An MPC based Motion Cueing Algorithm with side slip dynamics

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Abstract - *Although a great effort has been put in recent years to improve real-time Motion Cueing Algorithm (MCA) technology, perception of the driver is still a complex and debated topic. In this paper a Model Predictive Control (MPC) based MCA is proposed that integrates a novel feature to provide the driver with specific information on the side slip dynamics of the vehicle. An experimental test has been conducted, showing a significant improvement in the perception of vehicle limits and realism.*

Keywords: *Motion Cueing, Model Predictive Control, Side slip dynamics.*

Introduction

Most recent developments on Motion Cueing Algorithms (MCAs) have been focused on introducing perception and mechanical models in the motion control strategy by mean of advanced control techniques, such as Model Predictive Control (see [Bru17a, Bru17b]), or in optimizing tuning and scheme of the classical washout filter approach (see [Asa15]). In both cases the typical input to the algorithm are body frame translational accelerations and rotational velocities. Perception in a vehicle, however, does not only refer to those accelerations and velocities, but to the vehicle state itself, e.g. the condition of understeer or oversteer. Both in the case of a washout filter MCA and in the MPC based one the information on the vehicle state is modified, or by filtering/scaling or by the optimization itself, in an indiscriminate way. In [Gar12] a solution to this problem is proposed based on the simple, but effective idea, of reproducing only the side slip angle and neglecting all the other contributions, providing the professional driver with the crucial information for vehicle state evaluation. In [Sal17] a more complex strategy for race application is proposed based on linearizing the vehicle model on limit conditions and computing the ratio between lateral acceleration and yaw rate. A classical washout strategy is then optimized to reproduce the correct information. However this approach requires a heavy pre-processing step that is based on a detailed model of the vehicle, which makes it suitable only for race application in racing field. In this paper we propose a solution that provides the driver with information on the vehicle sliding dynamics, reproducing the instantaneous yaw center of rotation projected on the axis of the vehicle. In such a way the vehicle behavior in the various phases of the turn can be correctly provided to the driver.

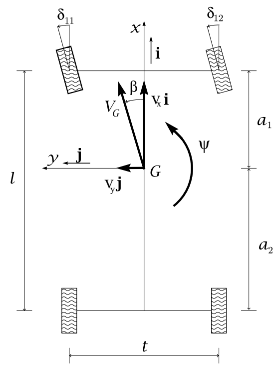


Figure 1: Modello di veicolo a tre gradi di libertá.

Vehicle Side slip dynamics

The reference system that will be used for the analysis is the body-fixed reference system (x, y, z ; G). It has origin in the center of mass G and axes fixed to the vehicle, with unit vectors (**i**, **j**, **k**), (Fig. 1).

During the turn maneuver, any rigid body in plane motion has a center of instantaneous rotation (C), which is the point at zero velocity. In the particular case of ”steady state” condition, it coincides with the center of curvature of the trajectory [Gui]. The velocity of a generic point P is equal to :

$$V_P = V_G + \dot{\psi}\mathbf{k} \times P \tag{1}$$

where V_G is the velocity of G and P is the vector connecting G to P. Being the center of rotation a point at zero speed it is possible to obtain its coordinates in the body-fixed reference system, i.e.

$$P_C = d_x\mathbf{i} + d_y\mathbf{j} \tag{2}$$

$$d_x = -\frac{v_y}{\dot{\psi}} \qquad d_y = \frac{v_x}{\dot{\psi}} \tag{3}$$

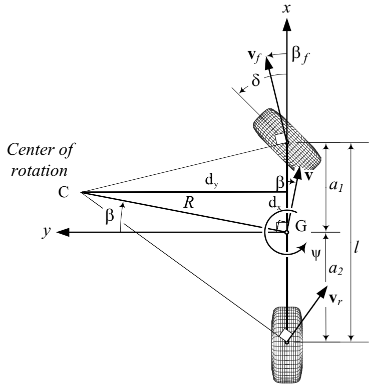


Figure 2: Kinematics of a single-track vehicle model.

