that the wash-out effect of the high-pass filter get lost for the initial time-variant structure.

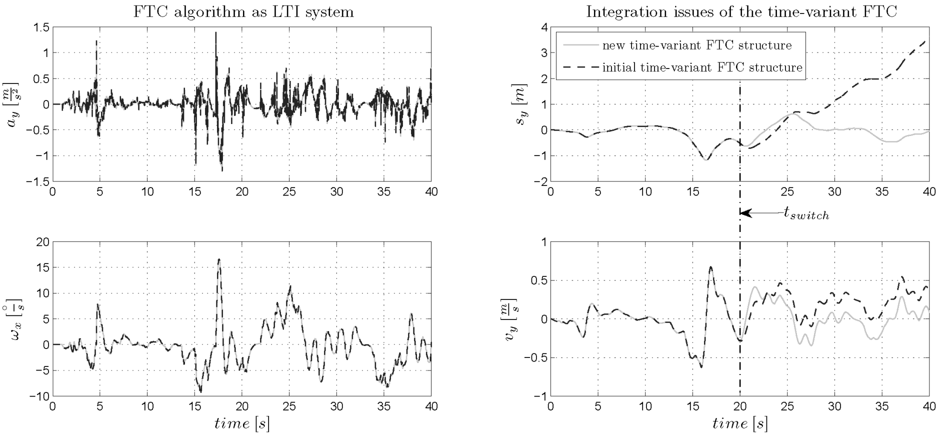

Figure 4. Comparison of the initial time-variant FTC structure and the new time-variant FTC structure

Constraints and Results for the Discrete Parameter-Switching

Constraints for the Moment of Parameter-Switching

Using the presented method of state adaption it is possible to switch the filter coefficients of high-pass filters within one single discrete simulation time-step. Certainly there is an influence on the signal flow of the output signal which should be kept as low as possible. Therefore it is meaningful to define constraints which have to be fulfilled before initializing the switching process. Considering the change of the filter coefficients for lateral movement the process should not be initialized when currently driving in a curve. Switching the filter coefficients within a curve would cause a movement of the simulator platform although there is a constant lateral acceleration which is presented by a constant tilt angle of the motion platform. In Table 1 the constraints which have to be fulfilled to switch the filter coefficients are outlined for the components of lateral movement. Thereby the perception thresholds for accelerations and angular velocities are taken into account as presented by Benson *et al*. [6,7]. The thresholds for the other motion quantities were gathered by experiments.

Table 1. Constraints for the discrete parameter switching

	$\|s_y\|$	$\|v_y\|$	$\|a_y\|$	$\|\phi_{tilt}\|$	$\|\omega_{x,tilt}\|$	$\|\dot{\omega}_{x,tilt}\|$
Limits	$\leq 0{,}1\, m$	$\leq 0{,}1 \frac{m}{s}$	$\leq 0{,}1 \frac{m}{s^2}$	$\leq 1°$	$\leq 2 \frac{°}{s}$	$\leq 2 \frac{°}{s^2}$

Presentation of the Results Using the State Adaption Method for Online Parameter-Switching

In Figure 5 the results of the evaluation tests are presented. Within these plots the signal flow of the output signal of the new time-variant FTC structure versus the initial time-invariant FTC structure are presented. In the left plots only very small switching effects are visible while the parameters are switched from highway to city driving.. In the moment of parameter switching $t_{switch,1}$ there is no discontinuity in the output acceleration or angular velocity. Considering the right plots the switching effects are slightly more clear-cut than in the left plots. Certainly there are no discontinuities in the output signals at the switching time $t_{switch,2}$. The difference in the effects is given by comparing the time from the point of parameter switching to the point where the signal flow of the time-variant algorithm equals the signal flow of the time-invariant algorithm. These effects are visible in the presented plots.

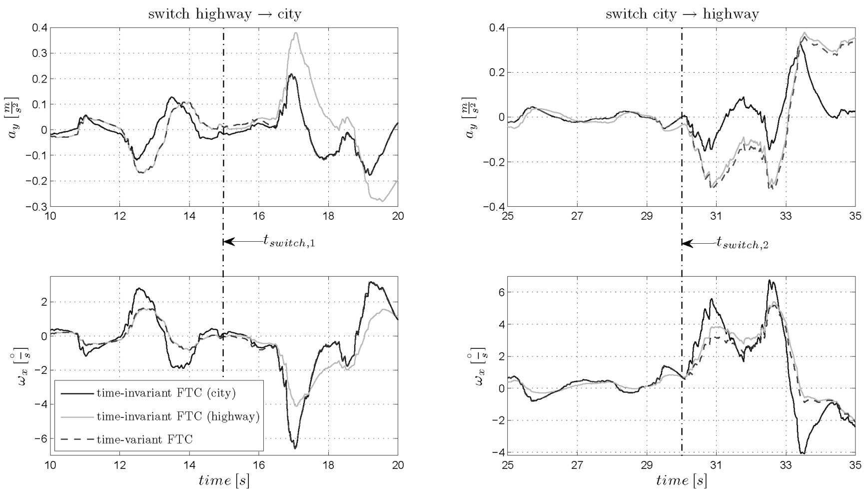

Figure 5. Comparison of the initial time-invariant FTC structure and the new time-variant FTC structure

Conclusion

Within this paper an approach to adapt the current set of parameters of a MCA to the current driving situation is presented. Thereby a method to switch the coefficients of a high-pass filter discontinuously without discontinuities in the filter output signal as well as its derivatives is outlined. The advantage of this method is that the filter coefficients can be switched within one single discrete simulation time step. So the moment of switching is chosen by the fulfillment of constraints regarding the actual motion quantities of the simulator platform.

Certainly it is meaningful to limit the adaption of the current set of parameters to superior driving situations as done in this paper (city, rural and highway driving). Otherwise when running a much more differentiated adaption of parameters the parameter switching can not be ensured because of the constraints for parameter switching.

In the future the method of state adaption should be applied to the lower path of the MCA (see Figure 1) where the high frequent parts of the angular velocities are presented by an angular movement of the simulator platform. A method to online adapt the scaling factors of the FTC algorithm is already presented in reference [2].

Keywords: fast tilt coordination, online parameter switching, state adaption, high-pass filter

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