where d_x and d_y are respectively the distance between the center of rotation C and the lateral axis and that between the C and the longitudinal axis of the vehicle, as shown in the Fig. 2. In real maneuvers, due to the side slip dynamics, during the initial turn-in phase of the corner, the driver perceives an additional lateral acceleration, indicating that the instantaneous center of rotation is behind the CG and towards the rear of the car. After the initial turn-in, the car starts to slide to a neutral attitude, since the instantaneous center of rotation is near the CG

Starting from expected driving feeling, the goal is that of reproducing on the platform the effect of the migration of the yaw axis. This latter is mainly characterized by the direct lateral acceleration, i.e. the variation of lateral velocity of the CG [MW].

$$\dot{v}_y = -\dot{d}_x\dot{\psi} - d_x\ddot{\psi} \tag{4}$$

An alternative expression for the direct lateral acceleration can be retrieved observing that the following relation holds

$$v_y = V_G sin(\beta), \tag{5}$$

where β is the side slip angle. Deriving w.r.t. time (5) we have

$$\dot{v}_y = \dot{V}sin(\beta) + Vcos(\beta)\dot{\beta} \tag{6}$$

and in particular, since β is generally less than $10°$, the following approximated expression can be derived.

$$\dot{v}_y \approx \dot{V}\beta + V\dot{\beta}. \tag{7}$$

Comparing (4) and (7), it can be noticed that the longitudinal component of the IC expressed w.r.t. the body frame is actually related the side slip dynamics.

During the steady state phase the vehicle side slip angle is constant, thus the side slip angle rate is zero and the direct lateral acceleration is also zero. During transient phases, the vehicle side slip angle is varying, thus the side slip angle rate and direct lateral acceleration are also non zero.

The side slip rate and, consequently, the direct lateral acceleration are two terms that exhibit high frequency contents, being that suitable to be reproduced in a reduced work space. This allows the reproduction without loss of information of the vehicle's attitude, as underlined in [Gar12] for the side slip angle.

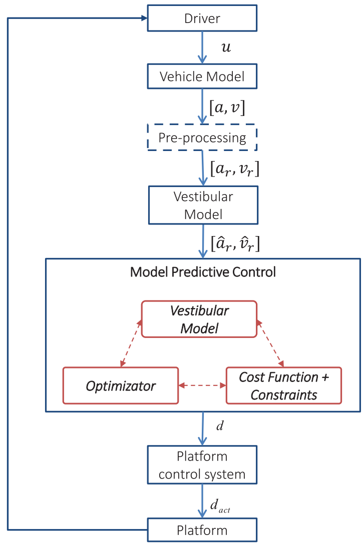


Figure 3: General scheme of an MPC-based motion cueing algorithm

Side slip dynamics motion cueing algorithm

MPC Based Motion Cueing Algorithm

An MCA based on MPC is then implemented inspired to the one described in [Beg12, Bru17a] and coupling the lateral and yaw dynamics by means of the side slip dynamics. A scheme is reported in Fig. 3. The complete system, as described in, [Bru17a], is $\Sigma_V = \{A_V, B_V, C_V, D_V\}$, where

$$A_V = \begin{bmatrix} A_S & 0 & 0 \\ 0 & A_{\bar{O}} & 0 \\ 0 & 0 & A_I \end{bmatrix} \quad B_V = \begin{bmatrix} 0 & B_S \\ B_{\bar{O}} & \\ B_I & \end{bmatrix}, \tag{8a}$$

$$C_V = \begin{bmatrix} C_S & 0 & 0 \\ 0 & C_{\bar{O}} & 0 \\ 0 & 0 & I \\ 0 & 0 & 0 \end{bmatrix} \quad D_V = \begin{bmatrix} 0 & D_S & \\ D_{\bar{O}} & 0 & 0 \\ 0 & I & \end{bmatrix}, \tag{8b}$$

and where the state, the inputs and outputs are respectively :

$$x_V = [x_S^T \; x_{\bar{O}}^T \; x_I^T]^T \tag{9}$$

$$u_V = [a_x \; a_y \; a_z \; \dot{\phi} \; \dot{\theta} \; \dot{\psi}]^T \tag{10}$$

$$y_V = [y_S^T \; y_{\bar{O}}^T \; y_I^T \dot{\beta}]^T. \tag{11}$$

where the actual angles, positions and velocities are obtained by integration from the inputs u, x_O and x_S are the state variable for the dynamical systems associated with the otoliths and semicircular canals. Finally, the system is split into 4 subsystem, namely : vertical, yaw, lateral\roll and longitudinal\pitch

Side slip contribution

In the pre-processing phase of the MCA strategy described in the previous section a simple scaling is typically applied. As a consequence the attitude of the vehicle, i.e. information about side slip dynamics, is typically lost. We propose here a different strategy

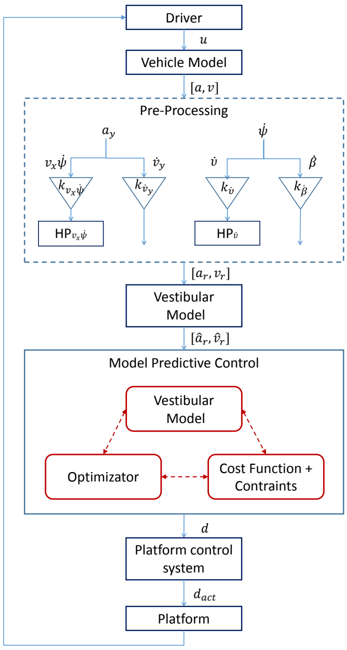


Figure 4

that combines the principle of the washout filters with the MPC based MCA.

The basic idea is that of isolating the side slip dynamics in the lateral acceleration and the yaw rate. More specifically the lateral acceleration can be written as

$$a_y = \dot{v}_y + v_x\dot{\psi}, \tag{12}$$

i.e. it is split into the direct lateral acceleration $\dot{v}_y$ and the centrifugal acceleration component $v_x\dot{\psi}$. Similarly the yaw velocity can be written as

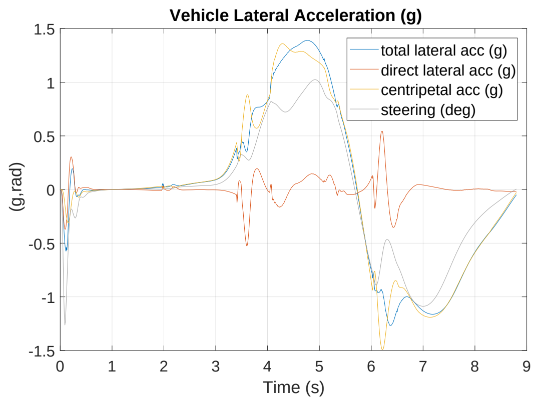
$$\dot{\psi} = \dot{\nu} - \dot{\beta}. \tag{13}$$

where the side slip angle rate and the course angle rate (the angle between the trace of the vehicle and the global reference frame) are the two components of the yaw angle rate [MW]. As mentioned above, both the direct lateral acceleration and the side slip rate do not exceed the limits of the platform and can therefore be reproduced entirely. The remaining part of the lateral acceleration, the centrifugal component, and the course angle rate are, instead, scaled filtered to fit the platform workspace.

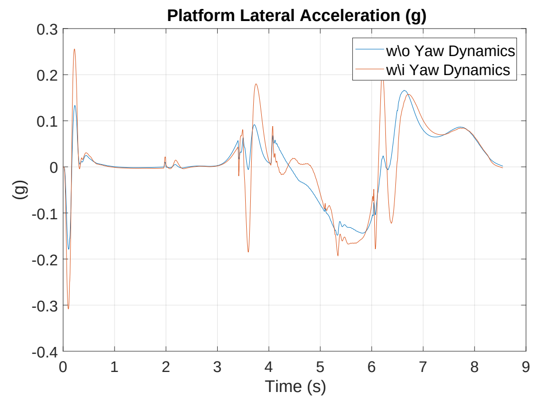
Summarizing, the proposed strategy allows to reproduce faithfully the vehicle local behavior, i.e. its attitude, and the high frequency component of the its global behavior. To achieve this, the reference in the pre-processing step is modified as (Fig. 4) :

$$\begin{cases} a_y^p = k_{v_x\dot{\psi}} HP_{v_x\dot{\psi}}(s) v_x\dot{\psi} + k_{\dot{v}_y}\dot{v}_y \\ \dot{\psi}^p = k_{\dot{\nu}} HP_{\dot{\nu}}(s)\dot{\nu} - k_{\dot{\beta}}\dot{\beta} \end{cases} \tag{14}$$

where $HP_{\cdot}(s)$ is the high pass filter operator, $k_{v_x\dot{\psi}}$, $k_{\dot{v}_y}$, $k_{\dot{\nu}}$ and $k_{\dot{\beta}}$ are the gain used to tune the algorithm.



(a) Vehicle lateral dynamics.



(b) Platform lateral dynamics comparison with and without yaw dynamics feature.

Figure 5: Lateral dynamics of the vehicle and of the platform for an S curve maneuver with radius 20m driven by a GT car.

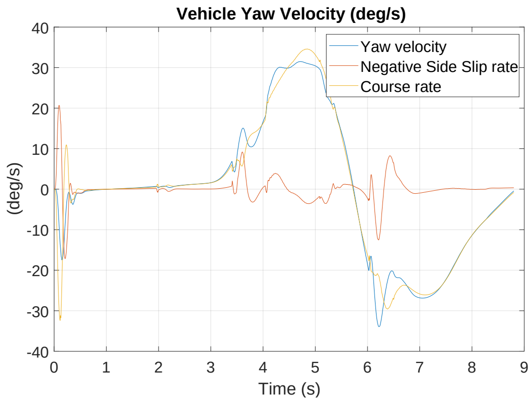
Experimental Test

	w\o Yaw Dynamics	w\i Yaw Dynamics
$k_{\dot{v}_y}$	–	0.5
$k_{v_x\dot{\psi}}$	–	0.5
$k_{\dot{\nu}}$	–	1
$k_{\dot{\beta}}$	–	1
k_{ay}	0.5	–
$k_{\dot{\psi}}$	1	–
$HP_{v_x\dot{\psi}}$	–	$0.5Hz$
$HP_{\dot{\nu}}$	–	$0.5Hz$
HP_{a_y}	$0.5Hz$	–
$HP_{\dot{\psi}}$	$0.5Hz$	–

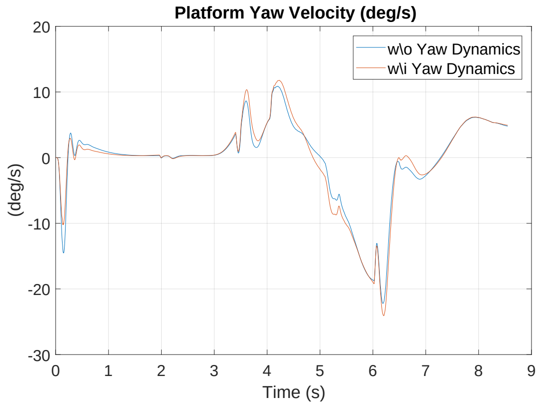
Table 1: Parameters used in the pre-scaling phase for the generation of the references for the MCA

The validation of the proposed MCA is performed on an innovative device, commercialized by VI-grade GmbH, referred to as Driver in Motion (DiM). DiM is based on a mechanical architecture with redundant DOF that allows to obtain larger operational workspace and system bandwidth for a given overall assembly size with respect to traditional hexapodal platforms (in Fig. 8 a picture of the DiM is reported).

A double S curve performed with a GT car is used as reference maneuver. The tuning of the parame-

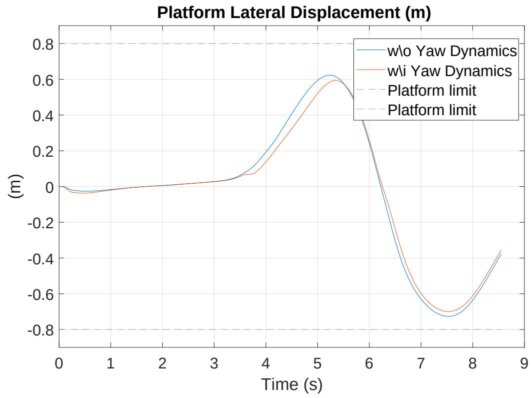


(a) Vehicle yaw dynamics.

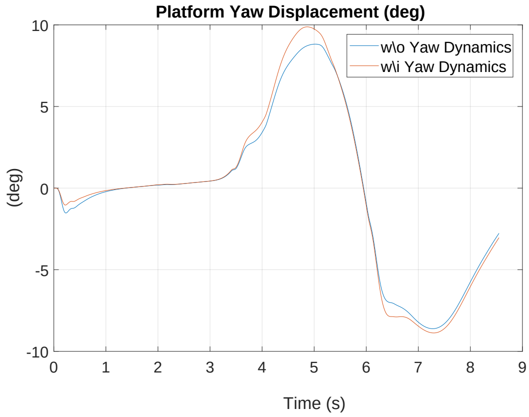


(b) Platform lateral dynamics comparison with and without yaw dynamics feature

Figure 6: Yaw dynamics of the vehicle and of the platform for an S curve maneuver with radius 20m driven by a GT car.



(a) Platform lateral displacement.



(b) Platform yaw displacement.

Figure 7: Comparison of lateral and yaw displacement with and without yaw dynamics feature.

ters has been conducted working with four professional drivers. In Tab. 1 the values are reported. In Figg. 5 and 6 lateral accelerations and yaw velocities of the vehicle and of the simulation platform are reported. A comparison with the MCA without yaw dynamics correction is reported as well. Three over-steer actions can be observed in the maneuver at second 3.5, 4.3 and 6.3. In those cases the direct lateral acceleration, $\dot{v}_y$, and the course rate, $\dot{\nu}$, shows a peak of intensity, as expected. Comparing the MCA with and without the yaw dynamics feature it is possible to observe that the most significant differences are in concurrence with the over-steer actions. Note that the relative impact of the yaw dynamics feature on the lateral acceleration is much greater than the yaw velocity. In fig. 7 the platform displacements are reported as well.

Drivers feedback can be summarized in a more fluid and natural transition between the linear and nonlinear behaviour of the tire dynamics, resulting in an easier driving experience.

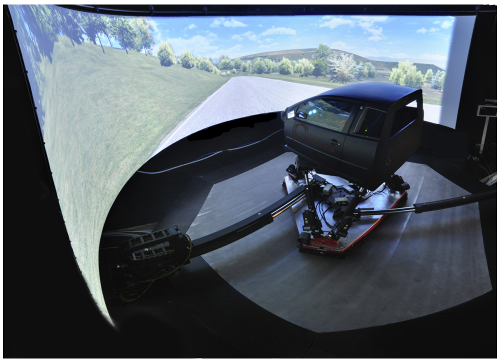


Figure 8: DiM platform.

Conclusion

In this paper an MPC based MCA is proposed with a new feature that allows to reproduce information on the side slip dynamics by means of a modification of the reference. The lateral acceleration and the yaw rate are split, isolating the side slip dynamics components. An experimental test has been conducted with a positive feedback from four professional driver. Summarizing, the advantages of the proposed solution a :

- a realistic reproduction of the vehicle's transient behaviours, giving a more natural feeling to the driver (oversteering/understeering) ;
- no need for pre-processing step and a-priori knowledge of the vehicle model ;

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